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Assessing Sustainability of Managed End-of-life Options for Bio-based Products in a Circular Economy

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Abstract

This report describes the development of an environmental impact assessment framework dedicated to evaluating the sustainability characteristics of managed end-of-life routes relevant to bio-based products. This environmental assessment framework was developed in coherence with the recommendations made within the Product Environmental Footprint guidance which in turn complies with the ISO14040 and EN16760 standards for life cycle assessment (LCA) of products. The framework consists of a set of LCA impact indicators and novel, non-LCA 'hybridised' indicators which were developed based on the combination of principles of resource efficiency and green chemistry.

The aim of this extended framework is to quantify and highlight the use of potentially hazardous chemicals, describe effective resource utilisation and waste reduction strategies employed in given technology routes, alongside reporting the impacts and credits associated to resource production and consumption during the management of post-consumer products. In addition to these indicators, science-based relative thresholds have been proposed. These thresholds were developed based on the qualitative guidance presented within global initiatives and goals including the United Nation's Sustainable Development Goals and Paris Climate Agreement. Nevertheless, this study does recommend the use of subjective thresholds based on consensus reached with a broad range of stakeholders.

To test the effectiveness of the framework, the developed methods and metrics were adopted for a follow-on environmental impact evaluation and applied to the end-of-life management of the selected bio-based products and their petroleum-derived commercial counterparts. As many managed end-of-life options as practical were captured within this study, following the guidance provided under CEN/TR/16957 for developing end-of-life inventory for bio-based products. The outcomes of this method evaluation, its strengths and limitations have been elaborated within this report.

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Abbreviations

AD	Anaerobic digestion
ASF	Alternative Solid Fuel
AWARE	Available Water Remaining
B2B	Business to Business communication
BoPLA	Biaxially Oriented Polylactic acid
BoPP	Biaxially Oriented Polypropylene
BSI	British Standards Institution
CE	Circular Economy
CED	Cumulative Energy Demand
CFF	Circular Footprint Formula
CHP	Combined heat and power
CO2	Carbon Dioxide
CTUh	Comparative toxic units (human)
ECHA	European Chemicals Agency
EC-JRC	European Commission Joint Research Centre
EMF	Ellen MacArthur Foundation
EoL	End of life
EoL-EI	EoL Energy Intensity
$EoL\text{-}EI_{Disp.}$	EoL Energy Intensity from disposal via incineration or landfill (without energy recovery
$EoL\text{-}EI_{AD}$	EoL Energy Intensity from Anaerobic Digestion
$EoL\text{-}EI_{Inc.}$	EoL Energy Intensity from Incineration (with energy recovery)
EoL-WF	EoL Waste factor
ER	Energy recovery
EU	European Union
E-waste	Electronic waste
GHG	Greenhouse gas
GWP-Bio	Biogenic Global Warming Potential
HDPE	High density polyethylene
kgCO2 eq	Kilograms of carbon-dioxide equivalent
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LDPE	Low density polyethylene
LHV	Lower Heating Value
LLDPE	Linear Low-Density Polyethylene
MFA	Material Flow Analysis
MJ	megajoule
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
NO_x	Nitrogen oxides
PB	Planetary Boundary
PCPF	Post-consumer Packaging film
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PET	Polyethylene Terephthalate
PLA	Polylactic acid
PP	Polypropylene
RRR	Recoverability, Reusability, Recyclability
SME	Small to Medium Enterprise
Sox	Sulphur Oxides
SRP	Secondary Resource Productivity
UNEP	United Nations Environment Programme
UN-SDGs	United Nations Sustainable Development Goals
UV	Ultraviolet

UVCB	Unknown, variable composition, complex reaction products or biological material
VOC	Volatile Organic Compounds
WFD	Waste Framework Directive
WID	Waste Incineration Directive

Executive Summary

This technical report describes the development of an environmental impact assessment framework dedicated to evaluating the sustainability characteristics of managed end-of-life routes relevant to bio-based products. The framework consists of a set of LCA impact indicators and novel, non-LCA 'hybridised' indicators which were developed combining the principles of green chemistry and resource efficiency. This environmental assessment framework was developed in coherence with the recommendations made within the Product Environmental Footprint (PEF) guidance which in turn complies with the ISO14040 and EN16760 standards for life cycle assessment (LCA) of products. The scope of the indicators was also aligned with the EN16751 standard for the sustainability criteria for bio-based products.

The aim of this extended environmental framework is to quantify and highlight the use of potentially hazardous chemicals, describe effective resource utilisation and waste reduction strategies employed in given technology routes, alongside reporting the impacts and credits associated to the material flow across the use and end-of-life management of post-consumer products. The LCA and the non-LCA indicators captured as a part of this EoL impact assessment framework include:

- Acidification;
- Particulate matter;
- Global warming potential;
- Terrestrial and freshwater eutrophication;
- Human toxicity;
- Fossil-resource depletion;
- Water scarcity.

The impact assessment framework has been extended with resource efficiency and circularity indicators which include:

- Presence of Hazardous chemicals (indicative only);
- Secondary resource productivity;
- EoL Waste factor;
- EoL Process material circularity;
- EoL Energy intensity;
- Product circularity.

In addition to these indicators, science-based relative thresholds have been proposed. These thresholds were developed based on the qualitative guidance presented within global initiatives and goals including the United Nation's Sustainable Development Goals and Paris Climate Agreement. Nevertheless, this study does recommend the use of subjective thresholds based on consensus reached with a broad range of stakeholders.

To test the effectiveness of the framework, the developed methods and metrics were adopted for a follow-on environmental impact evaluation and applied to the end-of-life management of the selected bio-based products and their petroleum-derived commercial counterparts. As many managed end-of-life options as practical were captured within this study, following the guidance provided under CEN/TR/16957 for developing end-of-life inventory for bio-based products. This report provides a detailed account of the environmental impacts, resource efficiency and circularity credentials that have been quantified for the bio-based case studies and the fossil-based case studies, using the proposed environmental framework. The benefits of utilising the proposed framework, embedded issues and recommendations for further improvement have also been captured.

1 Context

The average solid waste generated per person consumer amounts to 0.74kg per day, varying between 0.11 to 4.54 kg per day depending on the rate of development of a nation's economy[1]. According to the cited report by the World Bank (2019), 35% of the solid wastes are generated by high-income countries, despite only representing 16% of the world population. Particularly, construction waste contributes to about 33% of the total waste generated in the EU followed by mining and quarrying (29%), relative to other economic activities. Of all the waste generated, only 36% is recovered via recycling or energy recovery, while 41% gets landfilled, with the remaining back-filled, treated or subjected to incineration without further benefits[2]. These statistics may not reflect the amount of waste that is exported to other countries as *waste for recycling*. This is particularly relevant in the current situation where the lower and middle-income countries, that were previously accepting waste streams of plastics and e-waste, are now imposing strict standards on acceptable waste streams or bans on specific waste types (plastic) in a race to meet their committed targets for global waste reduction[3]. The world is currently facing a waste crisis. which is also directly related to climate crisis. There is now a global awareness on the environmental impacts of a "take, make and dispose"- style linear economy and a recognised need to commit and act upon the agreed climate change mitigation targets, including the Paris Agreement and the Sustainable Development goals (UN-SDGs). There is a common realisation in these targets that one of the most effective ways to reach sustainable development is through circular thinking. The Sustainable Development Goal 12 indicators are dedicated to measuring, monitoring and reporting responsible material consumption, re-utilisation (if possible) and disposal. De wit et al, 2019, in their report on climate change and circular economy, has highlighted that reaching the Paris Agreement targets for the reduction of global warming by about 1.5°C is possible only through the reduction of material extraction. It also indicated that the global industrial sector is only 9% circular, visually presenting a relationship between materials extracted, value added and its associated GHG emissions estimated to up to 2050 (Figure 1)[4]. This relationship has been termed the "Mass-Value-Carbon" nexus. Circularising the processing sectors has now been recognised as crucial to meet the Paris Climate Accord by the United Nations Climate Change committee[5].

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1 The World Bank, "Trends in Solid Waste Management".

2 European Parliamentary Research Service, "Towards a Circular Economy: Waste Management in the EU".

3 "ASEAN Urged to Adopt Full Ban on Plastic Waste Imports"; "India Bans Imports of Plastic Waste"; "South-East Asian Countries Are Banning Imports of Waste for Recycling".

4 De Wit et al., *The Circularity Gap Report: Closing the Circularity Gap in a 9% World*.

5 UNFCCC, "Circular Economy Crucial for Paris Climate Goals | UNFCCC".

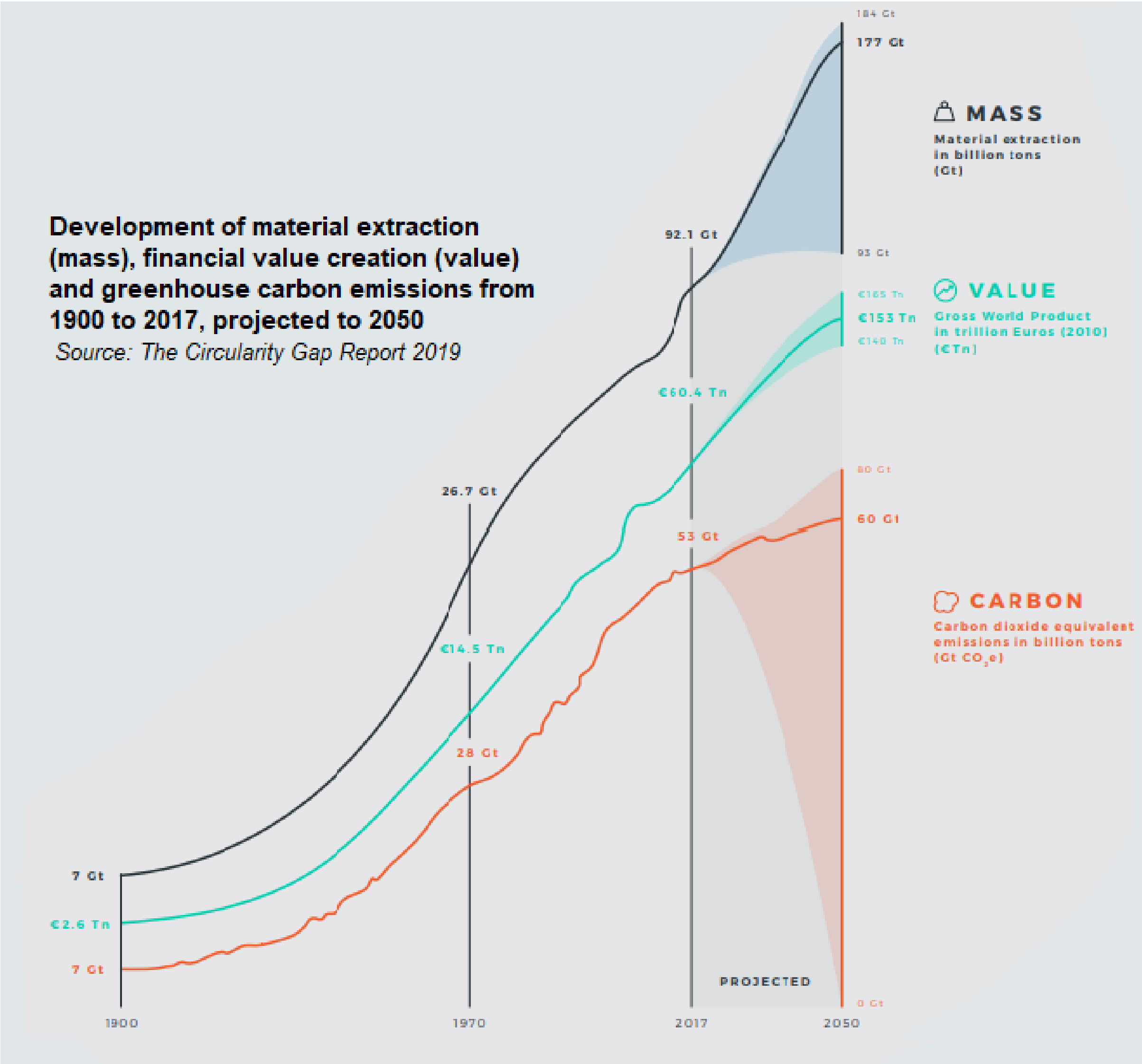

Figure 1: The Mass-Value-Carbon nexus highlighting the links between material consumption and global GHG emissions.

2 Introduction

The EU's Circular economy package was proposed with the intent to drastically reduce the amount of waste that is destined for landfilling and to encourage the recycling and reuse of materials already embedded in the economy. The bio-based sector in particular, which includes, agriculture, forestry, bio-energy and bio-products, provides a possible pathway to improve the circular potential of the industrial sector. In fact, the European Commission has set out a new bioeconomy strategy to augment the European bio-based sector through encouraging policy and decision-makers to work closely with bio-based SMEs and the value-chain actors, development of standards and certification protocols dedicated to fast-track the assessment and documentation of bio-based products, mobilisation of private and public stakeholders into research, innovation and deployment of sustainable solutions[6]. Circularising the bio-based sector caters directly to 14 out of the 17 UN SDGs. However, the success of this collaboration is influenced by a number of factors including the spatial spread of the supply chain, local practices and awareness of waste handling, responsibility and management (policy and jurisdictional influence), prevalence of technology routes and readiness for waste valorisation, material circularisation and infrastructure developmental preferences. Identification, techno-economic and policy support for sustainable bio-based solutions to conventional fossil-derived resources (oil and minerals) is a promising start for our journey towards a circular economy. The term "sustainable", refers to bio-based products that are not only fit-for-purpose but also designed adhering to the principles of green manufacturing and to be reused or effectively reclaimed; not to be landfilled relying on their biodegradation capabilities. This is particularly a challenge within the bio-based sector since the current economic activities and technology readiness for the majority of bio-based products are still at infancy. The lack of commercially viable volumes of bio-based products in the market limits the opportunity for these products to be effectively recovered and reclaimed. Polylactic acid is good example, in its current state, it is a contaminant in a waste polyethylene or waste polypropylene stream, destined for recycling. There is also limited coverage, via standards and certifications, on the overall life cycle of bio-products. This was evident from STAR-ProBio's review of 40+ standards and certification protocols, undertaken and elaborated in a gap analysis Deliverable 1.1[7], particularly the standards for bio-based products, CEN/TC/411. The reason for this lack in coverage of guidance is due to the limited availability of approaches that explicitly quantify the impacts and credits related to production and end-of-life management of bio-based products in the context of circular economy.

[6] Johnson, "New Bioeconomy Strategy Supports the 2030 Agenda and Paris Agreement".

[7] Majer et al., *Report on Identified Environmental, Social and Economic Criteria/Indicators/ Requirements and Related "Gap Analysis"*.

3 Objectives and Approach

The purpose of this research is to develop a novel EoL impact assessment framework, incorporating the principles of resource efficiency and circular economy into life cycle thinking to evaluate the environmental performance of bio-based products and processes, in a disaggregated and rather informative approach. Serving as a follow-on study from that reported for manufacturing and distribution processes in Deliverable 3.1[8], this study is dedicated to the identification, development and application of appropriate methods that create a level-playing field for the comparative environmental evaluation of bio-based products and fossil-based products from "product use" to their "end-of-life" management Figure 2. The proposed framework has been developed in adherence to the international life cycle assessment standards (ISO14044 and EN 16760), while complementing the sustainability criteria for bio-based products (EN16751 standard). A set of impact categories (and/or indicators) have been proposed to aid a systematic environmental evaluation of such bio-based products. The proposed methodology have been tested for robustness and validated through a comparative evaluation of bio-based and their fossil-based counterparts. The overall aim of the framework, applied between the "gate to grave" stages of the life cycle of selected bio-based products, was to determine if:

- Bio-based product can be a sustainable promising solution to their petro-derived or less-sustainable bio-derived commercial counterparts;
- Bio-based product can be produced via a process that has been designed for sustainable greener manufacturing approaches;
- Bio-based product, as a whole or in part, be circularised;
- Bio-based product is free of any substances of very high concern (hazardous substances);
- Bio-based product is designed to minimise production and product-level waste reaching the least desirable 'End-of-life' (EoL) option, landfill.

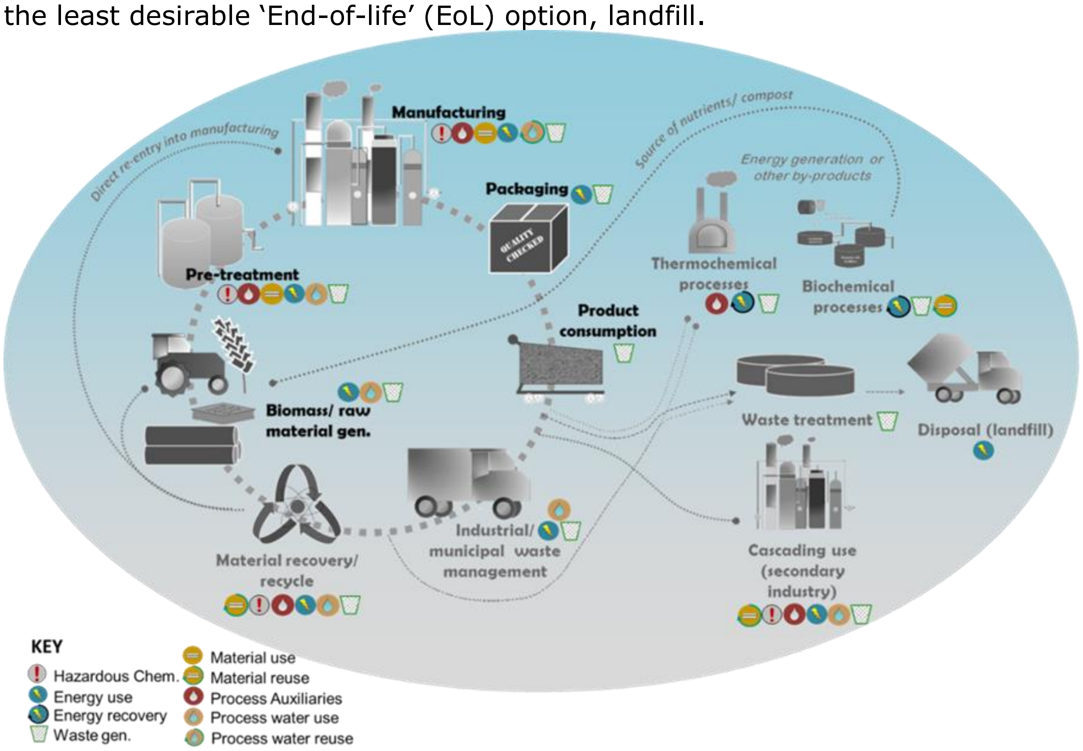

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Figure 2: A typical circular bio-based value chain with an overview of potential resource utilisation and wastage characteristics

[8] STAR-ProBio, *Deliverable 3.1: Expanding Environmental Sustainability Criteria to Address the Manufacturing and Other Downstream Processes for Bio-Based Products.*

3.1 Scope: Product use, recovery and end-of-life management

The proposed environmental impact assessment framework was subjected to a validation process applying it to the specific bio-based case studies and carefully chosen set of intended and alternative scenarios, exclusively within this report. The first half of the downstream impact assessment (represented as Stages 3, 4 and 5 in Figure 3) was included in Deliverable 3.1. The aim of this report is to undertake a similar exercise for Stage 6 of the cycle by proposing/ developing a unique and set of LCA and 'hybridised' indicators to apply to the relevant managed EoL options, thus providing a comparative environmental evaluation of the selected bio-based case studies and their fossil-derived counterparts.

