# D8.7 Roadmap for a sustainable end-of-life of TCs

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# Technical References

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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
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# Summary

This deliverable D8.7 aimed to analyse and select the best end-of-life option for each of the test cases developed in the project, by using a multiple criteria analysis (MCA). This activity corresponds to *Task 8.5 - Roadmap for a sustainable end-of-life of TCs.*

The analysis was performed based on the data gathered in *Task 8.2 Life-cycle Assessment and Life-cycle Costing Assessment* and *Task 8.3 Recyclability and Biodegradability Testing*, as well as state-of-the-art information about current end-of-life approaches for each test case.

The Multi-criteria analysis (MCA) was performed considering the different end-of-life scenarios selected (mechanical recycling, composting, anaerobic digestion for biogas production) and tested for each Test Case, resulting in a ranking of scenarios according to their overall feasibility.

The analysis considered various evaluation categories regarding technical, economic and environmental performance, which were broken down into several criteria for each performance category and scored with a weighting factor, according to its level of importance. The results of the MCA for each Test Case were compared, selecting those with the highest potential, also identifying the main challenges and enablers to overcome these, and preparing a roadmap for sustainability to be shared with relevant stakeholders and regulatory bodies (to be performed in *Task 9.2: Regulatory Analysis*).

# Disclaimer

This publication reflects only the author's view. The Agency and the European Commission are not responsible for any use that may be made of the information it contains.

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# Glossary

EoL: End of Life

MCA: Multi-Criteria Analysis

PA10.10: Polyamide 10.10

PHA: Polyhydroxyalkanoates

PHBV: Poly(3-Hydroxybutyrate-co-3-Hydroxyvalerate)

PLA: Polylactic acid

TC: Test Case

TPE: Thermoplastic elastomer

TPU: Thermoplastic Polyurethane

FU: Functional Unit

MBT: Mechanical – Biological Treatment

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# 1 Introduction

Multiple criteria analysis, or MCA, is a structured process for evaluating options with conflicting criteria and choosing the best solution. MCA is similar to a cost-benefit analysis but evaluates numerous criteria, rather than just cost.

Conducting an MCA aims to help determine which options are most effective, increasing the efficiency of the decision-making process. In addition to providing an ordered list of alternatives, it addresses the social aspects of decision-making, to encourage discussion between different decision-makers. Some additional benefits of this analysis are that the MCA can help further communication between different stakeholders, ensuring that everyone involved in the decision gets the opportunity to address the issue; it can help to discover useful insights that otherwise could be missed, allowing to make the most informed decision possible; and finally, the MCAs use a systematic approach to identifying and comparing different options, by assessing their impacts, performances, advantages and disadvantages, which can help to ensure that the decision-making is consistent, regardless of the issue.

In task 8.5 an MCA was performed on all test cases to evaluate each end-of-life scenario according to the criteria selected and scored. This analysis will help in selecting the best end-of-life choice, as well as to detect current limitations, to be addressed to the regulation bodies in WP9.

# 2 Multi-criteria Analysis (MCA)

## 2.1 Methodology

To perform a Multi-criteria Analysis, a process must be followed. This process is composed of different steps, which can be summarised in the following scheme, and are described below:

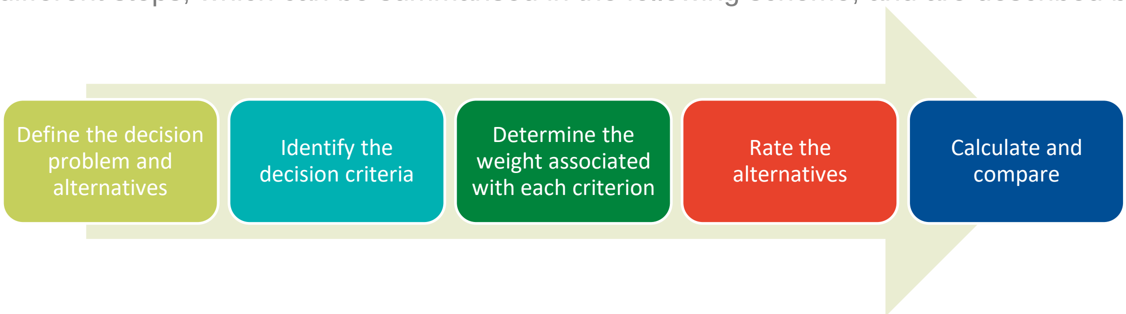


*Figure 1. Process to perform a Multi-criteria Analysis*

**Definition of the problem and alternatives.** The problem to assess is the objective to achieve in the MCA, and it considers the main categories for the analysis. To define the objective clearly, it is necessary to determine the need to fulfil and who the key stakeholders are. In the INN-PRESSME project, the objective of the MCA is to establish which is the most suitable end-of-life choice and identify the current impediments and limitations to be addressed. These end-of-life choices constitute the alternatives or categories of the study: mechanical recycling, aerobic biodegradation or anaerobic degradation.

**Identify the decision criteria.** From the defined objective and categories, different criteria can be established, which will be the base for the analysis. There can be multiple levels of criteria, which means there is a Level 1 general criterion that could be composed of more specific

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criteria (Level 2). The criteria selected for each EoL approach are based on technical, environmental, economic and regulation aspects.

**Determine the weight associated with each criterion.** Weight is how important each criterion is to the decision, represented as a fraction (all level 1 criteria must add 1). In this case, the selected criteria (level 1) and sub-criteria (level 2) are given a weight according to the relative relevancy of each. In addition, a performance value or score scale is also defined for each of the criteria.

**Rate the alternatives.** Rating the choices involves determining how each option compares to the criteria. In this step also a normalisation process is applied to each performance value, which refers to the act of adjusting the scoring values so that they operate on a common scale. In this study, all performance values were normalised to a scale of 100.

**Calculate and compare.** The normalised values are multiplied by the weight assigned to the corresponding criterion, represented as a decimal. This operation is performed for all the criteria. Finally, for each option, the weighted normalised values are added together within each criterion to calculate the performance scores. Once the performance score is calculated for each option, is possible to compare the scores. The option with the highest score would provide the most value, according to the selected criteria.

## 2.2 Categories and Criteria selected

As mentioned in the previous section, the categories being studied are the different end-of-life choices for each Test Case:

- Mechanical recycling.
- Aerobic biodegradation.
- Anaerobic degradation.

For the above categories, the criteria selected were based on technical, environmental, economic and regulation aspects, and for some criteria, sub-criteria was also defined. Three main criteria were defined for the MCA (Figure 2).

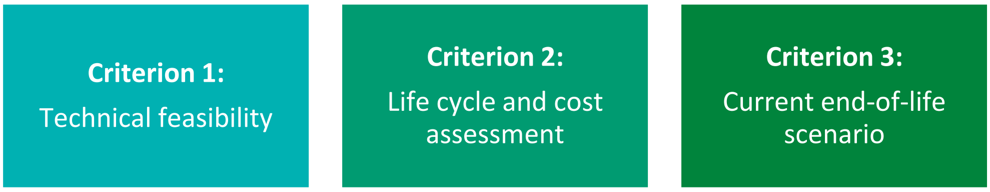


*Figure 2 Three main criteria for the MCA.*

These are described in the next sections, together with the weight and performance values associated.

### 2.2.1 Criterion 1: Technical feasibility

This criterion is identified as the possibility to perform the respective EoL option from the technical point of view, which depends on the specific material and the results of the evaluation done in Task 8.3. In this case, two sub-criteria (level 2) were defined: Suitable method and Result.

- *Suitable method*. This sub-criterion corresponds to the composition of the Test Case, which could limit the possibility of specific end-of-life choices. For example, non-biodegradable products will not be suitable for biodegradation.

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- *Result.* This sub-criterion is directly related to the results obtained during the evaluations performed in Task 8.3, referring to the overall results obtained for each TC. For this, multiple factors were considered such as processability under a specific method, performance and final result obtained. For example, biodegradation rate, performance compared to original material, etc.

The weight factor of each level (from the overall MCA), as well as the performance indicators and values established for these criteria, are presented in Table 1.