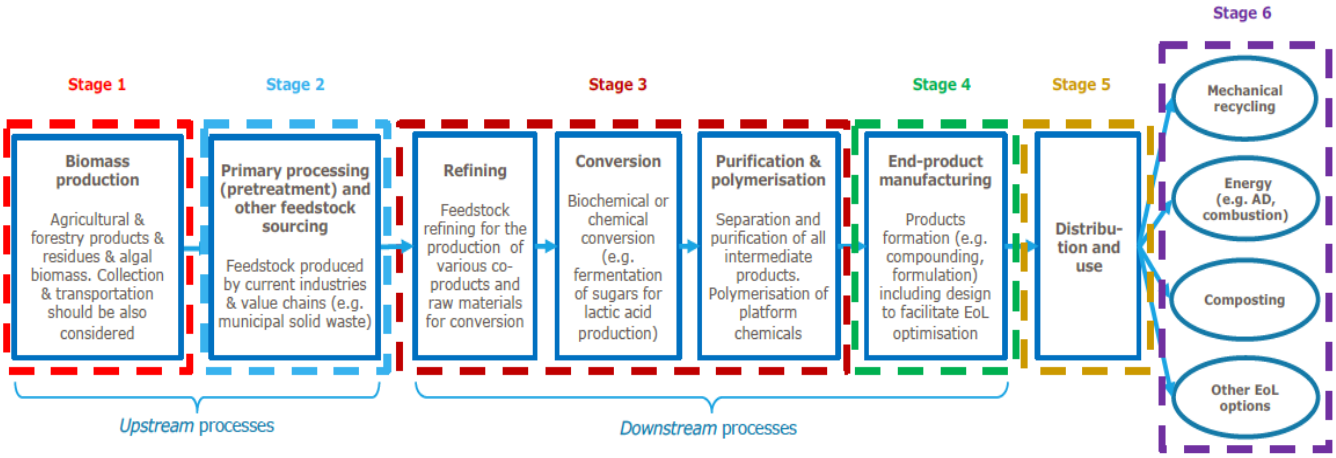

Figure 3: "Cradle-Grave" life cycle stages of a bio-based product

Once an appropriately designed product is used by a consumer (one or many times) it enters one of the managed end-of-life routes. A more detailed account of the different managed EoL routes for the bio-based products, has been provided in the supplementary section 7.1). From an environmental perspective, the sustainability credentials of a bio-based or a fossil-based product may be evaluated based on its hypothetical waste categorisation following the Waste hierarchy[9] as defined by the Waste Framework Directive[10] (WFD). The waste categorisation can be based both on the manufacturer recommended product functionality, life, and disposal methods and from a consumer's wisdom and imagination on maintaining the functionality of the product via responsible use of the product by repairing and re-using it beyond its recommended life-time. For example, the manufacturer recommends discarding used PET water bottles for recycling after first use versus the consumers refilling these PET bottles with water. In the second case, at the end of its first use, the product is functional and still in use, and therefore has not reached the end-of-life. When placing the product on the waste hierarchy, the two main tiers the product could fall under are either "prevention of waste" (products after consumption are reused) or "preparation for reuse" (where the product after consumption are cleaned, refurbished and repaired or in part).
This phase corresponds to the two of the three 3Rs of waste management and material recovery approaches recommended for circularisation of products[11].

[9] Waste hierarchy is a guidance framework that ranks the managed EoL routes based on which options is the best for the environment

[10] The Directorate General- European Commission, "Guidance on the Interpretation of Key Provisions of Directive 2008/98/EC on Waste".

[11] United Nations Department of Economic and Social Affair, "Promotion of the 3Rs (Reduce, Reuse, and Recycle) in Asia and the Pacific Promotion of the 3Rs (Reduce, Reuse, and Recycle) in Asia and the Pacific | Capacity Development".

3.2 Existing tools, techniques and conformity with standards and resource efficiency targets

A number of studies employ life cycle assessment (LCA)[12] to evaluate/quantify the EoL environmental impact, while other studies employ the inventory-based resource efficiency and material circularity methodologies, highlighting the significance of considering the transition of products and processes to that of a circular economy[13]. LCA is a standardised, fit-for-purpose approach that helps measure the environmental performance of products or processes. Use of a standardised set of impact categories, associated indicators and methodologies[14] mean that the assessors may employ these approaches to make a useful comparison between products sourced from different types of starting materials (bio-based, fossil-based and products from secondary resources). Moreover, the CEN/TC/411 standards for bio-based products recommend the environmental sustainability of bio-based products be evaluated following the guidance provided under EN16760: LCA of bio-based products[15].

A selection of relevant impact categories to evaluate the bio-based products from a 'cradle-grave' perspective and recommendations that appropriately interpret and visualise the environmental performance was completed. LCA fulfils the incorporation of impact categories suitable for product stewardship encompassing the overall GHG emissions, water and fossil-resource consumption, ecotoxicity and human toxicity. However, in our current transition to a robust, bio-based, circular economy, there is a greater need for trust and transparency in operational reporting procedures, and LCA provides limited visibility on the necessary information. Though LCA takes into account all forms of material flow, resource valorisation and circularisation strategies thoroughly, the technicality of the methods and the outcomes limit the efficacy with which the product's sustainability credentials could be communicated to the diverse nature of non-technical stakeholders embedded in a value chain, including investors, distributors, policy-makers and the consumers. Though this cannot really be called a 'gap', an exercise entailing a sustainability evaluation, within the context of circular economy, requires the incorporation of appropriate performance metrics to quantify the resource utilisation efficiency and waste reduction. "To measure is to know" and this is particularly true in visualising and optimising our transition to a fully-fledged circular economy. According to a study by Moraga et al, 2019, circular indicators, that are particularly being applied to life cycle thinking, should be able to capture the resource circularity either as a direct result of the technological cycles involved in the production process (for example, Recycling rate) or for the product itself (recoverability, reusability, recyclability (RRR)) [16].

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[12] Alarico, "Life Cycle Assessment Study of Polylactic Acid Packaging Including Food Waste"; Cosate de Andrade et al., "Life Cycle Assessment of Poly(Lactic Acid) (PLA)"; Choi, Yoo, and Park, "Carbon Footprint of Packaging Films Made from LDPE, PLA, and PLA/PBAT Blends in South Korea"; Franklin Associates, *Life Cycle Impacts for Postconsumer Recycled Resins: PET, HDPE and PP*; Gu et al., "From Waste Plastics to Industrial Raw Materials"; Maga, Hiebel, and Thonemann, "Life Cycle Assessment of Recycling Options for Polylactic Acid"; Rossi et al., "Life Cycle Assessment of End of Life Options for Two Biodegradable Packaging Materials: In Support of Flexible Application of the European Waste Hierarchy"; Rajendran et al., "Plastics Recycling".

[13] Lacovidou et al., "Metrics for Optimising the Multi-Dimensional Value of Resources Recovered from Waste in a Circular Economy"; Linder, Sarasini, and Loon, "A Metric for Quantifying Product-Level Circularity"; D'Amato et al., "Green, Circular, Bio Economy"; Ellen MacArthur Foundation, "Circularity Indicators"; Genovese et al., "Sustainable Supply Chain Management and the Transition towards a Circular Economy"; http://vlaanderen-circulair.be, "Indicators for a Circular Economy - Vlaanderen Circulair"; Pan et al., "Strategies on Implementation of Waste-to-Energy (WTE) Supply Chain for Circular Economy System".

[14] International organisation of Standardisation, "ISO14044:2006: Environmental Management -- Life Cycle Assessment -- Requirements and Guidelines".

[15] CEN European Committee for Standardization, "BS EN 16760:2015: Bio-Based Products: Life Cycle Assessment".

[16] Moraga et al., "Circular Economy Indicators".

In 2014, Eurostat published a *resource efficiency scoreboard* to be used as a vital tool in the monitoring and communication of effective resource utilisation, suggesting several indicators appropriate for the macro (for example, per capita) and micro-level (product-specific) analysis[17]. Some of the indicators proposed in this literature include quantification of waste generated, recycling rate of waste and landfill rate of waste. Similarly, Ellen MacArthur Foundation's Material circularity[18] Index suggests the use of a material circularity indicator which analyses the inventory-level information, including the amount of waste generated across the life cycle of a product and efficiency of secondary resources generated from the EoL processes. Needless to say, most of the global sustainability goals were based on UN-SDGs, which explicitly address efficient resource utilisation, environmental management of production process to reduce impacts on human and ecological health, in addition to addressing waste reduction through prevention, reducing, recycling and reuse of materials though SDG 12[19].

The practical implications of the RRR (recoverability, recyclability and reuseability) have posed a few hurdles when applied to real-world waste management practices. For example, when looking to apply the RRRs to plastics, within the material recovery facilities (MRFs), recoverability is hindered by a number of social and techno-economic factors, as highlighted in Table 1.

Table 1: Factors contributing to issues with the implementation of RRRs

Social factors	
Manufacturing	***Consumption***
Making sustainable product designs	Making sustainable product choices
Use of hard-to-separate polymer blends and potentially harmful additives – Affects disassembly of products	Only seeking products of convenience and potential 'Cult-brand'
Techno-economic factors	
Lack of appropriate state-run infrastructure to educate, communicate, collect and sort and process waste	
Wider lack of appropriate best available technologies (BAT) to sort, clean and recycle fractions that are 'currently non-recyclable' (due to heavily degraded nature of the components).	Limited opportunities to repair (too expensive to be done via the manufacturer's outlet or a complete lack thereof) or to difficulty in cleaning and disassembling a used product prior to its disposal (due to such a product design).

These factors have been particularly pronounced in the case of bio-based plastics, due to lack of demand, which in turn stems from their lower level of commercial circulation. Cross-contamination of starch in plastics and fabrics could result in the recovery of low-quality monomers, impacting the overall economic feasibility (and eventually the comparative environmental performance) of the resulting material[20]. Therefore, the quality of resources resulting from implementing the RRRs is as significant as the sustainability performance of the end-of-life management processes. Hence, Huysman et al, 2017, proposed the "circularity performance indicator" which is defined as the ratio of the actual environmental benefit obtained from the EoL process, relative to the environmental benefit obtained from an ideal set of EoL management approaches based on the composition and quality of the waste stream assessed: for example, a comparison of a closed loop product transformation to that of waste management via incineration[21].

[17] Demurtas et al., *EU Resource Efficiency Scoreboard 2014*.
[18] Ellen MacArthur Foundation, "Circularity Indicators".
[19] United Nations Initiative on global geospatial information management, "Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators".
[20] Alaerts, Augustinus, and Van Acker, "Impact of Bio-Based Plastics on Current Recycling of Plastics".
[21] Huysman et al., "Performance Indicators for a Circular Economy".

To overcome these challenges and seek ways to implement circular economy strategies at an organisational level, the British Standards Institution (BSI) developed an authoritative guidance "BS8001:2017: Framework for implementing the principles of the circular economy in organizations. Guide" [22]. With its guiding principles based on that of circular economy, this standard provides a set of terms, definitions and indicators that organisations implementing circular economy need to incorporate in their practices. However, it gives very little guidance on approaches to monitor, optimise and report these practices, according to a study by Pauliuk.S, (2017)[23]. This study also details information on other approaches on circularity assessments and material flow analysis linked to circular economy. Some of the indicators that are relevant to addressing the environmental sustainability of a product are presented in Table 2.

Table 2: Environmental indicators generally adopted within the industrial sector

Indicator	Source
Waste reduction (compared to baseline production process or products)	[24]
Active replacement of primary resources (via appropriate EoL activities)	[25]
Change in life cycle GHG emissions	[26]
Cumulative energy demand (CED)	[27]
Water, Land and Material footprint	[28]

In 2018, Walker et al[29], recommended dedicated approaches to quantitatively report life cycle emissions associated to a product following recycling and for reuse/ refurbishment routes of end of life management. These expressions are presented below:

- For recycling

$$E = E_{man} - (R_{2\_}R_1)Y(E_v - E_{recycle})$$

[22] British Standards Institution, "BS 8001:2017 Framework for Implementing the Principles of the Circular Economy in Organizations. Guide".

[23] Pauliuk, "Critical Appraisal of the Circular Economy Standard BS 8001".

[24] British Standards Institution, "BS 8001:2017 Framework for Implementing the Principles of the Circular Economy in Organizations. Guide"; Ellen MacArthur Foundation, "Circularity Indicators".

[25] Ellen MacArthur Foundation, "Circularity Indicators"; Geyer et al., "Common Misconceptions about Recycling".

[26] International organisation of Standardisation, "ISO14044:2006: Environmental Management -- Life Cycle Assessment -- Requirements and Guidelines"; International organisation of Standardisation, "ISO 14045:2012 : Environmental Management- Eco-Effcieincy Assessment of Product Systems - Principles, Requirements and Guidelines".

[27] International organisation of Standardisation, "ISO 14045:2012 : Environmental Management- Eco-Efficiency Assessment of Product Systems - Principles, Requirements and Guidelines"; International organisation of Standardisation, "ISO14044:2006: Environmental Management -- Life Cycle Assessment -- Requirements and Guidelines"; European Commission - Joint Research Centre - Joint Research Centre- Institute for Environment and Sustainability, "ILCD Handbook: International Reference Life Cycle Data System Handbook- General Guide for Life Cycle Assessment -Detailed Guidance".

[28] International organisation of Standardisation, "ISO 14045:2012 : Environmental Management- Eco-Efficiency Assessment of Product Systems - Principles, Requirements and Guidelines"; European Commission - Joint Research Centre - Joint Research Centre- Institute for Environment and Sustainability, "ILCD Handbook: International Reference Life Cycle Data System Handbook- General Guide for Life Cycle Assessment -Detailed Guidance".

[29] Walker et al., "Evaluating the Environmental Dimension of Material Efficiency Strategies Relating to the Circular Economy".

E = *Life cycle impact relative to the entire product life cycle after accounting for recycling*

E_{man} =*Life cycle impact relating to manufacture of a product containing a proportion of recycled content* (R_1)
E_v =*Life cycle impact relating to 100% primary production*
$E_{recycle}$ =*Life cycle impact relating to 100% secondary production*
R_1 =*The proportion of recycled content which is used in manufacturing the product*
R_2 =*The recovery rate of material at end-of-life which is recycled*
Y =*The efficiency, or yield, of the secondary production process*

- For refurbishment and reuse

$$E = E_{man} + nE_{reuse} - (R_2 - R_1)Y(E_v - E_{recycle})$$

E_{reuse} = *Life cycle impact relating to the refurbishment for reuse*
n = *Number of times the product is reused before disposal or recycling*

The sector that was considered as the reference for the proposal of the above indicator and calculation of material circularity is a well-established and technologically-advanced infrastructure, metal manufacture and recovery. Application of these approaches to the rather new bio-based sector may face hurdles from data availability. Additionally, the impact of the differences in the quality of secondary resources that are recycled, recovered and reused have not been captured by the above methodology.

Understanding the metrics that are currently in use for evaluating the environmental sustainability of a product or a process is an essential starting point to the development of unique approaches to address the goals of this environmental framework development. At the end of this literature consultation, a set of LCA and exclusively developed 'hybridised' indicators were proposed as a initiatory approach for quantitatively assessing the environmental performance of the EoL management of bio-based products. This approach was proposed in a way that it is coherent with the methods applied for upstream processes (manufacturing and product distribution stages 3, 4 and 5 in Figure 3). The environmental impact assessment methodology that has been applied has been elaborated in greater detail in the next section.

4 Environmental Sustainability framework: Methods and metrics

4.1 Goal, scope and functional unit of analysis

The purpose of this study is to identify or develop a robust environmental assessment framework to systematically quantify the burdens associated with the use and end-of-life treatment of bio-based post-consumer articles. The proposed framework is composed of a set of LCA and non-LCA indicators, in which the latter will be developed from a combination (hybridisation) of industrially-implemented resource efficiency, green chemistry and material circularity indicators and principles. This comparative environmental impact assessment will, therefore, encompass the following stages

- Product consumption (along the product's lifespan)
- Post-consumer product removal
- Transportation and management of the post-consumer article
- Product's end-of-life management

To test the effectiveness of the proposed framework, a comparative LCA of the bio-based product was undertaken, weighing its impacts and credits against those of the fossil-derived counterparts. The temporal and spatial boundaries for this environmental evaluation were assumed as follows: European average in the current time period. For the purpose of coherence and continuity with the upstream processes (from manufacturing to distribution to consumers, undertaken and reported in Deliverable D3.1), the same set of functional units have been adopted here.

Of the two case studies considered for the validation of the proposed methodology, the first one is **packaging film.** To ensure that the proposed framework is applicable to both the "assumed sustainable" bio-based product and the "conventional" fossil-based product, a comparative environmental evaluation was undertaken. The functional unit chosen for the *packaging film* case study is *1 piece*, which, in the case of the bio-based Biaxially Oriented Polylactic acid (BoPLA) films was 350 mm × 250 mm with a thickness of 0.025 mm to ensure the protection of a horticulture produce during transportation and shelf life, between packaging and consumption by consumer. The product specification in the case of the baseline candidate, biaxially oriented polypropylene (BoPP) for one film of is a thickness of 0.025 mm at dimensions of 350 mm × 250mm.

The second case-study was **agricultural mulch films** and the functional unit of analysis for partially bio-based PLA-based mulch film was that *required to mulch 1ha of agricultural land for a period of one crop rotation*. The mulch film synthesised from PLA (45%) and a co-polymer with UV-stabilisers and carbon black (remaining fraction) was assumed to be 0.012mm thick with a density of 1.4g/cm3, leading to an overall requirement of 152kg of PLA/co-polymer film per hectare of agricultural land. The fossil-based baseline case encompasses the environmental impact assessment of Linear Low density polyethylene (LLDPE) mulch film with an average thickness of 0.025mm and a density of 0.918g/cm3 requiring 185 kg of mulch film for a hectare of agricultural land.

The resource leakages occurring in the stages within the scope of this study will be taken into account during the environmental evaluation and reported as a part of the inventory information for reference. At the end of the study, the consolidated downstream environmental impact, spanning from the manufacturing phase to the product fate (end-of-life) has been presented, incorporating the outcomes from D3.1. Please refer to section 4.3 for details of the EoL scenarios, associated assumptions and cut-off criteria.

4.1.1 Coherence and gap analysis with EN16751 and the Environmental EoL Sustainability criteria

Within this project, the standard for sustainability criteria of bio-based products (EN16751) was adopted as the reference template on which the environmental sustainability criteria for the EoL processing and management of products have been developed. Methodologies and indicators that highlight the sustainability characteristics, in addition to fulfilling the criteria specified within the EN16751[30] are composed of a combination of LCA impact categories and non-LCA (hybridised) indicators. The LCA impact categories used in this study keep to the recommendations and evaluation standards specified within EN16760: Bio-based products: Life Cycle Assessment[31] which is based on the International life cycle assessment standards ISO14040 and ISO14044[32]. The non-LCA (hybridised) indicators were proposed by the project to fulfil some aspects of material/energy efficiency, in addition to addressing the waste reduction strategies that may have been employed by the economic operators within a given supply chain. Though the non-LCA (hybridised) indicators were developed within STAR-ProBio, the purpose of their development was to contribute to and complement the sustainability principles and criteria suggested in EN16751. They were developed to encourage trust, transparency and communication among the supply-chain actors about the *sustainability aspects* of a product and its supply chain *"for business-to-business (B2B) communication or for developing product specific standards and certification schemes"* which is also the shared goal of STAR-ProBio.

EN16751 does suggests that it "*can be used for two applications; either to provide sustainability information about the biomass production only or to provide sustainability information in the supply chain for the bio-based part of the bio-based product".* Conforming to the recommended scope of this standard, the LCA impact categories, non-LCA hybridised indicators and their methodologies were adopted to provide sustainability information associated with the supply chain of the bio-based product. Please note that the scope of this analysis and method development is the use and EoL management of bio-based products. As a result, biomass productions, and the associated information on their sustainability credentials, have been excluded from this report. Additionally, this study does not intend to provide information on the management of sustainability aspects since it is not fall within the scope of the suggested indicators.

4.1.2 Product Environmental Footprint

Product Environmental Footprint (PEF) is a method developed by the European Commission Joint Research Centre (EC-JRC) which utilises LCA approaches to measure the environmental performance of products, goods and services, taking into account all the supply chain activities, starting from raw material extraction, up to their EoL management. The PEF methodology[33] provides a unique approach to quantifying the environmental impact of a product under the standardised impact categories taking into account the various material (raw material and waste streams) and energy flows associated to the life cycle of that product. This approach was developed for use, particularly within the European resource efficiency strategy for 2020, to be able for relevant value chain actors to undertake a comprehensive technical evaluation of products and processes for internal and external sustainability reporting and for participation in voluntary and mandatory programmes.

[30] CEN European Committee for Standardization, "BS EN 16751:2016: Bio-Based Product. Sustainable Criteria".

[31] CEN European Committee for Standardization, "BS EN 16760:2015: Bio-Based Products: Life Cycle Assessment".

[32] International organisation of Standardisation, "ISO14044:2006: Environmental Management -- Life Cycle Assessment -- Requirements and Guidelines".

[33] Zampori and Pant, *Suggestions for Updating the Product Environmental Footprint (PEF) Method*.

The list of LCA impact categories and indicators selected for the analysis in this project, were drawn from the recommendations made within the PEF Guidelines, to demonstrate the life cycle impacts in a coherent manner. Specifically, in this report, these impact indicators will be applied to the stages including product consumption, post-consumer article removal and transportation to the appropriate EoL treatment facility. The chosen LCA impact indicators, their methodologies and other descriptions are presented in Table 3. The selection criteria for these LCA indicators can be found in Deliverable 2.2 [34].

Table 3: Environmental LCA impact categories and indicators adopted for the proposed framework (based on the PEF recommendations)

Environmental impact	Impact category	Unit	Method
Emissions to air	Global warming potential Bio	*kg of CO_2 eq*	IPCC $GWP1_{100}$ complemented by GWP-BIO for biogenic carbon[35]
	Particulate matter	*Disease incidence*	PEFCR Guidance 6.3- Respiratory inorganics (UNEP recommended model)
	Acidification	*Mol H^+_{eq}*	PEFCR Guidance 6.3 – Acidification (terrestrial and freshwater) Accumulated exceedance model [36]
Emissions to water	Eutrophication	*kg P_{-eq}*	PEFCR Guidance 6.3 – Terrestrial Eutrophication (Accumulated exceedance) Freshwater Eutrophication (EUTREND model – ReCIPe 2008)
Human health	Human toxicity, cancer	*CTUh*	PEFCR Guidance 6.3 USEtox model
Abiotic resources	Fossil resource depletion	*MJ*	PEFCR Guidance 6.3 – Resource use, energy carriers Abiotic resource depletion- fossil fuels (CML 2002
Water use	Water scarcity	*m^3 water deprived*	PEFCR Guidance 6.3- Water Scarcity Available Water Remaining (AWARE): User deprivation potential [37]

4.1.2.1 PEF's Circular Footprint Formula

The PEF's circular footprint formula (CFF) was employed in this study to model the EoL management scenarios for the comparative environmental impact assessment. The PEF guidance, besides providing a set of impact indicators for upstream processes, also provides a unique approach to determine and allocate the impacts and credits drawn from the EoL management activities, taking into account a number of relevant factors which are as follows.

- Production and EoL related impacts
- Resource recovery rate
- Secondary and primary resource quality
- Supply/demand for the secondary resource

[34] STAR-ProBio, *Deliverable D2.2: Selection of Environmental Indicators and Impact Categories for the Life Cycle Assessment of Bio-Based Products*.

[35] Guest et al., "Consistent Quantification of Climate Impacts Due to Biogenic Carbon Storage across a Range of Bio-Product Systems".

[36] Seppälä et al., "Country-Dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator (14 Pp)".

[37] Boulay et al., "The WULCA Consensus Characterization Model for Water Scarcity Footprints".

- Impacts and credits from displaced material and energy

Dedicated empirical expressions, for potential product fate i.e. via resource (material and energy recovery and disposal), has been provided and the CFF is a combination of these expressions.

Material

$$(1-R_1)E_v + R_1 \times \left(AE_{recycled} + (1-A)E_v \times \frac{Q_{Sin}}{Q_p}\right) + (1-A)R_2 \times E_{recyclingEoL} - E_v{}^{*} \times \frac{Q_{Sout}}{Q_p}$$

Energy

$$(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$$

Disposal

$$(1-R_2-R_3) \times E_D$$

A	*=Allocation factor of burdens and credits between suppliers and users of recycled materials*
B	*= Allocation factor of burdens and credits from energy recovery processes*
QS_{in}	*= Quality of the ingoing secondary materials, i.e. the quality of recycled material at the time of substitution*
QS_{out}	*= Quality of the outgoing secondary material that is recyclable at the point of substitution*
Q_p	*= Quality of the primary (virgin) materials*
R_1	*= Fraction of material in the input to the production that has been recycled from a previous system*
R_2	*= Fraction of the material in the product that will be recycled in a subsequent system. Any leakages in the collection and recycling processes and the outputs from the recycling plant is taken into account within R_2*
R_3	*=Proportion of material in the product that is used for energy recovery at EoL*
$E_{recycled}$ (E_{rec})	*=Specific emissions and resources consumed from recycling process of the recycled (reused) material, including collection, sorting and transportation processes (per functional unit)*
$E_{recyclingEoL}$ (E_{recEoL})	*= Specific emissions and resources consumed from the recycling process at EoL, including collection, sorting and transportation process (per functional unit)*
E_v	*= Specific emissions and resources consumed from acquisition and pre=processing of virgin material (per functional unit)*
E^*_v	*= Specific emissions and resources consumed from acquisition and pre-processing of virgin materials that is substituted by secondary materials (per functional unit)*
E_{ER}	*= Specific emissions and resources consumed from energy recovery process (for example, via incineration with energy recovery, landfill with energy recovery, etc) (per functional unit)*
$E_{SE,heat}$ and $E_{SE,elec}$	*= Specific emissions and resources consumed from specific substituted energy source, heat and electricity respectively (per functional unit)*
ED	*= Specific emissions and resources from disposal of waste material at the EoL of the analysed product*
X_{ER} and $X_{ER,elec}$	*= Efficiency of the energy recovery process for both heat and electricity*
LHV	*= Lower heating value of the material in the product that is used for energy recovery*

Information regarding specific emissions and resources consumed for each of the EoL activities has been captured for each of the case studies. Default parameters have been provided for the allocation factors and quality characteristics of materials (i.e. A, B, QS_{in}, QS_{out}, Q_p, R_1, R_2, R_3), determined by the choice of resource, nature of application, resource recovery and disposal infrastructure and many other factors, via market-wide analysis. In the case of bio-based products (the material recovery infrastructure for which is still at infancy), specific default parameters were chosen based on the recommendations provided within the PEF guidance. The default factors chosen for each of bio-based case study has been summarised in the supplementary annex section.

4.1.3 Environmental Non-LCA 'Hybridised' indicators

In line with adherence to the principles of resource efficiency and circular economy, consumption of resources and generation of waste will need to be quantified/ addressed, alongside the impacts and burdens associated to the resource consumption within the boundary of the products in question. An overview of the potential material and energy flows through the managed EoL processes have been identified and visualised in Figure 4.

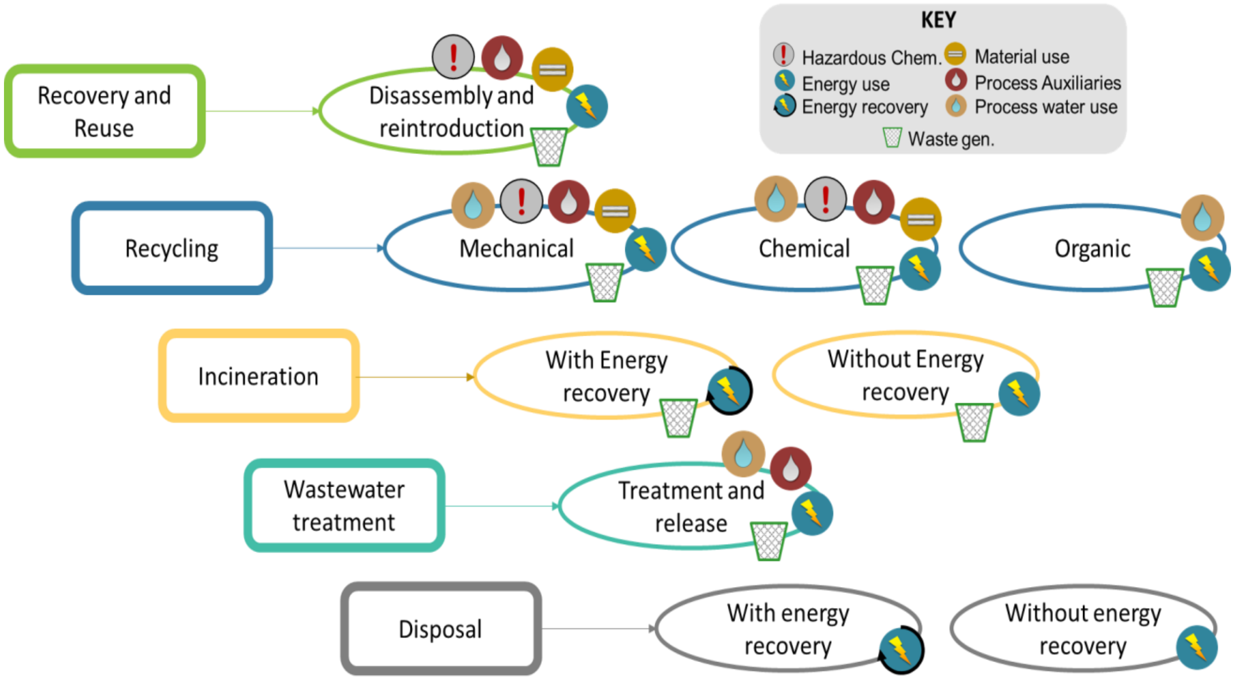


Figure 4: Identification of potential managed EoL options that fall within the scope of study and a visualisation of expected resource consumption and waste generation

Following this visualisation, a preliminary attempt was made at the development of dedicated resource efficiency environmental indicators employing the non-LCA indicators that were developed and applied to the manufacturing phase.

A list of the finalised EoL indicators has been provided below.

- Presence of Hazardous chemical (in the recycled material)
- Secondary resource efficiency
    - Secondary resource productivity
    - Recycled content of the product
- EoL Waste factor
- EoL Process Material Circularity
- Energy consumption
    - Energy intensity
    - Energy efficiency
- Product circularity

4.1.3.1 Presence of hazardous chemicals

When waste ceases to be waste, in accordance to the Waste Framework Directive, i.e., when resources/ materials have been recovered from the post-consumer bio-based product, either through mechanical or chemical recycling, it is mandated by ECHA to register a fully-analysed composition of the secondary material resulting from the process. The secondary material is defined as that which is produced at an annual capacity of more than 10 tonnes and incorporated into final products placed in the commercial market[38]. This to ensure that any substances of concern to human health and the environment are well documented and understood before they are permitted to be handled, transformed and utilised in commercial recycled products. These substances may be

- single, well-defined substances;
- mixtures of various well-defined substances, or;
- UVCB (unknown, variable composition, complex reaction products or biological materials) substances.

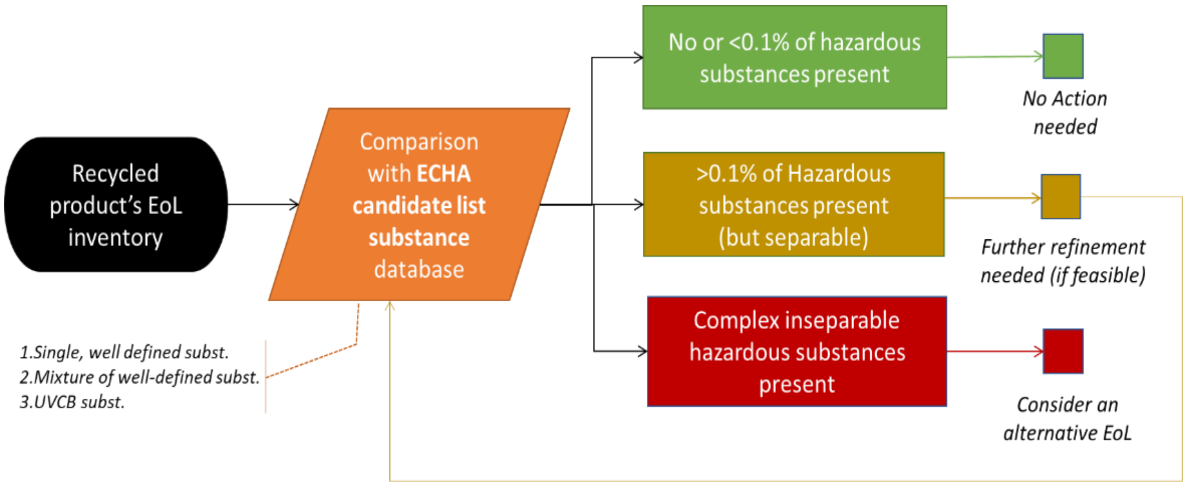


Figure 5: Process flow for the identification and flagging-up the presented of potentially hazardous substances in the secondary (recycled) material

For this purpose, an indicative metric that highlights the presence of any substances of concern is proposed. The EoL inventory that is developed for the post-consumer product, which at the end of its functional life is being disposed for mechanical or chemical recycling, must be comprehensive enough to capture the information required to use this indicator. To encourage circular economy and material circularity, ECHA is in the process of developing a database of candidate list substances that could be present in the secondary material drawn from the one of the material recovery approaches during the transformation of recyclates[39]. Screening of the inventory and the secondary material for hazardous chemicals, and identification of more than 0.1% of substances of high concern, is an indication that the material is destined for either: additional hazardous substance removal procedures (if techno-economically feasible) or identification of an alternative waste management options. It is essential to note that products of EoL from composting, anaerobic digestion and incineration (compost, digestates and biogas) are exempt from this regulation, according to the ECHA guidelines[40]. This indicator, will therefore, incorporate this advice and conform to the recommended product-based exemption.

[38] Jones, "EU Commission Issues Guidance on REACH and Waste".
[39] European Chemicals Agency, "Candidate List of Substances of Very High Concern for Authorisation - ECHA".
[40] European Chemicals Agency, "Guidance on Waste and Recovered Substances".

4.1.3.2 EoL Secondary resource productivity

Secondary resource productivity highlights the capability of the managed EoL process to transform the post-consumer product into re-useable useful secondary materials, which can be termed as the target product and co-products. Nevertheless, the quality of the secondary material resulting from the resource recovery process must be of acceptable quality for this process to be feasible. This aspect is taken into consideration within the PEF-CFF approach where secondary resource productivity is defined as the ratio of the total amount of recycled target fraction (kg) (secondary material) generated from the process to the per unit mass of the recyclate (feedstock for the recycling process) (kg) entering the material recovery facility for recycling (mechanical or chemical). This is a quantitative indicator suitable for application to mechanical or chemical recycling approaches only. It is essential to note that these indicators can either be used independently or in combination with LCA, with outcomes interpreted in accordance to an appropriate functional unit. In this case, the outcome will be measured as kg of recycled fraction per functional unit of study.

$$Secondary\ resource\ productivity\ (SRP)\ = \frac{M_{main.re.frac}}{M_{recyc}}$$

$M_{main.re.frac}$ *=Fraction of the target recycled material resulting from the process (kg)*

M_{recyc} *=Total mass of the recyclate (feedstock for the EoL process) (kg) (can also be alternated with a functional unit of study)*

4.1.3.3 EoL Waste factor

The waste factor indicator, proposed for the EoL phase, is similar to that proposed for the manufacturing phase. Based on the metric commonly used in the industry to achieve waste reduction, the EoL Waste factor quantifies the total amount of waste generated including the solid, liquid and gaseous emissions (which may include fractions of the main feed, solvents and catalysts) and unusable products of mechanical or chemical recycling, slag from incineration and residual material from composting processes that are destined for landfill with or without treatment. The EoL Waste factor is defined as the total amount of waste generated from a given EoL operation applied to the unit mass to the total amount of secondary materials generated as main product and co-products.

$$EoL\ Waste - factor\ (EoL - WF) = \frac{M_{TotW}}{M_{main.re.frac} + M_{co.re.frac}}$$

M_{TotW} *=Total mass of waste generated from the process (kg)*

$M_{co.re.frac}$ *=Total mass of recycled co-products generated from the EoL process (kg)*

$M_{main.re.frac}$ *=Total mass of recycled main product generated from the EoL process (kg)*

(Note: The parameters $M_{main.re.frac}$ and $M_{co.re\text{-}frac}$ can be alternated with the functional unit of study)

When used independently, a product waste-factor of "0" is considered ideal. This approach may be utilised as a standalone quantification of waste generated or can be incorporated with LCA in which case, the waste factor will be measured as kg of waste generated per functional unit of analysis.

4.1.3.4 EoL Process material circularity

The EoL Process material circularity is defined as the ratio of the sum of all the process consumables (solvents, catalysts and columns etc) that have been recovered and reused to the total mass of all those consumables used during an EoL operation which includes handling and transformation of the recyclate.

$$EoL\ Process\ material\ circularity\ = \frac{\sum_{i=1}^{n}\left(\frac{M_{rec.Pro.aux}}{M_{Pro.aux}}\right)_1 + \left(\frac{M_{rec.Pro.aux}}{M_{Pro.aux}}\right)_2 + \cdots}{n} \times 100$$

$M_{Pro.aux}$ = *Net mass of a specific EoL process auxiliaries (deducting losses during use) used in the production (kg)*

$M_{re.\ Pro.aux}$ = *Net mass of EoL process auxiliaries (deducting losses during recovery, re-processing, if any) that have been circularised (kg)*

n = *Number of process auxiliaries*

i = *List of EoL process auxiliaries used in the product synthesis at a given stage*

The EoL process material circularity must be measured as a percentage, ranging between 0% and 100%, where "100%" means that all the process auxiliaries are successfully circularised while "0%" represents a rather linear process with no circularisation strategies employed.

4.1.3.5 EoL Energy consumption

Energy use is a key environmental performance characteristic that most production-related stakeholders aim to optimise, and potentially circularise. In most cases, energy circularity is limited by a number of factors including the nature of the EoL process, characteristics of the waste stream (including high moisture content, relatively little to no energy content) and limited technological maturity in terms of material or energy recovery efficiency and re-distribution into heat or power. In some EoL processes, there is neither any energy recovery nor nutrient recovery. Calculation of energy use for processes that involve environmental factors such as assimilation by micro-organisms, ambient temperature and its impact on a compost heap, etc, become too complex to fit into an empirical expression. However, an attempt has been made to quantify energy intensity specific to particular EoL process. They are as follows.

EoL Energy intensity (Recycling) This metric was developed in accordance to the one of the principles of green chemistry, which states that any given process must be optimised to only consume an amount of energy required for optimal product yield. Therefore, EoL energy intensity is defined as the ratio of the total amount of energy (fossil-derived, renewably sourced and internally derived) used in the EoL operations (collection, handling, sorting, processing, transporting EoL products) to the total amount of target recycled (secondary) resources and useful co-products generated from the process. This parameter is therefore measured as energy intensity per unit mass of the recycled or recovered material.

$$EoL\ Energy\ intensity\ (EoL - EI) = \frac{E_{FosD} + E_{RenD} + E_{IntD}}{M_{main.re.frac} + M_{Co.re.frac}}$$

E_{FosD} = *Total fossil-derived energy for the given EoL process (kWh)*

E_{RenD} = *Total renewable energy required for the given EoL process(kWh)*

E_{IntD} = *Total internally derived energy utilised required for the given EoL process (kWh)*

$M_{main.re.frac}$ = *Total mass of target product generated (kg)*

$M_{Co.re.frac}$ = *Total mass of co-product from the recycling process (kg)*

Energy that has been fed into the process may be in the form of heat and/or electricity. It is essential to note that the expression may be used only for processes which do not involve any form of energy recovery. Electricity inputs, within LCA, are multiplied by a factor of 3 to reflect the primary energy invested in the production and distribution of electricity to the final destination. This factor 3 is considered a sufficient approximation of typical efficiency of primary energy conversion to electricity, in the context of this indicator.

EoL Energy Intensity (Incineration with energy recovery): Though this is a second-least desired option within the waste hierarchy, utilising the energy-rich nature of the undesirable waste streams, which were collected separately and received from the material recovery facility, is still a sound waste reduction strategy. In this case, a different empirical approach is recommended. It is essential to highlight the amount of energy expended into such energy recovery solutions (including feed-handling, logistics, transformation operations and energy recovery strategies). This expression helps measure the efficiency of energy recovery and is defined as the ratio of total energy invested to the energy content per unit mass of the product incinerated. The parameter, $E_{proc.inp}$ represents all the energy that is invested, including preparation (drying), handling and the preparation of the incineration feed and fuel added. $E_{wast.EC}$ represents the energy content value of the waste sent for incineration.

$$EoL\ Energy\ intensity_{Inc.}(EoL - EI_{inc.}) = \frac{E_{proc.inp.}}{E_{wast.EC}}$$

$E_{wast.EC}$ = *Energy content embedded in the waste feed (lower heating value of the product) (kWh)*

$E_{proc.inp}$ = *Energy consumed in handling and preparation of the feed (kWh)*

EoL Energy intensity (Anaerobic digestion and landfilling with energy recovery): Defined as the ratio of the total amount of energy invested into collection, handling and preparation of the post-consumer products as feedstock for the anaerobic digester, to the energy content of the biogas collected from relevant EoL processes (AD and/or landfill). The operator will be required to have details regarding the total amount of biogas collected (taking into account the recovery efficiency and after the deduction of biogas losses via leakage). A suitable empirical expression has been provided below.

$$EoL\ Energy\ intensity_{AD}\ (EoL - EI_{AD}) = \frac{E_{proc.inp.}}{E_{coll.BG}}$$

$E_{proc.inp}$ = *Energy consumed in handling and preparation of the feed (kWh)*

$E_{coll.BG}$ = *Per unit energy contained in the net amount of biogas collected at the end of the AD process (MJ)*

EoL Energy intensity (with no material or energy recovery): In the case of post-consumer products entering the disposal phase with no form (material or energy) of resource recovery, the following empirical expression may be used:

$$EoL\ Energy\ intensity\ _{disp.}(EoL - EI_{Disp.}) = \frac{E_{proc.inp.}}{M_{prod.EoL}}$$

$E_{proc.inp}$ = *Energy consumed in handling and preparation of the feed (kWh)*

$M_{prod.EoL}$ = *Unit mass of the bio-based product composted, incinerated or landfilled (kg)*

This includes the cases of compositing without nutrient recovery, incineration without energy recovery, landfill without energy recovery.

4.1.3.6 Product circularity

The *product circularity* metric has been designed to give a circularity score between "0-3" based on the consolidated performance of the product at the end of its use prior to entering a single or a combination of EoL routes to their "grave". The metric bases its scoring principle on the material and energy consumption/ conservation preference laid out within the WFD's Waste Hierarchy[41].

[41] European Commission, "Directive 2008/98/EC on Waste (Waste Framework Directive) - Environment - European Commission".

A linear progression scoring system was adopted to provide a unique score for each of the tiers in the Waste Hierarchy, with the most preferred "preparation for reuse" taking the score of 3 and the least preferred "disposal" taking a score of 0. It would be possible to introduce or granularize the scores further to sub-parameters, for example, pyrolysis and gasification within the option "other recovery" may carry exemplary scores like 0.5 or 0.7. However, this kind of disaggregation has not been adopted within this study, as it depends on a number of market-based variables including current and expected trends in waste management approaches, technology transition, national and global policies, environmental and economic feasibility etc. Nevertheless, this is a recommendation for future work.