*Table 1. Weight factor and levels for Criterion 1: Technical Feasibility*

| Criteria | Level 1 | Level 2 | Performance value |
|---|---|---|---|
| Technical feasibility | 0.4 | | |
| Suitable method | | 0.5 | |
| Suitable technology | | | 100 |
| Non-suitable technology | | | 0 |
| Result | | 0.5 | |
| Recyclable/biodegradable | | | 100 |
| Downgrade recycling/partially biodegradable | | | 50 |
| Non-recyclable/non-biodegradable | | | 0 |

The definition of each performance indicator is the following:

- *Suitable technology.* Indicates that the Test Case/material can potentially be processed by the respective end-of-life technology.
- *Non-suitable technology*. The Test Case/material can not be processed by respective end-of-life technology.
- *Recyclable/biodegradable*. The result obtained in the recyclability/biodegradability assessment is good-excellent. In mechanical recycling, there is good processability and good performance, which will allow the recycled material to be used in the same or other applications (with similar requirements). In the case of paper products, the recyclability standard mill score is in the range 0-100. The biodegradation result is above 90%.
- *Downgrade recycling/partially biodegradable*. The result obtained in the recyclability/biodegradability assessment is medium. In mechanical recycling, there is a variation in processability (processing issues) and lower performance with respect to the original material, which will allow the recycled material to be used in other applications (with lower requirements - downcycling). The biodegradation result is 70-90%.
- *Non-recyclable/non-biodegradable.* The result obtained in the recyclability/ biodegradability assessment is low. In mechanical recycling, there are major issues in processability (not processable) and the performance is very low with respect to the original material, which will not allow the recycled material to be used in any application, without first performing an upgrade or blending it with virgin material. In the case of paper products, the recyclability standard mill score is below 0. The biodegradation result is below 70%.

### 2.2.2 Criterion 2: Life cycle and cost assessment.

This criterion is related to the feasibility of each end-of-life option, from a sustainable and economic point of view. The criterion is partially related to the results of the evaluation done in Task 8.2 for each test case, as well as to parallel investigation on the state of the art for each method (that was not under the scope of T8.2). In this case, two sub-criteria (level 2) were defined: Sustainability and Cost.

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- *Sustainability.* This sub-criterion corresponds to the relative environmental impact of each EoL method. In general terms, there is reduced information about the environmental impact of each EoL method. In specific studies, anaerobic digestion is combined with composting in one process, and this seems to be the most impactful EoL treatment, due to the low quality of the compost that is eventually sent to landfill. On the other hand, mechanical recycling has lower environmental impacts due to the high recycling efficiency and credits received from avoided virgin material and the energy recovery from the non-recycling plastic sent to incineration. Composting or Aerobic MBT (mechanical–biological treatment) are usually combined with incineration with energy recovery, which has a similar environmental impact to mechanical recycling (slightly higher).[1,2,3]
- *Cost.* This sub-criterion corresponds to the relative cost of each EoL technology, including operation cost and revenues. In this case, according to specific studies, it appears that mechanical recycling has a high operational cost per functional unit (FU) (1 ton of bio-based plastic waste) due to Material Recovery Facility (i.e. optical sensors, magnetic separators), and is similar to Composting/Aerobic MBT. However, the total cost, including revenues, is still lower than anaerobic degradation.[4]

The weight factor of each level (from the overall MCA), as well as the performance values established for these criteria, are presented in Table 2.

*Table 2. Weight factor and levels for Criterion 2: Life cycle and cost assessment.*

| Criteria | Level 1 | Level 2 | Performance value |
|---|---|---|---|
| Life cycle and cost assessment (LCA and LCC) | 0.2 | | |
| Environmental impact | | 0.3 | |
| Low Environmental impact | | | 100 |
| Medium Environmental impact | | | 50 |
| High Environmental impact | | | 30 |
| Cost | | 0.7 | |
| Low cost of technology | | | 100 |
| Medium cost of technology | | | 50 |
| High cost of technology | | | 30 |

Each performance value is defined as relative (low, medium and high) between each EoL technology.