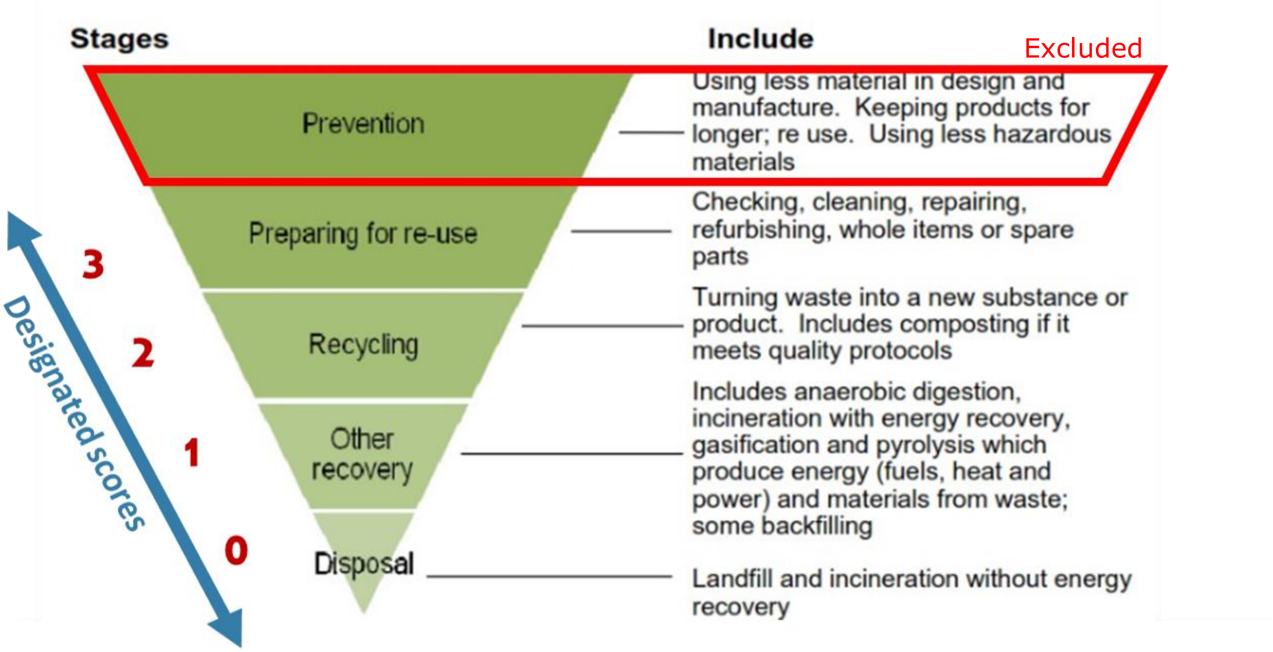


Figure 6: Waste Hierarchy and the proposed definitions of each of the waste management options and their designated circularity scores ("prevention" option excluded)

The *"waste hierarchy"* ranks waste management options according to *what is best for the environment*. The definitions of each of these EoL options, within the context of this metric, have been adopted as they are. Only post-consumer products fall within the scope of this metric's applicability. As a result, the "Waste prevention" option which addresses the reduction in material consumption and reuse of production scrap has been excluded. According to the WFD (2008), *reuse is a means of waste prevention, nevertheless, it is not a waste management operation*[42]. Relevant definitions for the other waste management options can be found in Figure 6 and for further descriptions, please refer to the suggested source literature[43]. Products in use and post-consumer products will ultimately enter one or a combination of the different EoL routes presented within the waste hierarchy.

[42] The Directorate General- European Commission, "Guidance on the Interpretation of Key Provisions of Directive 2008/98/EC on Waste".

[43] Department of Environment, Food and Rural Affairs, "Guidance on Applying the Waste Hierarchy"; The Directorate General- European Commission, "Guidance on the Interpretation of Key Provisions of Directive 2008/98/EC on Waste".

$$Product\ circularity\ (PC) = [(a \times 3) + (x \times 2) + (y \times 1) + (z \times 0)]$$

Where

a	*= Fraction of the post-consumer product prepared (repaired, refurbished etc) for reuse*
b	*= Fraction of the post-consumer product recycled (recycling and composting)*
x	*= Fraction of the post-consumer product that is subjected to other forms of recovery (for e.g. incineration/ landfill with ER, AD, gasification, pyrolysis etc)*
y	*= Fraction of material disposed (e.g. landfill/ incineration without ER)*
Z	*= Designated scores for the different forms of waste management based on the EoL product value*
3,2..0	*= Fraction of the post-consumer product prepared (repaired, refurbished etc) for reuse*

The desirable score for the *product circularity* is "3" and the product is deemed not circular at a score of "0". With single use products becoming a thing of the past, a number of products are being designed to be reused (by an individual or succeeding consumer) through a number of schemes including leasing and selling pre-owned items. Products that have been designed for easier disassembly serving multiple purposes such as for cleaning, repairing, refurbishment, retrofitting are returned to the "end-of waste" status, extending their lives after use. For a product with multiple lives that go through different waste management options before reaching their end of life, an average score can be calculated as presented below:

$$Avg. product\ circularity = \frac{PC_{1st} + PC_{2nd} + PC_{3rd} \ldots \ldots \ldots \ldots PC_n}{n}$$

where, PC_{1st}, PC_{2nd}, PC_{3rd} PC_n represents product circularity demonstrated by the product that is capable of being reused and recycled and *n* refers to the product's number of lives taken into account.

Example: For the purpose of demonstration, a post-consumer non-biodegradable mulch films is assumed to be collected, transported and fractionated into different streams destined for a particular type of waste management option: 5% mechanically recycled; 40% incinerated with ER; 55% landfilled. The product circularity score of the mulch films with the adopted EoL assumptions is determined as follows.

$$Product\ circularity = [(0 \times 3) + (0.05 \times 2) + (0.40 \times 1) + (0.55 \times 0)] = \mathbf{0.5}$$

The simplicity of this approach is its strength in terms of enabling its applicability to a wide-range of post-consumer products, irrespective of whether the latter is bio-based or fossil-based. This metric may not directly incorporate a way to integrate potential raw material displacement and resource circularity, unlike the Ellen MacArthur Foundations' Circularity Index. However, this *product circularity* metric allows for the consideration of a product's modularity, design for refurbishment [44] and potential recovery beyond recycling and reuse (including composting, incineration with energy recovery, AD), which is also a gap in EMF method.

[44] Saidani et al., "How to Assess Product Performance in the Circular Economy?"

4.2 Proposed thresholds for the LCA and the hybridised indicators

This section of the report summarises the thresholds that were developed in the project for proposed environmental indicators. Planetary boundary (PB) is an established concept of environmental boundaries proposed by Rockström et al, 2009[45]. It is acknowledged that PB cannot be used to set a maximum limit for emissions from a product and therefore defining "absolute thresholds" for these indicators has been ruled out from this exercise. However, indicator-specific exceedance ratios, which can be calculated using the appropriate PB thresholds, were adopted to develop relative sustainability thresholds.

The purpose of these thresholds is to highlight how the supposedly environmentally-sensible alternative (assumed bio-based) to the conventional (assumed fossil-based) product helps return the overall product environmental performance to a *safe operating space* that is also "sustainable". The life cycle indicators and their thresholds applied to the production and distribution phases are also applicable across the "cradle-grave" stages of a product and they have been applied in this study. Similarly, efficiency and circular metrics for the EoL were built in a similar way as those built for the earlier life cycle stages, i.e. to set subjective values as a starting point and a progression curve in line with general sustainability objectives, notably the Sustainable Development Goals[46,47]. When a new product (assumed bio-based) is substituting a former product (assumed fossil-based), any improvements to the former's environmental performance is acknowledged. However, only products reaching (appropriately falling within or above the proposed thresholds can be credited with the "sustainable" label. The method to calculate the value for each indicator is included in section 4.2. A description of the adopted thresholds for each of the hybridised indicator has been proposed below.

4.2.1 Presence of Hazardous chemical

Ideally, the EoL processes that are assessed for sustainability must avoid or find a suitable greener alternative to any substance of high concern listed in the SINLIST[48] and SUBSPORT[49] owing to their potential to cause harm to humans and the environment. As this environmental indicator is used only to highlight the presence of potential substances of concern, it is not necessary to provide thresholds providing min-max measures for such substances. However, it can recommend the best practices. This non-quantitative indicator should always meet the "No hazardous chemicals" state.

4.2.2 Secondary Resource Productivity

This indicator should have as high a value (towards 1) as possible. It can even be above 1 when a chemical reaction increases the molar mass of the material, for instance. However, as co-products are not considered in this method, it might be difficult to obtain 1 on this indicator (except for metals, which are not the focus of this methodology). In time, with improvement in sorting and recycling processes, a final productivity of 95% (0.95) should be possible. This can be used as an objective for year 2035, starting from lower values in 2020.

Table 4: Proposed thresholds for Secondary Resource Productivity

Year	2020	2025	2030	2035
Secondary Resource Productivity *(kg main secondary mat/kg waste input)*	0.80	0.85	0.90	0.95

[45] Rockström et al., "Planetary Boundaries".
[46] United Nations, "Transforming our world: The 2030 agenda for sustainable development", 2015.
[47] https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[48] The International Chemical Secretariat, "SINLIST".
[49] Schmitz-Felten et al., "SUBSPORT – Substitution Support Portal- Moving towards Safer Alternatives".

4.2.3 Waste Factor

This indicator should be as low (towards 0) as possible. Note that liquid waste is included in the calculation, except for water. This is important since many processes involve water cleaning or a dissolution in a water bath. The contaminants in the wastewater are included in the calculation, but not the water itself. Therefore, a waste factor below 1 is expected.

Assuming an effective sorting system, a reasonable recovery efficiency and good co-product valorisation, a final waste factor of 0.1 should be possible, so this value can be used as a baseline for year 2020. The improvement of recovery efficiency and co-product valorisation over time induces the proposed thresholds as presented in the table below.

Table 5: Proposed thresholds for Waste Factor

Year	2020	2025	2030	2035
Waste Factor *(kg waste output/kg useful prod)*	0.10	0.075	0.05	0.025

4.2.4 Process material circularity

This indicator only addresses auxiliaries consumed during the waste treatment process (including solvents, catalysts, stabilising chemicals, columns and other items). It should be as high and close to 100% as possible. The proposed thresholds below are determined based on empirical review of existing processes.

Table 6: Proposed thresholds for Process material circularity

Year	2020	2025	2030	2035
Process material circularity (-)	90%	95%	99%	99%

4.2.5 Energy intensity (Material recovery via recycling)

This indicator should be as low as possible. The rationale behind the proposition of the energy intensity target is that the energy intensity for the EoL material recovery process must be lower than that for the production of the primary material, E_p. Also, across the time period of the threshold development, it is anticipated that better energy savings is possible.

The thresholds proposed here are determined based on this basic requirement for 2020 but then follow ambitious reduction targets.

Table 7: Proposed thresholds for Energy intensity (Material recovery)

Year	2020	2025	2030	2035
Energy intensity *(relative to primary material, E_p)*	1 E_p	0.75 E_p	0.55 E_p	0.40 E_p

4.2.6 Energy intensity (Incineration with Energy recovery)

This indicator should be as low as possible. The rationale behind the proposition of the energy intensity target is that the energy demand for the EoL energy recovery process must be lower than that required to run the energy recovery operation. So the physical energy content of the material, $E_{wast.EC}$ above which there could be is no further energy gain. However, it can be anticipated that the energy gain might be very important for plastics.

The thresholds proposed here are determined based on an energy intensity at maximum 50% of the energy content for 2020, and then follow reduction targets that are not too ambitious, to take into account materials with low $E_{wast.EC}$.

Table 8: Proposed thresholds for Energy intensity (Incineration with Energy recovery)

Year	2020	2025	2030	2035
Energy intensity *(relative to energy content, $E_{wast.EC}$)*	0.50 $E_{wast.EC}$	0.40 $E_{wast.EC}$	0.30 $E_{wast.EC}$	0.25 $E_{wast.EC}$

4.2.7 Energy intensity (Anaerobic digestion and landfilling with energy recovery)

This indicator should be as low as possible. There is an intrinsic physical rationale to determine an objective energy intensity target, which is the chemical energy content of the collected gas, here below called $E_{coll.BG}$. Above that, there is no potential energy gain.

It is similar to the previous indicator, but the conversion step from material to methane and the collection step are added, which may result in a significantly lower amount of potential energy available. This is taken into account in the proposed thresholds, which appear a little bit less ambitious in comparison.

The thresholds proposed here are determined based on an energy intensity at maximum 75% of the energy content for 2020, and then follow reduction targets that are not too ambitious, to take into account materials with low methane production potential.

Table 9: Proposed thresholds for Energy intensity (Anaerobic digestion and landfilling with energy recovery)

Year	2020	2025	2030	2035
Energy intensity *(relative to collected energy content, $E_{coll.BG}$)*	0.75 $E_{coll.BG}$	0.60 $E_{coll.BG}$	0.45 $E_{coll.BG}$	0.35 $E_{coll.BG}$

4.2.8 Energy intensity (Landfill)

There is no threshold proposed for this EoL option, since it is considered not sustainable in all cases.

4.2.9 Product circularity

This indicator is applicable only to a post-consumer product and not to the production scraps that may be reused. Once a post-consumer waste has been processed for secondary resources, it satisfies the "end-of-waste" criteria by delivering potential feedstock for another product (of the same or different quality). However, transformation of post-consumer waste into a potential energy source suitable for energy recovery must also be credited. From the context of circular economy and the waste hierarchy, material recovery is favoured over energy or other forms of recovery and disposal. Therefore, taking into account an increase in products designed for easier disassembly, reuse and material recovery, and a decline in single use products, a linearly improving score for the different time periods has been proposed.

Table 10: Proposed thresholds for Product circularity

Year	2020	2025	2030	2035
Product circularity (-)	2.0	2.25	2.75	3.0

4.2.10 Summary of the proposed thresholds

This section is a summary of the proposed sustainability thresholds for the LCA and the hybridised environmental indicators. Please note that these thresholds are possible yet debatable. Table 11 summarises how each of the planetary boundary indicators relate to each of the environmental LCA indicators. Only relative sustainability thresholds have been defined in comparison with a substituted counterpart. As mentioned earlier this exercise does not define absolute thresholds.

The approach to threshold applicability is presented as follows. For example, if a fossil-based product has a particulate matter of 2 disease incidence per functional unit, the bio-based counterpart should have an impact equal to 0.833×2=1.67 disease incidence per functional unit or lower to pass the sustainability criteria. The thresholds presented for the hybridised indicators (Table 12), however, have been proposed to evolve with time and to align with more ambitious sustainability objectives.

Table 11: Relative sustainability thresholds proposed for environmental LCA indicators

Environmental LCA indicator	Planetary Boundary indicator	Exceedance ratio	Relative sustainability threshold
Acidification (mol H+eq)	*Ocean acidification (-)*	95%	1.053
Particulate matter (resp. inorganics) [disease incidence]	*Atmospheric aerosol loading (-)*	120%	0.833
Global warming potential (kg CO_2-eq)	*Climate change (ppm)*	113%	0.885
Terrestrial Eutrophication (mol N-eq)	*Biogeochemical flows-nitrogen (Tg N/a)*	242%	0.413
Freshwater Eutrophication (kg P-eq)	*Biogeochemical flows – phosphorus (Tg P/a)*	226%	0.442
Human toxicity- cancer (CTUh)		-	
Fossil resource depletion (MJ)	*None*	-	
Water scarcity (m^3 water deprived- eq)	*Freshwater abstraction (km^3/a)*	65%	1.538

Table 12: Sustainability thresholds proposed for hybridised indicators

Year	2020	2025	2030	2035
Hazardous chemical use (-)	No hazardous chemicals			
Secondary Resource Productivity (kg main secondary mat/kg waste input)	0.80	0.85	0.90	0.95
Waste Factor (kg waste output/kg useful prod)	0.10	0.075	0.05	0.025
Process material circularity (-)	90%	95%	99%	99%

Energy intensity (relative to primary material, E_p)	1 E_p	0.75 E_p	0.55 E_p	0.40 E_p
Energy intensity (relative to energy content, $E_{wast.EC}$)	0.50 $E_{wast.EC}$	0.40 $E_{wast.EC}$	0.30 $E_{wast.EC}$	0.25 $E_{wast.EC}$
Energy intensity (relative to collected energy content, $E_{coll.BG}$)	0.75 $E_{coll.BG}$	0.60 $E_{coll.BG}$	0.45 $E_{coll.BG}$	0.35 $E_{coll.BG}$
Energy intensity (Landfill) (kWh/kg waste input)	No threshold because not sustainable			
Product Circularity	2.0	2.25	2.75	3.0

4.3 End-of-life Environmental framework: Case study introduction

4.3.1 Packaging film

BoPLA packaging films: The bio-based packaging films, composed of 99.8% compostable polylactic acid and additives, is assumed to serve its purpose of protecting the fresh produce during its storage and transportation(s) prior to consumption by the end-user. For this EoL study, the starting point of the impact assessment exercise is that the end-user disposed the post-consumer packaging film (PCPF) for collection, destined for different forms of waste management. The disposal of the product has been assumed to be both through curbside collection and through drop-off at the recycling facility. The distance travelled by the consumer or the waste collectors was assumed to be the 5 km, with the PCPF destined for one of the different EoL options considered in this study: recycling, aerobic composting, incineration with energy recovery and disposal onto an MSW landfill.

BoPLA packaging film, according to the manufacturer, conforms to the *compostability criteria* for compostable packaging, in accordance to EN 13432:2000[50]. As a result, composting of the PCPF was adopted as its intended EoL scenario. The bio-based PCPF is assumed to be degraded by up to 90% in accordance to the EN13432. Analysis of the composition of the BoPLA packaging film earlier in the project, demonstrated the use of no hazardous chemicals (or substances of very high concern) in the production of this product. Therefore, this study assumed that the PCPF contains no such chemicals to release into the compost during the composting process. While the study acknowledges composting of packaging film as the benchmark EoL route, the manufacturer's claims for the product to potentially enter other EoL routes have also been assessed. This study follows present European waste management scenario for packaging waste (mechanical recycling [41%], Incineration with energy recovery [39%] and landfill [20%]), also in coherence with that of other recent dedicated European packaging waste EoL impact assessment literature [51]. Based on this review, the average plastic packaging disposal scenario was also adopted for both BoPLA and BoPP packaging waste case studies.

Alternative EoL Scenario: Present packaging waste management strategies may be limited to the fossil-based packaging material and drop-in bio based plastic alternatives including bio-PET (bio-based polyethylene terephthalate), bio-PP (bio-based polypropylene) and bio-PE (bio-based polyethylene) treating other bio-based waste plastic stream as contaminants. Nevertheless, it is crucial for this study to foresee the impacts of post-consumer bio-based packaging waste management when a certain level of techno-economic maturity is reached in the material recovery arena (for example, via production waste recovery and recycling). Thus, we assume bio-based BoPLA-PCPF from the "drop-off" waste collection facility and from the curb-side collection is directed to the Material Recovery Facility (MRF).

At this point, the incoming fraction including the PCPF needs to be sorted to ensure a pure stream of PLA films is available for material recovery through mechanical recycling (40.9%). The remaining waste fraction is directed towards incineration with energy recovery (38.8%) and disposal (20.4%) due to their inability to satisfy the quality demands for recycling or incineration. The fate of the different fractions of the PCPF is dependent upon the quality of the collected material, which in turn is determined by the level of degradation the material has undergone during its shelf life. The fraction of materials being recycled is also determined by a

[50] Taghleef Industries, "Environmentally Alternatives for Nativia® End of Life - Ti".

[51] Mazzetti et al., *Support to Research and Innovation Policy for Bio-Based Products (BIO-SPRI): Innovative Bio-Based Products: Investment, Environmental Impacts and Future Perspectives*; Nessi et al., "*Environmental Sustainability Assessment Comparing through the Means of Lifecycle Assessment the Potential Environmental Impacts of the Use of Alternative Feedstock (Biomass, Recycled Plastics, CO2) for Plastic Articles in Comparison to Using Current Feedstock (Oil and Gas)*.

number of environmental factors such as the technology maturity, economic feasibility and waste collection and sorting employed. Compositional details and the EoL treatment for the post-consumer bio-based packaging films is presented in Table 13, in accordance to the guidance provided within the standard CEN/TR/16957.

Table 13: Material properties of the post-consumer bio-based packaging film, as per inventory development guidelines of CEN/TR/16957

Parameters	Values	Unit	Comments
Combustion characteristics			
Lower Heating Value (LHV)	*19.5*	*MJ/kg*	*Calculated from composition*
Share of biodegradable carbon decomposed into inorganic components within a defined time period			
In composting	100*	%	**Intended EoL only*
In landfill (Time period covered)	20.4	% years	*Part of alternative EoL*
In incineration	38.8	%	*Part of alternative EoL*
In anaerobic digestion	0	%	
Water content	<0.1	% wt	*Source:*[52]
Chemical composition (in dry mass)			
Carbon (fossil) (C)	1.29	g/kg	*Calculated from composition*
Carbon (biogenic) (C)	641.71	g/kg	*Calculated from composition*
Hydrogen (H)	--	g/kg	
Nitrogen (N) and other elements	--	g/kg	

BoPP packaging films: BoPP packaging films are assumed to be 100% oil-derived (including the additives) and are non-biodegradable, based on the data provided by the manufacturers[53]. As no specific EoL route was recommended by the product manufacturers and taking into account the non-biodegradable nature of the PCPF, 100% disposal onto an MSW landfill was assumed as the intended EoL route. The intended EoL scenarios adopted for the post-consumer BoPP and BoPLA packaging films examined in the study may not have created a level playing field, with an imbalance in the resource-requirements. The intention of this baseline analysis is to examine and quantify the environmental burden of currently available EoL routes. An alternative scenario meeting the average European plastic waste management targets, specific to packaging films[54] has been considered for both the bio-based and fossil-based case studies where it will be possible to eliminate the aforementioned limitation in the intended EoL scenario analysis.

Alternative Scenario: Mechanical recycling [40.9%]; Incineration with energy recovery [38.8%] and landfill [20.4%]). In the alternative scenario, upon the use and disposal for collection, the fossil-based PCPW is assumed to be collected via curbside collection as a mixed plastic waste. This is then transported to the material recovery facility (MRF) where the mixed plastic waste is assumed to be sorted, cleaned and fractioned to enter the European average plastic waste management approach employed specific to polypropylene films[55] secondary materials. Unlike PLA-based secondary material, PP can be recovered with greater efficiency owing to a better mechanical integrity of the oil-based (mechanical recycling [40.9%], Incineration with energy recovery [38.8%] and landfill [20.4%]). These assumptions apply conveniently to the recovery of polypropylene building blocks owing to the use of a matured

[52] Taghleef Industries, "Environmentally Alternatives for Nativia® End of Life - Ti".
[53] Taghleef Industries, "Data Collection: Industrial Data for Production of Packaging Films (Confidential)".
[54] Mazzetti et al., *Support to Research and Innovation Policy for Bio-Based Products (BIO-SPRI): Innovative Bio-Based Products: Investment, Environmental Impacts and Future Perspectives*; Belley, *Comparative Life Cycle Assessment Report of Food Packaging Products*.
[55] Mazzetti et al., *Support to Research and Innovation Policy for Bio-Based Products (BIO-SPRI): Innovative Bio-Based Products: Investment, Environmental Impacts and Future Perspectives*; Belley, *Comparative Life Cycle Assessment Report of Food Packaging Products*.

technology route (for oil-based plastics) and demand for the resulting films over their shelf life, compared to the bio-based PLA films. Owing to the confidential nature, an inventory detailing the material and energy consumption associated to the intended and alternative EoL management of the post-consumer BoPLA packaging film has been reported within the upcoming confidential deliverable D3.3. The inventory has been developed in conformity to the CEN/TR/16957 standards for EoL inventory development for bio-based products.

4.3.2 Agricultural Mulch

PLA based mulch films: The EoL impact assessment methodology, presented in sub-sections 4.1.2 and 4.1.3, will be applied to the downstream stages of product use and their EoL management.

The 70% bio-based, biodegradable mulch film is applied to one hectare of agricultural land using appropriate machinery fuelled by low-sulphur agricultural diesel. The mulch film is designed to stay intact for the duration of the cultivation phase. At the end of the cultivation and harvest phase, the film is assumed to be rototilled into the soil to enable biodegradation via microbial action by up to 92% [56], in compliance with the EN17033 standards for biodegradable mulch films, releasing significant amount of biogenic and fossil-derived carbon-dioxide. This has been assumed as the intended EoL scenario.

Similar to that proposed for the BoPLA packaging film, an alternative EoL scenario was adopted for the PLA-based mulch films. In Here, the mulch film (at the end of its functional life) was assumed to be removed and processed for material and energy recovery. The purpose of this assumption was to evaluate the performance of indicators when applied to a range of managed EoL management routes. Though removal of the PLA-based mulch film may in the real world prove to be challenging (due to the rather high-soil attachment rate (80%)[57], attributed to the design of thin films (0.012mm thickness)), a hypothetical scenario was adopted, involving the removal/ baling of the post-consumer mulch, transportation to a sorting facility and fractionation of the collected mulch based on its quality suitable to enter the different EoL processes. ***Alternative EoL Scenario:*** The waste feed was assumed to be separated into three fractions based on the quality of collected mulch. The fraction (5% of the collected waste stream) that was less contaminated with soil (5% or less by wt of the collected mulch) was assumed to enter to an intensive cleaning process (energy and water intense process). The technical specifications for these recycling processes were adopted from the supporting data found in the peer-reviewed literature [58]. The mulch film fraction that was contaminated by more than 5-30% of soil by wt of the collected mulch was assumed to be destined for incineration with energy recovery. This fraction was transformed into an alternative solid fuel (ASF) adjusting its calorific value with additional fuel material in preparation for incineration. The remaining heavily contaminated mulch was assumed to be disposed by landfill. In reality, considering the existing waste management infrastructure (including the recycling infrastructure), the assumptions are applicable only to the petroleum-based, non-biodegradable, removable mulch film. However, these assumptions were adopted for the PLA based mulch film to create a level-playing field for the purpose of testing the environmental methodology developed and proposed within this study. These assumptions, relevant to the petroleum-based mulch film were adopted from a similar bioeconomy research-study

[56] BASF SE, "Ecovio F Mulch C2311: Biodegradable Compound for Agricultural Films".

[57] BASF SE, "The New European Standard BS EN17033 for Biodegradable Mulch Films: Scientific Findings on Full Biodegradability in Soil".

[58] Schrijvers et al., "Ex-Ante Life Cycle Assessment of Polymer Nanocomposites Using Organo-Modified Layered Double Hydroxides for Potential Application in Agricultural Films"; Mazzetti et al., *Support to Research and Innovation Policy for Bio-Based Products (BIO-SPRI): Innovative Bio-Based Products: Investment, Environmental Impacts and Future Perspectives*; Maga, Hiebel, and Thonemann, "Life Cycle Assessment of Recycling Options for Polylactic Acid"; Ragaert, Delva, and Van Geem, "Mechanical and Chemical Recycling of Solid Plastic Waste"; Sorema Plastic recycling systems, "Agricultural Film Recycling – Sorema".

undertaken by Mazzetti et al, (2018)[59]. Compositional details and the EoL treatment for the post-consumer bio-based mulch film is presented in

Table 14, in accordance with the guidance provided within the standard CEN/TR/16957.

Table 14: Material properties of the post-consumer bio-based mulch film, as per inventory development guidelines of CEN/TR/16957

Parameters	Values	Unit	Comments
Combustion characteristics			
Lower Heating Value (LHV)	24.1	MJ/kg	Calculated from composition
In composting	-	%	
In landfill (Time period covered) (Alternative EoL)	55	%	Part of alternative EoL
In incineration (Alternative EoL)	(100) 45	%	(Intended EoL scenario) and Part of alternative EoL
In anaerobic digestion	0	%	-
Water content	<5	% wt	Only when heavily contaminated[60]
Chemical composition (in dry mass)			
Carbon (fossil) (C)	128.6	g/kg	Calculated based on composition
Carbon (biogenic) (C)	347.7	g/kg	Calculated based on composition
Hydrogen (H), Oxygen (O) Nitrogen (N) or other elements	--	g/kg	

LLDPE Mulch films: The baseline candidate for this study, was assumed to be 100% petroleum derived and synthesised with no recycled content, as used elsewhere in the project. For the intended EoL scenario, the applied mulch (175.78 kg) is assumed to be removed at the end of the cultivation period using appropriate agricultural equipment and transported to the consolidation station. Please refer to the assumption in the supplementary section 7.2, for further information on transport-related assumptions. At the consolidation station, the collected degraded and soil contaminated (100%) mulch film is prepared to be utilised as an alternative solid fuel to be incinerated for energy in the cement kiln. Initially, the film is cleaned to remove soil by up to 50% (87.89 kg of soil removed) after which the calorific value of the processed mulch is adjusted with sawdust (38.5 kg) and compressed. The resulting alternative solid fuel has a calorific value (26.5MJ/kg) capable of replacing 296 kg of coal that is conventionally used in the cement kiln. (Assumption: incineration for energy supply to the kiln).

Alternative EoL Scenario: For the alternative scenario, we assume that the collected LLDPE mulch film is fractionated carefully based on the quality (level of degradation) and soil contamination similar to the assumptions quoted for the PLA-based mulch film. Three fractions result from their fractionation at the sorting facility, where the fraction suitable for recycling (5%) enters the recycling facility; the fractions that are slightly more soil-contaminated enters the 40% incineration facility and the 55% heavily contaminated fraction is sent off to a MSW landfill for disposal. These assumptions were adopted from published literatures that review the current waste management approaches practiced within the EU for agricultural plastic was-

[59] Mazzetti et al., *Support to Research and Innovation Policy for Bio-Based Products (BIO-SPRI): Innovative Bio-Based Products: Investment, Environmental Impacts and Future Perspectives*.

[60] OWS nv, "(Bio)Degradable Mulching Films : Expert Statement"; Nessi et al., *Environmental Sustainability Assessment Comparing through the Means of Lifecycle Assessment the Potential Environmental Impacts of the Use of Alternative Feedstock (Biomass, Recycled Plastics, (CO2) for Plastic Articles in Comparison to Using Current Feedstock (Oil and Gas)*.

te[61]. Owing to the confidential nature, the inventory detailing the material and energy consumption associated to intended and alternative EoL management of the post-consumer mulch film has been transferred to the supplementary section in the STAR-ProBio Deliverable D3.3. The inventory has been developed in conformity to the CEN/TR/16957 standards for EoL inventory development for bio-based products.

Detailed descriptions of the procedures associated with the mechanical recycling and incineration (with energy recovery) of the post-consumer mulch films can be found in the supplementary section 7.1.2. Assumptions, uncertainties and limitations associated to the packaging films and mulch film impact assessment exercises have been included in the supplementary section 7.2.

[61] Mazzetti et al., *Support to Research and Innovation Policy for Bio-Based Products (BIO-SPRI): Innovative Bio-Based Products: Investment, Environmental Impacts and Future Perspectives*; Nessi et al., *Environmental Sustainability Assessment Comparing through the Means of Lifecycle Assessment the Potential Environmental Impacts of the Use of Alternative Feedstock (Biomass, Recycled Plastics, (CO2) for Plastic Articles in Comparison to Using Current Feedstock (Oil and Gas)*.

5 Product Use-to-Grave Impact Assessment and Interpretation

The goal of this study is to identify and develop appropriate methods that can effectively evaluate the environmental performance of the specific bio-based products and processes encompassing their production-level burdens, resource efficiency and circularity characteristics. The environmental assessment framework, suggested in section 4, was tested for robustness and performance to deliver crucial information for stakeholders (like manufacturers, end-users and policy makers) in order for them to make appropriate decisions in terms of product/ process design choices, optimisation protocols and product choices. This section provides the preliminary outcomes of this study.

5.1 Packaging films: Use and End-of-life Impact assessment

5.1.1 Intended EoL scenario- Outcomes and discussion

BoPLA packaging films: 100% Industrial Composting; BoPP Packaging films: 100% landfill

The impacts relevant to the product's degradation in 12 weeks (as per the guidance within EN13432) are reported in this section. The embedded carbon content of the PCPF was assumed to be degraded (by upto 90% in accordance to the "compostability" criteria) releasing biogenic CO_2 emissions. Avoiding biogenic CO_2 and any potential CH_4 emissions from composting the PCPF (sourced from a feedstock from annual crops) contributed significant GHG savings and subsequently lowering the GWP_{bio} by up to (-280%), compared to that of the post-consumer BoPP packaging film. Additionally, the bio-based PCPF delivered impact savings in a number of other impact categories including -99.2% in respiratory inorganics and -178% in human toxicity. Composting the bio-based PCPF limited the release of any leachates into water bodies, reducing its overall freshwater eutrophication by about 67%, relative to the baseline case study. If the packaging were to be disposed, remnants of food waste would have a significant impact on both GHG emissions and eutrophication. Water consumption for the industrial composting process increased the water scarcity impacts for the bio-based case study, as expected (+150%), relative to the lowered need associated with EoL incineration. The quantified impact for the both the bio-based and fossil-based candidate is presented in Table 15.

The EoL inventory is expected to highlight any potentially hazardous chemicals (as a single identifiable or a mixture of unidentifiable compounds) that may be released from the composting and incineration process. However, the data acquired from our industrial partners shed no light on whether this impact was observed during the waste treatment of the post-consumer products when certain EoL options were recommended. This can only be attributed to the industry's lack of comprehensive EoL related test procedures and data on their products, which in turn is influenced by a lack of standards to monitor and design products incorporating life cycle thinking. As a result, we are unable to report an outcome on this impact. When assessing the products from a resource efficiency and circularity perspective, neither of the products generated any useful secondary resources (raw material). Incorporating the approaches suggested by Rossi et al (2012) and Hermann et al, (2011)[62], composting the bio-based PCPF could deliver 0.475 kg of compost per kg of the PLA feed, resulting in 2.65 g of compost per functional unit. However, this composting the packaging films does not add any nutrients to the soil. The long-term degradation of the residual film fragments in the compost heap have been excluded as it falls outside the scope of the EoL modelling.

[62] Rossi et al., "Life Cycle Assessment of End of Life Options for Two Biodegradable Packaging Materials: In Support of Flexible Application of the European Waste Hierarchy"; Hermann et al., "To Compost or Not to Compost".

Table 15: Comparative environmental impact assessment of the intended and alternative fate of a functional unit (1 packaging film) of BoPLA and BoPP based packaging film

Analysis Impact Assessment		Production and distribution	Intended EoL	Alternative EoL Scenarios		
			Aerobic composting	*Incineration (38.8%)*	*Mech. Recycling (40.9%)*	*Landfilling (20.4%)*
Global Warming Potential	**BoPLA Packaging films**	4.46×10^{-3}	-4.50×10^{-3}	4.67×10^{-3}	9.15×10^{-4}	9.50×10^{-2}
Respiratory inorganics		1.67×10^{-9}	6.33×10^{-11}	5.37×10^{-10}	1.62×10^{-11}	3.72×10^{-7}
Human toxicity, cancer		2.10×10^{-7}	6.54×10^{-12}	5.13×10^{-11}	5.01×10^{-12}	8.77×10^{-9}
Acidification, Terrestrial and freshwater		1.35×10^{-4}	1.39×10^{-5}	8.40×10^{-5}	5.09×10^{-6}	5.67×10^{-2}
Freshwater Eutrophication		8.94×10^{-4}	6.47×10^{-7}	2.72×10^{-4}	6.59×10^{-6}	1.46×10^{-1}
Terrestrial Eutrophication		5.23×10^{-6}	5.46×10^{-7}	1.40×10^{-6}	7.55×10^{-7}	8.22×10^{-4}
Water Scarcity		6.20×10^{-4}	6.57×10^{-5}	1.68×10^{-4}	7.13×10^{-5}	0.102
Fossil resource depletion		2.34×10^{-2}	9.80×10^{-6}	1.06×10^{-3}	7.48×10^{-5}	3.02×10^{-5}
Presence of Hazardous Chemicals		■		-	-	
Secondary Resource productivity		-	-	0	0.96	0
EoL Waste factor		2.20×10^{-3}	2.65×10^{-3}	5.95×10^{-4}	5.08×10^{-3}	1.14×10^{-3}
Product Circularity		-	2	1.206		
EoL Process Material Circularity		0.85	-	0	0.922	0
EoL Energy intensity		7.20×10^{-3}	2.71×10^{-4}	3.88×10^{-4}	2.01×10^{-3}	2.69×10^{-4}
Baseline Impact Assessment		**Production and distribution**	**Intended EoL**	**Alternative EoL Scenarios**		
			100% Disposal	*Incineration (38.8%)*	*Mech. Recycling (40.9%)*	*Landfilling (20.4%)*
Global Warming Potential	**BoPP Packaging films**	8.10×10^{-3}	2.45×10^{-3}	1.81×10^{-2}	9.14×10^{-4}	9.64×10^{-2}
Respiratory inorganics		5.58×10^{-10}	1.12×10^{-3}	5.52×10^{-9}	1.28×10^{-11}	1.11×10^{-7}
Human toxicity, cancer		3.52×10^{-7}	1.15×10^{-10}	1.22×10^{-11}	1.03×10^{-12}	7.54×10^{-10}
Acidification, Terrestrial and freshwater		6.11×10^{-4}	9.08×10^{-6}	2.40×10^{-5}	5.09×10^{-6}	1.24×10^{-2}
Freshwater Eutrophication		9.37×10^{-4}	1.36×10^{-5}	3.61×10^{-4}	6.58×10^{-6}	1.86×10^{-2}
Terrestrial Eutrophication		3.52×10^{-6}	1.10×10^{-7}	1.59×10^{-6}	7.54×10^{-7}	6.59×10^{-4}
Water Scarcity		1.54×10^{-2}	8.65×10^{-6}	1.39×10^{-2}	7.12×10^{-5}	9.40×10^{-2}
Fossil resource depletion		3.97×10^{-2}	2.16×10^{-2}	4.89×10^{-3}	7.48×10^{-5}	1.34×10^{-4}
Presence of Hazardous Chemicals		■				
Secondary Resource productivity		-	-		0.98	0.98
EoL Waste factor		0.35×10^{-2}	4.76×10^{-3}	4.98×10^{-4}	8.75×10^{-3}	9.53×10^{-4}
Product Circularity		-	0	1.206		
EoL Process Material Circularity		No data	*No data*	No data	No data	No data
EoL Energy intensity		5.14×10^{-3}	9.69×10^{-4}	3.32×10^{-4}	1.33×10^{-3}	2.69×10^{-4}

Any residue or waste remaining at the end of the modelling period were measured as "waste" drawn from the composting process. The waste factor reported for the bio-based PCPF was 60% lower, compared to that of the BoPP film which was landfilled. No significant process level circularity was observed in either of the EoL routes. However, the composting process was observed to be less energy intense (-97%) compared to the EoL scenario of the baseline case study.

5.1.2 Alternative EoL Scenario- Outcomes and discussion

BoPLA and BoPP packaging films: 40% Mechanical recycling, 38.8% incineration and 20.4% landfilling

Based on the assumptions adopted for the alternative EoL scenario, the BoPLA based packaging films were identified to perform environmentally better than that of the BoPP packaging film in most impact categories. The bio-based PCPF delivered -74% GHG savings via their biogenic emission from their incineration and landfilling. Upon application of the circular footprint formula, significant changes to the original impacts were observed as presented in Figure 7 and Figure 8.

Reallocation of emissions from virgin article production and EoL process-level characteristics led to a significant difference in BoPLA's environmental performance. Savings in GHG emissions from upstream processes contributed to an overall GWP_{bio} savings of up to 16.4% compared to the BoPP packaging film. The use of agrochemicals required to produce raw feedstock (glucose) and the use of inorganic acids in the life cycle of BoPLA packaging film, contributed to significant levels of respiratory inorganics (+67.9%). Energy consumption associated to the primary product synthesis and the subsequent EoL scenarios can be associated to the release of a NOx and SOx emissions that could potentially lead to terrestrial and freshwater eutrophication. The capability of the BoPP packaging films to effectively displace some amount of conventional energy mix not only reduced their overall release of acidifying agents during the EoL processes but also reduced the need for conventional energy source, compared to that of the BoPLA packaging film. Reductions in the eutrophication potential of the BoPLA films can be attributed to the capability of the process-design (Gate-gate) to circularise process auxiliaries, energy and the effective waste minimisation strategies employed in the virgin material and final product formulation processes. No such approaches were assumed for the BoPP packaging films, as little to no relevant industrial data was available. As anticipated, BoPP packaging film was determined to consume more fossil resources (+38%), including the use of precious metal catalyst during the virgin material production phase. Displacing a conventional energy source when the PCPF was incinerated for energy recovery, succeeded in delivering significant savings in a number of other impact categories (Table 16).

Table 16: Comparison of quantified impacts from energy generation via incineration of the bio-based PCPF and the displaced conventional electricity generation (EU-average mix)

Impact category	**Impacts from producing displaced energy** (0.031 kWh)	**Impact savings** *from incinerating PCPF for energy recovery*
Global warming potential (GWP bio)	6.55×10^{-3}	1.88×10^{-3}
Respiratory inorganics	4.11×10^{-12}	5.33×10^{-10}
Human toxicity, cancer	3.10×10^{-13}	-5.10×10^{-11}
Acidification, terrestrial and freshwater	3.31×10^{-6}	-8.07×10^{-5}
Freshwater Eutrophication	1.42×10^{-5}	-2.85×10^{-4}
Terrestrial Eutrophication	5.61×10^{-8}	-1.34×10^{-6}
Water scarcity	4.53×10^{-8}	-2.13×10^{-4}
Fossil Resource depletion	0.13	-0.128

As was seen for the baseline case study, the lack of material circularity strategies overshadowed any possible benefits, demanding additional resources and affecting the overall environmental performance. A mature material recovery approach (mechanical recycling) available for the acquisition of secondary polypropylene from the BoPP waste stream was demonstrated by the *secondary resource productivity* parameter. Please note that in this study a standard quality of recycled polymer was assumed from mechanical recycling of pure waste streams of the polymers.

The resource efficiency and circularity characteristics embedded within the BoPLA films production process (for example, recovery and reuse of process water during lactic acid production, waste heat recovery and usage during the production stages, reduction of inorganic acids and residual monomer waste reduction during the intermediate production processes [63]) were observed to significantly contribute to the reduction of overall waste factor by 45% compared to the "gate-grave" processes of BoPP packaging film. On the other hand, the bio-based candidate was determined to be energy intense (+26.6%) compared to that of fossil-based candidate. Unlike fossil-resource depletion, energy intensity was designed to calculate the energy consumption pattern across the life cycle of a product, per functional unit. From this perspective, energy intensity from the final article production phase, particularly the downstream processes responsible for the extraction, purification and crystallisation of lactic acid and its subsequent transformation to polylactic acid contributed significantly to the energy intensity upstream. Any savings in the energy recovery strategies employed within the "gate-grave" processes (during production and EoL incineration) were insignificant compared to the rather energy-rich BoPP packaging films and therefore, these savings were overshadowed by the energy demand from the production process.

[63] STAR-ProBio, *Deliverable 3.1: Expanding Environmental Sustainability Criteria to Address the Manufacturing and Other Downstream Processes for Bio-Based Products*.

5.1.3 Packaging films: Impacts and Threshold Applicability

In this section, we aim to demonstrate the applicability of the relative sustainability thresholds developed and presented in section 4.2.10 to the environmental performance of the bio-based packaging film (Figure 7 and Figure 8) to identify if the product falls within or outside the *safe operating sustainable space*. Please note that this evaluation has been undertaken only for the bio-based PCPF, since it is assumed to be a "potentially sustainable alternative" to the fossil-based packaging film. For the hybridised indicators, the thresholds defined for the year 2020 have been used. Also, unlike in the other relative thresholds, "secondary resource productivity" operates in a different manner. With its linearly progressive threshold, the ability to produce more secondary material has been credited with a "PASS" code.

Table 17: Sustainability threshold application for packaging films

Parameters	Units	BoPP Packaging film	BoPLA Packaging film	Relative sustainability Threshold	Pass/ Fail
LCA Impact categories					
Global warming potential (GWP bio)	*kgCO2eq*	3.43×10^{-2}	2.85×10^{-2}	0.885	PASS
Respiratory inorganics	*Disease incidence*	2.53×10^{-8}	7.78×10^{-8}	0.833	PASS
Human toxicity, cancer	*CTUh*	3.52×10^{-7}	2.12×10^{-7}	N/A	N/A
Acidification, terrestrial and freshwater	*mol H+eq*	2.59×10^{-2}	1.17×10^{-2}	1.053	FAIL
Freshwater Eutrophication	*kg P eq*	3.90×10^{-2}	3.07×10^{-2}	0.442	PASS
Terrestrial Eutrophication	*mol N eq*	1.72×10^{-4}	1.73×10^{-4}	0.413	PASS
Water scarcity	*m3 deprived*	3.51×10^{-2}	2.15×10^{-2}	1.538	FAIL
Fossil resource depletion	*MJ*	1.86×10^{-2}	1.26×10^{-2}	N/A	N/A
For hybridised Indicators (per kg of product)					
Secondary Resource Productivity	*kg of recycled material*	0.97	0.96	0.8	PASS
EoL Waste factor	*kg of waste*	1.86	0.942	0.1	FAIL
Process Material Circularity	%	0	92.2	90%	PASS
Energy Intensity (mat. rec)	*kWh*	3.90	4.53	1	PASS
Energy intensity (Waste ER)	*kWh*	1.53×10^{-2}	1.92×10^{-2}	0.5	PASS
Energy Intensity (Landfill)	*kWh*	0.054	0.0482	Not sustainable	FAIL

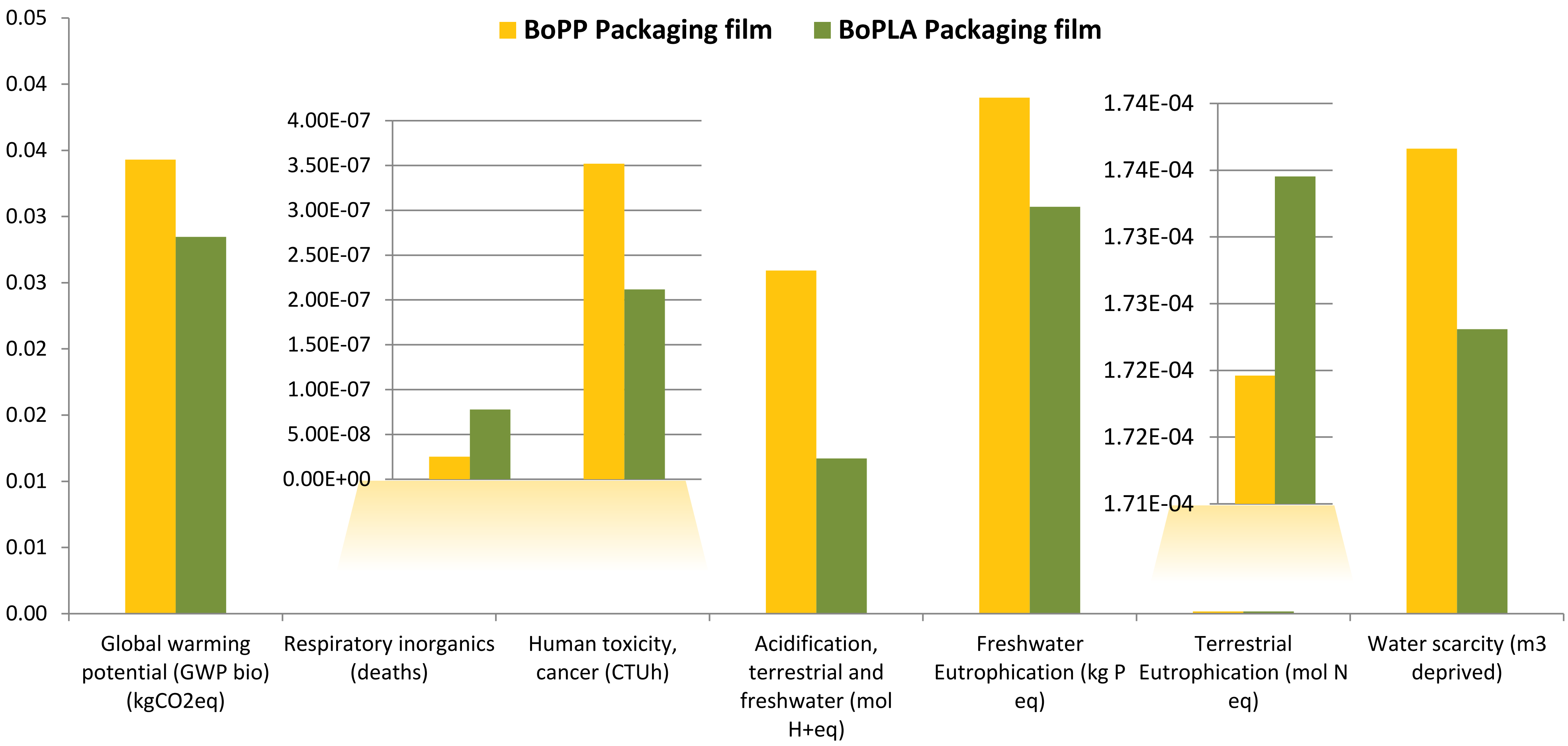
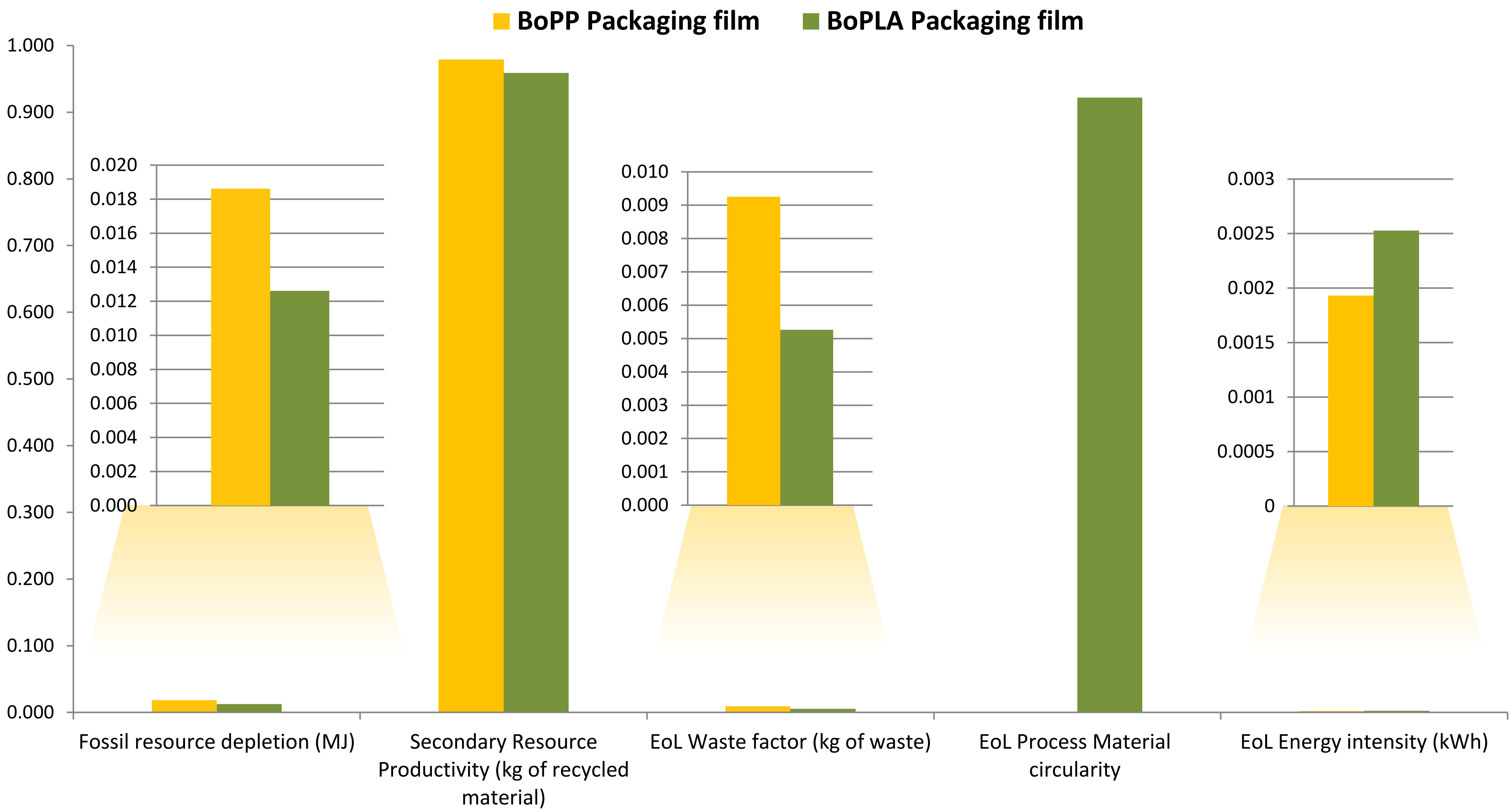


Figure 7: *Comparative environmental impact assessment (CFF implemented only for LCA impact categories) for the alternative EoL routes adopted for the BoPLA Packaging films and BoPP packaging films*



adopted for the BoPLA and BoPP Packaging films (inc. hybridised Indicators).

5.2 Mulch films: End-of-life Impact assessment

5.2.1 Intended EoL scenario- Outcomes and discussion

PL based mulch films: 100% in-situ biodegradation; LLDPE based mulch film: 100% incineration with energy recovery

The rototilled disintegrated fibres undergo in-situ biodegradation by up to 90% via microbial activity, releasing both bio-based and fossil-based carbon emissions over a period of 180 days, in accordance to the EN17033 standards for biodegradable mulch films. A combination of biogenic and fossil-based CO_2 emissions, amounting to a total of 76.11 kg was observed to be released from the film's biodegradation in soil. Biogenic CO_2 emissions were deducted, resulting in net CO_2 emissions of about 35.32 kg CO_2 eq from the biodegradation alone, despite which the PLA mulch films deliver GHG savings of about 108%, compared to the incinerated contaminated LDPE mulch film. However, this may not be a valid comparison owing to the unbalanced nature of the adopted comparative EoL scenarios.

In the case of the baseline case study, the preparation of an alternative solid fuel (ASF) out of the discarded LLDPE mulch films and its incineration for energy recovery provided significant benefits by displacing a conventional energy source (coal), providing savings within the different impact categories. The environmental impact of the displaced the net environmental impacts resulting from the deduction of avoided burden have been presented in Table 18. Despite these GHG savings, the bio-based case study still emerges as a relatively sustainable better option providing roughly 35% GHG savings. Acidification can also be attributed to the release of acidifying pollutants from a variety of sources including energy generation (both in the case of power generation and for transport) and biodegradation of the product in question. Koitabashi et al, 2012 [64] and Briassoulis.D [65], have uncovered the mechanisms of microbial activity on biodegradable mulch, including the release of enzymes and subsequently acids, which in turn affects a multitude of soil characteristics including pH. Modelling microbial activity on mulch and its impacts on soil falls outside the scope of this study, and, therefore has not been considered.

Table 18: Comparison of quantified impacts from energy generation via use of the alternative solid fuel and the displaced conventional fuel (coal)

Impact category	Displaced energy impacts *(from producing 1367 kWh worth of coal)*	Net emissions from burning ASF at the cement kiln
Global warming potential (GWP bio)	178	119
Respiratory inorganics	3.37×10^{-7}	2.39×10^{-6}
Human toxicity, cancer	2.37×10^{-7}	-1.57×10^{-7}
Acidification, terrestrial and freshwater	0.28	-0.15
Freshwater Eutrophication	0.42	-0.41
Terrestrial Eutrophication	0.53	-0.06
Water scarcity	3.68	2.35
Fossil Resource depletion	146	149

64 Koitabashi et al., "Degradation of Biodegradable Plastic Mulch Films in Soil Environment by Phylloplane Fungi Isolated from Gramineous Plants".
65 Briassoulis, "An Overview on the Mechanical Behaviour of Biodegradable Agricultural Films".

By displacing a conventional energy source, the ASF was able to reduce its overall acidification and eutrophication impacts for the LLDPE mulch films, compared to impacts from the fate of the PLA mulch film.

The analysis of the composition of virgin mulch films (for both the bio-based and fossil-based mulch films), based on the industrial data acquired for upstream environmental impact assessment, showed the presence or use of no substances of very high concern (SVHC). However, no industrial or secondary data regarding potential release of any hazardous chemicals during in-situ biodegradation or incineration is available to draw a conclusion. Hence, in this case, the indicators have been left blank. There is a need for a technical evaluation of the products in questions that will help evaluate their disintegration pattern and monitor potential release of any substances of concern across use and their EoL phase. This information must become a part of the product inventory.

The responsibility of the waste factor indicator, within the context of circular economy, is to address the ability of the product design and process to reduce the amount of waste generated that is destined for landfill, incineration without energy recovery or for other least desirable forms of disposal. In the case of the PLA mulch film, ideally, no residue or waste should be left at the end of the in-situ biodegradation, owing to the product's compliance with the EN17033 standards for biodegradable mulch films. However, if we were to consider the 10% residual mulch film present in the soil as potential waste, the waste factor for the product, at the end of the permissible period of biodegradation, in accordance to above standard, would be 0.1 kg per functional unit. The environmental burden from potential accumulation of any residual fractions and their disintegration over long time periods has not been considered in this study, since it falls outside the scope of analysis. Nevertheless, investigation of environmental impacts from long-term biodegradation is recommended for consideration in the future work. Recovery of significant amount of energy from incineration compared to that invested into the incineration process resulted in the LLDPE mulch film being relatively less energy intense (-48%) compared to that of the PLA based much film.

5.2.1 Intended EoL scenario- Outcomes and discussion

Bio-based and fossil-based mulch films: 5% Mechanical Recycling; 40% Incineration; 55% Landfill

The rationale for the inclusion of an alternative EoL scenario for the mulch films candidates was to create a level-playing field to evaluate the impacts from a fair stand-point. The outcomes of this stand-alone evaluation have been presented in Table 19. The variability of these outcomes, upon the application of the PEF's CFF methodology has been visualised in Figure 9 and Figure 10.

Among the different fractions of the post-consumer PLA based mulch films, the 40% entering incineration with energy recovery was determined to contribute relatively lower GHG emissions, compared to the other two options (mechanical recycling and landfill) within the boundary set of this analysis. Deducting the biogenic CO_2 emissions, the overall emissions amounted to 86.2kgCO_2 eq, with 30% contributed by the incinerated non-biogenic fraction. Mechanically recycling the 5% for intensely cleaned and decontaminated post-consumer mulch film resulted in a GWP which when determined upon implementing a factor of 8 (assuming recycling 40% of the post-consumer film) would result in roughly 90kgCO_2 eq/functional unit. In any case, the collection and disposal of mulch film in a landfill was determined to be more burdensome (roughly +40%) compared to incineration with energy recovery and mechanical recycling approaches.

Table 19: Comparative environmental impact assessment of the intended and alternative fate of a functional unit (1ha) of PLA based and LLDPE derived mulch films

Analysis Impact Assessment		**Production and distribution**	**Intended EoL**	**Alternative EoL Scenarios**		
			Soil Biodegradation	Incineration (40%)	Mech. Recycling (5%)	Landfilling (55%)
Global Warming Potential-Bio	**PLA based Mulch films**	292	35.32	86.2	11.5	54.7
Respiratory inorganics		2.52×10^{-5}	1.18×10^{-7}	4.37×10^{-6}	2.47×10^{-7}	2.66×10^{-5}
Human toxicity, cancer		7.90×10^{-6}	3.68×10^{-9}	3.44×10^{-8}	2.13×10^{-8}	1.98×10^{-6}
Acidification, Terrestrial and freshwater		3.31	0.134	0.703	0.0744	3.05
Freshwater Eutrophication		0.106	0.0000327	0.0139	0.00939	0.0521
Terrestrial Eutrophication		1.08	1.46	2.26	0.122	1.89
Water Scarcity		3.51	0.0166	1.73	1.34	2.09
Fossil resource depletion		1630	128	662	9.61	724
Presence of Hazardous Chemicals		■	-	-	-	-
Secondary Resource productivity		-	-	0	0.95	0
EoL Waste factor		0.155	(0.1)	6.84	0.05	83.6
Product Circularity		-	0	0.5		
EoL Process Material Circularity		0.78	-	0	0.85	0
EoL Energy intensity		203	2.98×10^{-2}	9.39×10^{-3}	3.32×10^{-2}	1.26×10^{-2}
Baseline Impact Assessment		**Production and distribution**	**Intended EoL**	**Alternative EoL Scenarios**		
			*Incineration with ER**	Incineration (40%)	Mech. Recycling (5%)	Landfilling (55%)
Global Warming Potential	**LLDPE Mulch films**	574	119	262.730496	11.3	58.6
Respiratory inorganics		3.09×10^{-5}	2.39×10^{-7}	8.53×10^{-6}	2.36×10^{-7}	1.30×10^{-5}
Human toxicity, cancer		1.67×10^{-6}	-1.57×10^{-7}	6.17×10^{-7}	9.15×10^{-7}	8.13×10^{-6}
Acidification, Terrestrial and freshwater		4.08	-0.15	1.14	5.59×10^{-2}	1.96
Freshwater Eutrophication		0.144	-0.41	4.34×10^{-3}	7.42×10^{-3}	0.0579
Terrestrial Eutrophication		1.44	-0.06	3.45	1.06	1.41
Water Scarcity		18.72	2.35	2.26	2.48	2.56
Fossil resource depletion		1764	149	543	7.32	826
Presence of Hazardous Chemicals		■	-			
Secondary Resource productivity		-	-	0.98	-	0.98
EoL Waste factor		8.12	24.31	8.415	102.85	111.285
Product Circularity		-	1	0.5		
EoL Process Material Circularity		No data	-	No data	-	No data
EoL Energy intensity		297	1.53×10^{-2}	6.14×10^{-2}	1.39×10^{-2}	4.57×10^{-2}

Note:
* Quantified impacts are net emissions after the deduction of avoided impacts from the displaced energy source

Upon application of the Circular Footprint Formula (CFF), the "gate-grave" emissions associated to the bio-based and fossil-based case studies were observed to fluctuate relative to the quantification presented in Table 19. The PLA based mulch films emerged better than their fossil-derived counterpart, with lower GHG emissions providing significant savings from the following

- The production of virgin material, with the implementation of circularity strategies (78% process material circularity) delivered almost 200% GHG savings per functional unit.
- The energy recovered from incineration of 40% of the post-consumer PLA delivered enough energy to displace 1367 kWh of energy generated using a conventional energy source (coal).

Extrusion operations and the need for natural gas to generate steam lead to greater acidification impacts associated to the fossil-based case study. Resource recovery and reuse, for example, the utilisation of waste heat to generate steam and other circularity strategies embedded in the virgin PLA production led to 25% savings in acidification impacts. These strategies were also beneficial in significantly reducing the PLA related eutrophication impacts between the ranges of 8-25% relative to that of the LLDPE based mulch films. Similarly, the direct disposal of post-consumer articles into the landfill signifies the disposal of all the resources invested directly and indirectly (process auxiliaries) as waste. Since the LLDPE based mulch film have been assumed to be a linear production process, unlike in the case of their bio-based counterpart, the EoL waste factor was significantly greater for the former candidate. The material recovery capabilities associated to the chosen EoL scenario for both the PLA and LLDPE mulch film is demonstrated by the secondary resource efficiency, which in this case was observed to be similar to that of the baseline case study. According to Brunklaus and Riise, (2018)[66], there are limited EoL directives that provide guidance as a target or minimum levels of material recovery from bio-based products. This is attributable to the limited availability of promising bio-based alternatives to fossil-based products. Moreover, the ability of an appropriate EoL options to effectively recover materials from a used and discarded product depends on a variety of factors including the rate of disassembly which has been fore-designed and embedded into the product; product-life and the level of degradation from product wear and tear. Since these characteristics are primarily associated to the technical evaluation performance, they fall outside the scope of this environmental impact assessment.

[66] Brunklaus and Riise, "Bio-Based Materials Within the Circular Economy".

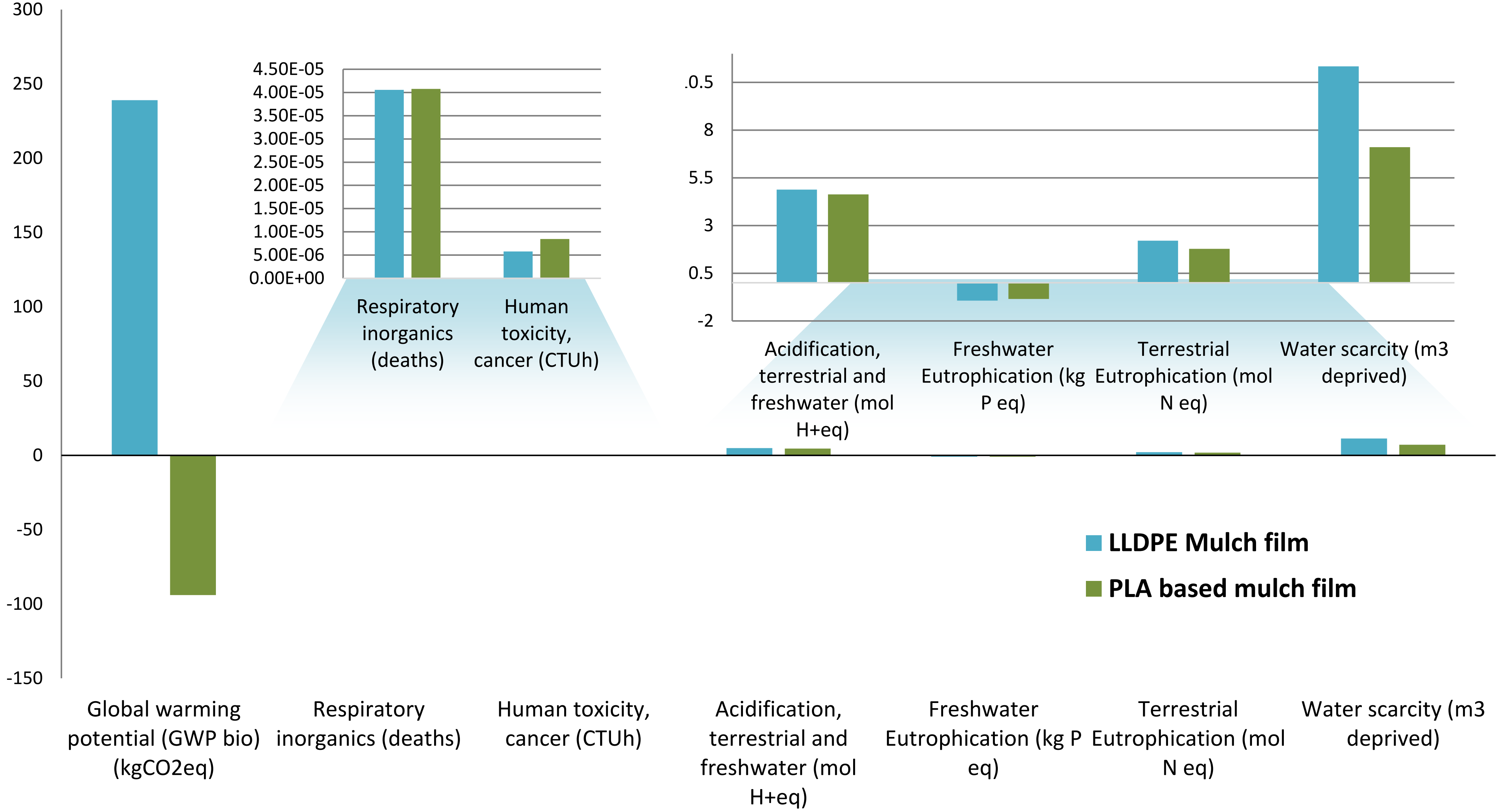


Figure 9:Comparative environmental impact assessment (CFF implemented) for the alternative EoL routes adopted for the PLA based mulch films and LLDPE based mulch film

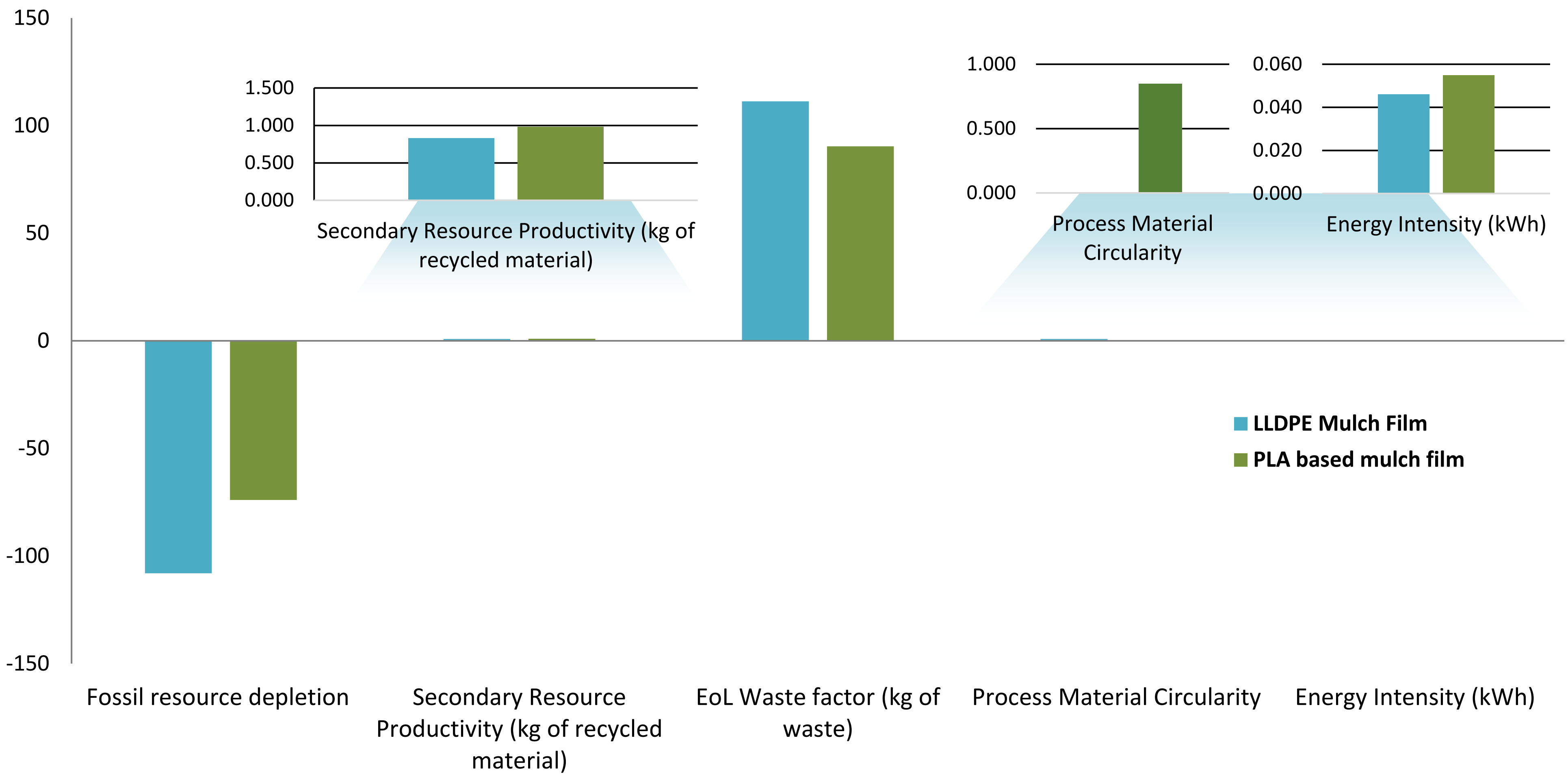


Figure 10: Comparative environmental impact assessment (CFF implemented only for LCA impact categories) for the alternative EoL routes adopted for the PLA based mulch films and LLDPE based mulch film (inc. hybridised Indicators)

Though, waste factor is also partially influenced by the above-mentioned characteristics, process-level resource efficiency and waste valorisation strategies implemented by the economic operators also contributes to the reduction of the amount of waste that ultimately reaches landfill or release into the environment. Considering this scenario, we can observe that these strategies pay off for the PLA based mulch films reducing the overall waste factor by about 20% compared to that of LLDPE mulch films. The energy-rich incinerator feed prepared from LLDPE mulch films (ASF to coal) however, improved the relative energy intensity ratio for the fossil-based case study thus leading to a greater energy intensity (+18.5%) demonstrated by the PLA mulch film waste management strategy.

5.2.2 Mulch films: Impacts and Threshold Applicability

The environmental burden quantified for the mulch films case studies (PLA based and LLDPE mulch film) were adapted to for this study to apply the relative sustainability thresholds that have been developed and presented in section 4.2.10. Table 20 represents the quantified environmental impacts, relative sustainability threshold applied and the outcomes of this comparative evaluation.

Table 20: Sustainability threshold application to the bio-based mulch films

Parameters	Units	LLDPE Mulch film	PLA based Mulch film	Relative sustainability Threshold	Pass/ Fail
LCA Impact categories					
Global warming potential (GWP bio)	*kgCO2eq*	239	-94	0.885	PASS
Respiratory inorganics	*Disease incidence*	4.05×10^{-5}	4.07×10^{-5}	0.833	PASS
Human toxicity, cancer	*CTUh*	5.78×10^{-6}	8.44×10^{-6}	N/A	N/A
Acidification, terrestrial and freshwater	*mol H+eq*	4.88	4.62	1.053	PASS
Freshwater Eutrophication	*kg P eq*	-0.93	-0.85	0.442	FAIL
Terrestrial Eutrophication	*mol N eq*	2.21	1.78	0.413	PASS
Water scarcity	*m3 deprived*	11.34	7.11	1.538	PASS
Fossil resource depletion	*MJ*	-108	-74	N/A	N/A
For hybridised Indicators (per kg of the product)					
Secondary Resource Productivity	*kg of recycled material*	0.83	0.98	0.8	PASS
EoL Waste factor	*kg of waste*	0.60	0.59	0.1	FAIL
Process Material Circularity	%	0	85	90	PASS
Energy Intensity (mat. Rec)	*kWh*	1.59	1.33	1	FAIL
Energy intensity (Waste ER)	*kWh*	1.53×10^{-2}	1.92×10^{-2}	0.5	PASS
Energy Intensity (Landfill)	*kWh*	0.022	0.0126	Not sustainable	FAIL

5.3 Strengths, Limitations and Recommendations

Resource circulation via recovery and reuse strategies may already be captured within the LCA methodology. However, there is a need to showcase the disaggregated information related to material flow and wastage, substances of very high concern and resource (material and energy) circularisation strategies. Demonstration of the performance of the proposed framework on both the bio-based and fossil-based case studies demonstrated its capability to create a level-playing field. The methodology can also be applied to the comparison of two bio-based candidates. Needing no further information than that required for an screening LCA, the proposed method eases disaggregating information regarding material flow, suitable for communication of a product's sustainability credentials, in compliance with the EN16751 standards on *'sustainability criteria'* for bio-based products. Nevertheless, pursuing a performance evaluation of the proposed framework of a case study which is also a secondary (recycled) bio-based product or a product, capable of being reused before being discarded to enter their end-of-life scenario, would be a valuable contribution and a recommendation for future work. This falls outside the scope of the main goals of downstream impact. Despite serving the purpose of their conception and incorporation into the environmental assessment framework, there are a few further refinements that could be made to boost the robustness of these indicators. For example, the indicator *presence of hazardous chemicals* can be developed further to quantify the hazardous chemicals present in the secondary (recycled) material, in addition to highlighting this with a hazard code. Availability of an exhaustive list of hazardous chemicals, published by the ECHA, that could potential enter and result from a bio-based supply chain (during production and end-of-life treatment) would overcome this restriction. Availability of thresholds to classify the quality and the market demand for secondary (recycled) material would be valuable in enhancing the effectiveness of impact allocation (within the CFF methodology) and value-based resource efficiency and circularity evaluation of resources and products.

This study has made an attempt at developing thresholds for the indicators and metrics developed within the proposed EoL environmental framework. The proposed thresholds have been set based on practitioner experience and calibrated on a limited number of practical examples. Moreover, the initial values and their evolution over time have been estimated without the inputs of various other stakeholders who might bring valuable viewpoints and nuances. In that sense, the proposed thresholds are adopted in the present report as demonstrators of how they can be applied in a real case. However, the process of setting these thresholds should be developed in a way that allows consensus among sustainability scientists and stakeholders.

In conclusion, the subjective pathway requires a consensus that should be built through a wide consultation that was not possible to include in the scope of the present deliverable. A recommendation is to follow the work done by the JRC for developing an evidence-based weighting set for the environmental footprint[67], in the context of the Environmental Footprint Pilots.

It is also essential to note that the proposed threshold relies heavily on the degree of transparency of organisations, in terms of their best and actual sustainability practices. This leads to two main concerns. Firstly, the environmental credentials of the product for which the assessment is undertaken is only as good as the quality and quantity of data provided by the stakeholder. Secondly, owing to the nature of data demanded, the proposed EoL framework may not be applied to products entering unmanaged end-of-life routes including illegal on-site burning, unmonitored release of effluents into the environment, fly-tipping, terrestrial and marine littering.

[67] Cerutti et al., *Development of a Weighting Approach for the Environmental Footprint.*

5.4 Conclusions

An innovative and robust environmental impact assessment framework has been proposed as a part of this report suited to evaluate the sustainability characteristics of bio-based products during their use and when they approach their managed end-of-life phase. Within the scope of this framework, the sustainability characteristics account for the crucial information regarding resource utilisation via circularisation strategies, in addition to the standard practice of evaluating the impacts and credits associated to resource production and consumption. For this purpose, the framework was developed incorporating PEF recommended LCA approach (in accordance to the ISO14040 and 14044 standards for environmental management and life cycle assessment). To explicitly quantify the resource efficiency and circularity characteristics of a given product or a technology route, hybridised indicators, exclusively drawn from the combination of green chemistry principles and industrially applied sustainability metrics, have been proposed. Their applicability and robustness were demonstrated through a dedicated bio-based case study evaluation encompassing the *'use'* and *'EoL'* scenarios that reflect the current trend and prospective trajectories for waste management (since the bio-based sector is still in its early stages).

The quantified outcomes of this environmental evaluation have been reported in a comparative fashion between the bio-based products and their fossil-based counterparts. The proposed sustainability thresholds were applied to these quantified impacts which brought to light the '*sustainability credentials' of* specific to the products and processes from an exceptional angle. Nevertheless, this study acknowledges that the proposed thresholds suffer from weaknesses and should, therefore, be considered as a preliminary attempt which is in need of further refinement through extensive stakeholder engagement and consideration of an exhaustive environmental evaluation of bio-based products and product groups for the development of conclusive absolute thresholds.

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7 Supplementary Annex

7.1 Description and the definition of the different managed end of life options (within the scope of this study)

7.1.1 Reduce and reuse:

'Reduce and reuse' are a part of the characteristic '3Rs' suggested within the waste hierarchy. The proportionality between the material extraction followed by value addition, to the overall greenhouse gas emissions and other environmental impacts have been demonstrated by a study by De Wit et al, 2019 [68]. The concept of 'reduce' proposes that the production processes and the product design must be optimised to use only the required amount of resources, as opposed to the business-as-usual scenario. However, the concept of 'reduce' can also be applied to improving the product functionality where the new product replaces the need for an allied component that was conventionally used with an old product to serve the same purpose. For example, today we have edible bio-based and relatively readily biodegradable plates and cutleries that are resistant to sogginess from hot and wet food, compared to conventional bio-based (and or paper) plates that required a protective coating of plastic. In the case of 'reuse', the products are designed to serve their purpose for a shelf-life longer than single-use products. Reuse is also encouraged by either consumer's own choice to repair the product and reuse or via an equivalent service provided by the retailer, for example, via Extended producer responsibility. The goal of this task is to develop an EoL sustainability assessment approach for the bio-based products that could enter the different managed end of life options that have been suggested within the waste hierarchy. The ultimatum of circular economy is to eliminate wastage of resources by keeping the resources in a closed loop for as long as possible. A schematic of the managed end of life routes for a post-consumer product on its pathway to 'grave' has been elaborated below

7.1.2 Recycling

Occupying a desirable tier for material recovery within the Waste Hierarchy, recycling enables the reclamation of materials embedded in the post-consumer product through three possible routes which are as follows

Mechanical recycling: Prior to entering these three routes of recycling, municipal and industrial waste streams are collected separately and transported to the material recovery facility (MRF), where the materials are further disassembled and sorted. In the case of paper, reusable paper is separated from cardboard, contaminated paper and other types. Similarly plastics are sorted based on the types and the nature (such as bio-based from fossil-based and recyclable from non-recyclable ones). The materials are subjected to another stage of disassembly, when made of multiple components of either purely bio-based or fossil-based nature or form environmental contaminants (for example, nails, dye, glue or other components, dirt). Upon disassembly, an additional stage of sorting will improve the quality of the sorted materials destined for either recycling or other more suitable EoL options. The efficiency of the sorting process is a major determining factor on the quality of the recycled material. This is particularly relevant to recycled plastics. This is followed by shredding of the material which is then washed, dried, melt-flow extruded, pelletized and packaged to be sold as recycled plastics. The mechanically stressful nature of the recycling process, in combination with the moisture from the cleaning process and other acidic contaminants are likely to degrade the molecular properties of the recyclates to some extent.

[68] De Wit et al., *The Circularity Gap Report : Closing the Circularity Gap in a 9% World*.

In the case of bio-based plastics, this is overcome by the use of chain-extenders to boost the molecular weight, and thus, the quality of the recycled material[69]. From an industrial perspective, the sorting processes, in combination with the main recycling procedures is likely to generate waste, including heavily degraded fractions unsuitable for mechanical recycling, additives, internal leakages of resources such as process auxiliaries and recyclate spillages, etc. Resource consumption, circularisation and wastages that are relevant to both the processes and specific bio-based processes will determine their suitability for this specific end of life option. This study will employ appropriate case studies to demonstrate this aspect, from a resource efficiency and environmental sustainability viewpoint, through the use of identified LCA and the EoL hybridised indicators.

Chemical Recycling: Chemical recycling is a technology that is currently being developed for other plastics. It is primarily applied for recycle PET (Polyethylene Terephthalate) though approaches to pyrolyse PP waste stream into feedstock for virgin plastic has also been recommended[70]. This option is currently recommended for bio-based plastic products, particular where mechanical recycling will further deteriorate the quality of the recyclates, rendering them unusable. Though chemical recycling is relatively expensive, its potential as a desirable EoL route for waste plastic management comes from the relatively higher efficiency of recyclate transformation and the relatively high-quality recycled materials resulting from the process. The preparatory steps of collection of waste, sorting, decontamination, washing, shredding and drying, leading to chemical recycling, are similar to that followed in mechanical recycling. As this point, the granulated particles, at a molecular level are snipped into monomers by opting for one of the 10+ depolymerisation approach (including hydrolysis, glycolysis, pyrolysis methanolysis etc). The monomers are then subjected to a polymerisation step, in the presence of a catalyst at specific temperature and pressure to create polymers of desirable molecular weight, and subsequently, high-quality recycled resin. The resin is then pelletised and packaged. Chemical recycling is a very selective process and, is therefore, feasible only with high-quality waste plastic streams. Therefore, the preparatory phase is rather resource intensive. Owing to the sensitivity of the sub-processes to potential embedded contaminants in the waste plastic stream (for example, glue, additives, or other incompatible sub-assemblies), care must be taken to ensure the waste stream may contain only acceptable levels of such articles. Waste from the chemical recycling process may include those from the sorting phase, impurities from the hydrolysis reaction and the unreacted monomers from the polymerisation step, in addition to the process-level spillages of the recyclates and recycles resin pellets. In terms of resource consumption, water and energy consumptions, particularly the ability of the process to use and reuse catalysts have to be taken into account. Presence of any hazardous chemicals that have either been separated from the recyclate material or present in the recycled material have to be identified and highlighted.

7.1.1 Organic recycling- Nutrient recovery

Aerobic composting: Bio-based products (or/and some fossil-based products) are often designed in such a way that the products contain elements such as magnesium, potassium, nitrogen or other potential soil nutrients that are destined to enter 'organic recycling' as the intended route at the end of its functional life. Organic recycling closes the loop in the material life cycle of a post-consumer product via an opportunity for nutrient enrichment of soil or compost. Whole products (for example, neat packaging films) or sub-assemblies (for example, wood and paper components) of a product that are destined for organic recycling are generally prepared for biodegradation by the micro-organisms present in the compost heap or in the soil, resulting in the formation of biomass, carbon-di-oxide and water.

[69] Cosate de Andrade et al., "Life Cycle Assessment of Poly(Lactic Acid) (PLA)".
[70] Achilias et al., "Chemical Recycling of Plastic Wastes Made from Polyethylene (LDPE and HDPE) and Polypropylene (PP)".

EN13432[71] standard for the treatment of packaging material through composting and biodegradation" provides appropriate measure to quantify biodegradability, while also capturing the eco-toxicity and heavy metal release. However, it is essential note that not all bio-based products are biodegradable and not all biodegradable products or sub-assemblies necessarily contribute to soil enrichment.

The rate of biodegradation on the other hand is influenced by a number of factors such as the mechanical properties of the product (for example, the thickness of the material, level of degradation) and from the environmental factors such as ambient or process temperature and pressure, frequency of turning the heap or agitation, aeration rate, residence time etc. Organic recycling can be undertaken via aerobic composting, anaerobic digestion or by industrial composting. However, it is essential to note that such a process can qualify for 'recycling' only if there is direct element of nutrient addition to the soil. In other cases, where there is little to no nutrient addition, it is considered as 'controlled biodegradation, a process that is monitored closely, where the outcome eliminates the environmental burden that would be otherwise be drawn from other end of life options like incineration or landfilling. Being the simplest of EoL processes, organic recycling does require the post-consumer waste streams to be free of hazardous chemicals and other deterrents (for example, additives, anti-microbial agents non and/or only partially biodegradable articles) that will negatively impact the biodegradation process. It is upto the industrial practioner to determine the appropriate ambient conditions, moisture content, carbon to nitrogen ratio of the product/ compost mix, aeration rate and other parameters to enable optimum conditions for almost completely biodegradation of the product. The gaseous emissions resulting from composting may contain carbon dioxide (CO2), water and some amount of methane. The degree of formation of the greenhouse gas, methane, which is a 25% more potent in causing greenhouse effect than carbon dioxide, is influenced by the rate of aeration of the composting mix. Limited aeration leads to biodegradation taking place in oxygen-starved pockets of the heap leading to the formation of methane. In the case of industrial composting facilities, bio-filters are often utilised to limit the release of these gases into the atmosphere.

Anaerobic Composting: *Please refer to Anaerobic digestion*

7.1.1 Energy recovery

Incineration with Energy recovery: Unprocessable, hazardous and post-recycling waste is either destined to be disposed via incineration for further energy recovery (provided the waste stream has higher energy content), incineration without energy recovery or landfill. Incineration involves burning of waste stream at a temperature more than 850°C, reducing the overall weight of the waste per unit mass by 80%. These incinerators are often integrated with combined heat and power (CHP) plants. The heat energy is recovered (conventionally at an efficiency of about 70-80% , which is used for district heating and the power is generated at an efficiency of about 20-30& which is fed to the national grid. Other ferrous and non-ferrous articles such as glass, metals and stones get collected at the bottom of the incinerators as a part of the "Bottom ash". These articles are recovered and sent off to be recycled appropriately. A number of factors influence environmental (and primarily the techno-economic) feasibility of incinerating incoming post-consumer and post-recycling waste. Particularly the moisture content and the lower heating value of the waste stream, the transformation and recovery efficiency of the technology in place, availability and the effective functionality of appropriate gas scrubbers etc[72].

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[71] CEN European Committe for Standardization, "BS EN 13432:2000: Packaging. Requirements for Packaging Recoverable through Composting and Biodegradation. Test Scheme and Evaluation Criteria for the Final Acceptance of Packaging".

[72] Cosate de Andrade et al., "Life Cycle Assessment of Poly(Lactic Acid) (PLA)"; Alarico, "Life Cycle Assessment Study of Polylactic Acid Packaging Including Food Waste"; Rossi et al., "Life Cycle Assessment of End of Life Options for Two Biodegradable Packaging Materials: In Support of Flexible Application of the European Waste Hierarchy".

Incineration does provide a solution to reduce the amount of waste sent to the landfill. Additionally, from a resource efficiency perspective, incineration with energy recovery may come across as better off than composting as an overall valuable resource recovery approach[73]. Nevertheless, the failure of this EoL option to recover and retain the value of the material resources in commercial circulation, in addition to being intense in terms of energy consumption and environmental impacts via emission of particulate matter, GHGs, heavy metals, VOC and other contaminants to air, need for precious metals as catalysts for the process undermines the overall sustainability and renders this option the least-desirable among recovery EoL options.

Anaerobic digestion: Anaerobic digestion (AD) is one of the commercially practiced energy recovery options that a post-consumer bio-based product (for example, wood, paper, biodegradable packaging) may enter, depending upon the product's design, in terms of mechanical properties post-consumption and the intended EoL route. As the name suggested, the bio-based products embedded in the solid waste stream are digested by a combination of different microbes systematically, in the absence of oxygen. The AD process is methodically carried out in four phases. Firstly, the solid waste is acted upon by a first category of microbes that release hydrolytic enzymes causing the breakdown of complex molecules.
Secondly, via acidogenesis, the monomers from the first phase are fermented to higher volatile fatty acids, followed by the third phase (acetogenesis), where the fatty acids are transformed into acetic acid, carbon di-oxide and hydrogen. Finally, the methanogenic microbes consume hydrogen to convert acetic acid into bio-methane or biogas and carbon-di-oxide. The biogas is recovered and can be circulated or sold as an energy carrier. Often, the extracted biogas is upgraded to bio-methane which has a wide range of application both in the energy and the renewable chemicals sector. AD has also been suggested as a potential biorefinery to generate high vale intermediates from low-value inputs[74].
The entire operation takes place in a controlled and monitored facility with in-situ biogas recovery strategies. This process will involve a preliminary 'feed preparation' phase where the solid waste stream is screened for microbial inhibitory components such as additives, ferrous or non-ferrous metals and other contaminants. There is some level of energy and process auxiliary consumption for the entire operation. Nevertheless, the environmental performance of an AD has been heavily criticised by a number of studies[75]. Some of the factors that are likely to affect the overall environmental performance of AD include the energy efficiency of the entire process, the strategies implemented to ensure the gaseous emissions from the process are appropriately captured and recovered, off-gas leakages and the quality of the resulting compost (potential presence of heavy metals, hazardous chemical contaminants that could accumulate in the soil or leach into water bodies upon application).

Pyrolysis and Gasification: Unlike incineration and anaerobic digestion, pyrolysis and gasification can be identified as a mature technology that has not reached commercial application for the treatment of post-consumer waste streams. Pyrolysis is a process which involve conversion of solid waste (fossil or bio-based) into energy carriers, in the complete absence of oxygen. This brings about the decomposition of complex molecules resulting in the formation of syngas (carbon monoxide, carbon dioxide and hydrogen) which can be engineered into energy carriers (fuels) for application in power generation or transport.

[73] Yang, Zhou, and Xu, "Eco-Efficiency Optimization for Municipal Solid Waste Management"; Piemonte, "Bioplastic Wastes".

[74] de Jong and Jungmeier, "Chapter 1 - Biorefinery Concepts in Comparison to Petrochemical Refineries"; Liu, Liao, and Liu, "A Sustainable Biorefinery to Convert Agricultural Residues into Value-Added Chemicals".

[75] Domingo et al., "Health Risks for the Population Living in the Vicinity of an Integrated Waste Management Facility"; Paolini et al., "Environmental Impact of Biogas"; Fruergaard, Hyks, and Astrup, "Life-Cycle Assessment of Selected Management Options for Air Pollution Control Residues from Waste Incineration".

Gasification of solid waste follows the same approach except that there is insufficient amount of oxygen leading to incomplete combustion of the solid waste[76]. The environmental performance of these pathways, similar to the other energy recovery options, depend upon the efficiency with which undesirable and high-environmental impact emissions are scrubbed from the gaseous outputs, the fate of the pyrolytic char and their impact when disposed onto a landfill (leaching of heavy metals and other contaminants in unmanaged landfills.

Landfill with energy recovery: Landfill, as the name suggests, is the final destination for a number of organic or fossil-based unprocessable, untreatable hazardous waste from the various life cycle stages of a product. There are two type of landfills, managed and unmanaged. There are designated landfills based on the type of waste generated, for example, for coal combustion waste, construction and demolition debris, hazardous waste etc. These wastes are generally disposed off in a responsible manner, at fit-for-purpose created landfill sites. Municipal solid waste is also disposed of on such managed landfill sites to prevent seepage of leachates into underground aquifers. While the organic waste degrades in the landfill, under anaerobic conditions, the biogas is generated which may be recovered, processed into an energy carrier. Though not widely found, in terms of application, it has been credited with the potential to reduce the overall methane generation compared to that seen in the conventional practice.

7.1.1 Disposal

Incineration without energy recovery: Combustion of solid wastes which are untreatable, unprocessable or hazardous to be disposed of in a landfill are generally incinerated (for example, medical, pharmaceutical and industrial waste). The main purpose of this activity is to treat the hazardous waste and convert the same into flue gas and heat. In this case, however, there are no energy recovery steps involved. Additionally, the conventionally lower energy content of incineration feed will incur a need for assistant fuel to initiate the incineration process. The Waste Incineration Directive (WID) 2000/76/EC, mandated by the European Commission, provides guidance on the emissions (air, land and water) limits which are to be closely monitored and regulated by the incinerator operators. Similar to the incineration with energy recovery, this EoL option may provide an option to reduce the total amount of waste being sent to the landfill. However, from a resource efficiency perspective, there is very little to be gained from it. Hence this is considered as one of the least desirable pathways to a product’s grave.

Landfill without energy recovery: Being one of the oldest and most widely used methods of disposing a product post-consumption, landfill without energy recovery is the least desired EoL pathway for a product against the backdrop of circular economy and resource efficiency. Realistically speaking, untreatable and unprocessable waste from some production process, product consumption and from other EoL operations such as recycling, incineration and other forms of waste treatment need to be disposed. Unlike the earlier case, where there are landfills with energy recovery, there is a greater prevalence of managed and unmanaged landfills in every industrialised and non-industrialised nations.

[76] Czajczyńska et al., “Potential of Pyrolysis Processes in the Waste Management Sector”; Zevenhoven et al., “Combustion and Gasification Properties of Plastics Particles”.

7.1.2 Process Description: Mechanical recycling and Incineration with Energy recovery (PLA based mulch film)

The least contaminated fraction of the collected mulch film was assumed to be transported to the material recovery facility where the received waste film undergoes a hydro-cleaning process after which the floating film is sent into a wet-granulator reducing the risk of material melt down prevalent in conventional processes. A series of cleaning and separation steps, involving washing and centrifugation, are undertaken to remove the remaining dirt from the recyclable fraction. This step is crucial to ensure that the material is sufficiently prepared for the upcoming recycling process. The granules are thoroughly dried before being melt-extruded and pelletised. Due to lack of sufficient industrial data and for the purpose of simplicity (and subsequently to reduce the level of uncertainties associated to these factors), the quality of the secondary material was assumed to be equivalent to that of the virgin material, though this study fully acknowledges the quality of the recycled material to be questionable.

The fraction entering incineration for energy recovery (82.08 kg of contaminated mulch) was assumed to be sent off to the consolidation plant to be prepared as an alternative soil fuel (a replacement for conventional energy source, coal). Excess soil contaminations were removed via mechanical agitation and the calorific value of the processed mulch film was adjusted with loose saw dust (18kg).

The prepared alternative solid fuel was then assumed be incinerated for energy supply at a designated cement kiln, replacing 50.6 kg of the conventional used energy source, coal. Besides the soil recovered from the consolidation phase (which is assumed to be returned to the environment), the bottom ash resulting from the film incineration is assumed to be disposed onto a MSW landfill. One of the most common forms of mulch film disposal strategies (landfill) is prevalent in the EU due to the lack of an efficient material recovery or waste management strategy[77]. However, for the purpose of this alternative EoL evaluation, a fraction of the overall collected mulch film (55%) which is heavily degraded and contaminated is assumed to be disposed onto a landfill.

[77] Briassoulis et al., "Review, Mapping and Analysis of the Agricultural Plastic Waste Generation and Consolidation in Europe".

7.1.3 Default factor chosen for the End-of-life modelling and allocation using the Circular Footprint Formula

S. Table 1:Choice of default factors used in the PEF-CFF approach for end of life modelling of the bio-based case studies

Bio-based product	Parameter	Value	Comments
BoPLA Packaging film	*A*	0.5	Due to limited demand and limited supply of recycled material
	B	0	"0" as default recommended by PEF
	Qs_{in}/Q_p	0	"0" chosen since material quality is not considered in this study (due to lack of industrial data on recyclate quality)
	Qs_{out}/Q_p	0	"0" chosen since material quality is not considered in this study (due to lack of industrial data on recycled material quality)
	R_1	0	No recycled content in the final product
	R_2	0.408	Assumptions from alternative scenario, please refer to section 4.3.1
	R_3	0.388	Assumptions from alternative scenario, please refer to section 4.3.1
PLA based mulch films	*A*	0.5	Due to limited demand and limited supply of recycled material
	B	0	"0" as default recommended by PEF
	Qs_{in}/Q_p	0	Default values recommended only for packaging films
	Qs_{out}/Q_p	0	Default values recommended only for packaging films
	R_1	0	No recycled content in the final product
	R_2	0.05	Assumptions from alternative scenario, please refer to section 4.3.2
	R_3	0.4	Assumptions from alternative scenario, please refer to section 4.3.2

7.2 : Environmental Impact Assessment: Assumption and limitations

I. The environmental impact assessment undertaken for both the packaging film and mulch films (bio-based and fossil-derived) were centred around the primary product of analysis.

II. The bio-based PCPF that was collected and composted was assumed simply add organic matter to the resulting compost by encouraging microbial activity, adding no additional nutrients.

III. The post-consumer mulch film and packaging film that were incinerated for energy recovery were assume to displace a conventional energy source (coal) used for energy generation for industrial and district heating.

IV. Post-consumer packaging film (PCPF) waste was assumed to be disposed clear of any residual food waste for the purpose of coherence in the assessment carried out.

V. The collected mulch film is assumed to be soil-contaminated by about 50%. This assumption is applicable only to the LLDPE mulch films. PLA based mulch film on the other hand, is assumed to not undergo any degradation during its functional life. At the end of its functional life, PLA based mulch films is assumed to be rototilled into the soil after which the mulch film undergoes biodegradation by up to 90% (in compliance with the EN17033 standards for Biodegradable mulch films.

VI. The PCPF waste is assumed to be collected by the waste collection authorities via curbside collection, travelling a distance of about 5kms to the material recovery facility. Upon sorting and cleaning, the processed films are assumed to be transported to the following facilities which are located at the assumed distances
   a. mechanical recycling facility located at a distance of about 150 kms
   b. Facility for incineration of mixed waste streams with energy recovery, which is located at a distance of about 50 kms from the material recovery facility
   c. Facility for composting the processed BoPLA PCPF located at a distance of 50km.
   d. For the disposal of PCPF waste located at a distance of about 250 km.

VII. In the case of the collected mulch films, the collected, soil-contaminated mulch film is assumed to be transported to the consolidation baling facility located at a distance of 5 kms. The baled mulch films is assumed to be transported to the alternative solid fuel (ASF) plant which is assumed to be allocated at a distance of about 50 km. The Alternative solid fuel is consumed at a cement kiln for a fuel source, located at a distance of about 100 km.

7.2.1.1 Assumptions for Mechanical recycling

I. The incoming post-consumer packaging film waste stream is assumed to be sorted, in accordance to the European packaging waste management approach, where 5% of removed recoverable oil-based mulch films and 40% of propylene packaging films can be recycled[78]. These waste management figures were applied to both the bio-based case studies for two reasons: firstly, to be able to foresee the waste management burden, in the event where the technology maturity to treat and recovery material/ energy from bio-based products has been established and implemented; secondly, for the purpose of coherence in the comparative environmental impact assessment undertaken, where potential impacts related to the different end of life options have been determined.

II. Post-consumer BoPP films are assumed to be recycled at an efficiency of about 99.8% while the post-consumer BoPLA films are recycled at an efficiency of about 96%.

III. Any additives, that may be present in the packaging films and mulch films entering mechanical recycling option, is assumed to not hinder overall recycling process.

IV. The contaminants (soil) separated from the mulch films are not treated as waste since they are assumed to be returned to the environment.

[78] Eurostat, "Packaging Waste Statistics - Statistics Explained"; Eurostat, "Waste Statistics - Statistics Explained".

7.2.1.2 Assumptions for Incineration with energy recovery

I. For the purpose of uniformity in the assessment undertaken and to avoid any additional uncertainties, incineration is assumed to take place under stoichiometric conditions and associated gaseous emissions were adopted and combined with the process related burdens, within both the mulch films and packaging film case studies;
II. The lower heating value, attributable to the PLA, PP and PE, for the purpose of energy recovery was assumed to be 19.5 MJ/kg, 30.78 MJ/kg and 42.47 MJ/kg, respectively[79] For the PLA based mulch film, a lower heating value of 25.5 MJ/kg was calculated in accordance to the guidance provided in CEN/TR/16957.
III. The fraction of post-consumer packaging films and mulch films reaching the incineration facility was assumed to be 38.8% and 40% respectively [80];
IV. The incinerator is assumed to be integrated with a combined heat and power (CHP) plant to enable energy recovery for district heating. The electricity and heat recovery efficiencies from the incineration of packaging films (prepared as a mixed waste stream) were assumed to be 9% and 22% respectively[81];
V. Biogenic and non-biogenic emissions, released from the incineration of the waste stream, were based on stoichiometric calculations.
VI. Biogenic emissions released from the incineration of bio-based case studies were omitted since the embodied carbon (released from incineration of the post-consumer waste) is derived from annual crops[82].

7.2.1.3 Assumptions for disposal via landfilling

I. Landfilling is applicable only to the specified fraction of the post-consumer article within the alternative EoL scenario alone;
I. When landfilling the GHG emissions, resulting from potential anaerobic biodegradation of the post-consumer products (bio-based packaging films and mulch films) in a landfill, were stoichiometrically calculated;
II. The biodegradation rate of the products (PLA-derived), in an anaerobic landfill conditions were assumed to be about 1% over a span of 100 days based on the consensus of the finding of PLA's behaviour in a landfill reported within open literature[83].

The material landfilled as a part of this disposal scenario was calculated as the total amount of waste generated from this process.

[79] Department of Environment, Food and Rural Affairs, *Incineration of Municipal Solid Waste*; Fruergaard, Hyks, and Astrup, "Life-Cycle Assessment of Selected Management Options for Air Pollution Control Residues from Waste Incineration"; Shonfield, *LCA of Management Options for Mixed Waste Plastics*; Irvine, Lamont, and Antizar-Ladislao, "Energy from Waste".
[80] Eurostat, "Packaging Waste Statistics - Statistics Explained"; Eurostat, "Waste Statistics - Statistics Explained".
[81] Shonfield, *LCA of Management Options for Mixed Waste Plastics*; O. Reimann, *CEWEP Energy Report III:Results of Specific Data for Energy, R1 Plant Efficiency Factor and NCV of 314 European Waste-to-Energy (WtE) Plants*.
[82] Guest et al., "Consistent Quantification of Climate Impacts Due to Biogenic Carbon Storage across a Range of Bio-Product Systems".
[83] Rossi et al., "Life Cycle Assessment of End of Life Options for Two Biodegradable Packaging Materials: In Support of Flexible Application of the European Waste Hierarchy"; Hottle, Bilec, and Landis, "Biopolymer Production and End of Life Comparisons Using Life Cycle Assessment"; Kolstad et al., "Assessment of Anaerobic Degradation of Ingeo™ Polylactides under Accelerated Landfill Conditions".