### 2.2.3 Criterion 3: Current end-of-life scenario

This criterion corresponds to the current approaches taken for similar products to the Test Cases, to evaluate the existing end-of-life possibilities and limitations, and thus, propose the implementation of actions to overcome the detected shortcomings. The sub-criteria defined is directly related to the definition of recyclability given by the principal recyclers' associations

[1] Gadaleta, G., et al. Life cycle assessment of end-of-life options for cellulose-based bioplastics when introduced into a municipal solid waste management system, Science of the Total Environment, 2023, 871, 161958.

[2] Spierling, S., et al. End-of-Life Options for Bio-Based Plastics in a Circular Economy—Status Quo and Potential from a Life Cycle Assessment Perspective. Resources 2020, 9, 90.

[3] Abrha, H., et al. Bio-Based Plastics Production, Impact and End of Life: A Literature Review and Content Analysis. Sustainability 2022, 14, 4855.

[4] Gadaleta, G., et al. Carbon Footprint and Total Cost Evaluation of Different Bio-Plastics Waste Treatment Strategies, Clean technologies, 2022 4, 570–583.

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(Plastic Recyclers Europe and Association of Plastic Recyclers)[5,6]. These sub-criteria are directly translatable to the biodegradability concept.

- *Collection, sorting and processing infrastructure*. This sub-criterion is related to current collection systems, sorting streams and dedicated processing facilities for similar applications to the Test Cases studied. In this case, following the recyclability definition, the products must be sorted and aggregated into defined streams for the recycling/biodegradation processes, and the products should be processed and reclaimed/recycled/biodegraded with commercial recycling/biodegradation technologies.
- *Policy and regulations*: The product must be made of a material that is collected for recycling, has market value, and/or is supported by a legislatively mandated program.

The weight factor of each level (from the overall MCA), as well as the performance values established for these criteria, are presented in Table 3.

*Table 3. Weight factor and levels for Criterion 3: Current end-of-life scenario.*

| Criteria | Level 1 | Level 2 | Performance value |
|---|---|---|---|
| Current end-of-life | 0.4 | | |
| Collection and infrastructure | | 0.5 | |
| Available collection scheme and processing facilities | | | 100 |
| Available collection scheme but few or none processing facilities | | | 50 |
| No collection scheme available nor processing facilities | | | 0 |
| Policy and regulations | | 0.5 | |
| Existing policies and regulations | | | 100 |
| Non-existing policies or regulations | | | 0 |

Each performance value is defined as relative (available/exists, partially available, non-available/non-existent) between each EoL technology and for the respective Test Case.

In the following sections, the MCA performed for each TC is presented, followed by a comparison between all the TC's results.

[5] What is recyclability? RecyClass - Plastics Recyclers Europe. https://recyclass.eu/recyclability/definition/

[6] APR Definition of Recyclable. APR – Association of Plastic Recyclers. https://plasticsrecycling.org/apr-design-hub/apr-design-guide-overview/#gettingstarted

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# 3 End-of-Life scenario evaluation for each TC

## 3.1 Test Case 2 (bio- and fibre-based stand-up pouch)

Test Case 2 corresponds to coated fibre-based products for the production of stand-up pouches. The MCA was performed on the specific products: Solide Lucent POP (PLAX-ORMOCER-PLAX coating) and Asendo POP (PLAX-ORMOCER-PLAX coating). PLAX is an aqueous PLA-based dispersion and ORMOCER is a biobased inorganic-organic hybrid polymer dispersion. The results for each product are presented in Table 4 and Table 5, followed by the respective reasoning.

*Table 4. MCA for Asendo POP coated paper (TC2)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 100 | 100 |
| Result | 100 | 100 | 50 |
| *Score* | *40* | *40* | *30* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 50 | 30 |
| Cost | 100 | 50 | 30 |
| *Score* | *20* | *10* | *6* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 100 | 50 | 50 |
| Policy and regulations | 100 | 100 | 100 |
| *Score* | *40* | *30* | *30* |
| **Total** | **100** | **80** | **66** |

*Table 5. MCA for Solide Lucent POP coated paper (TC2)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 100 | 100 |
| Result | 0 | 100 | 100 |
| *Score* | *20* | *40* | *40* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 50 | 30 |
| Cost | 100 | 50 | 30 |
| *Score* | *20* | *10* | *6* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 100 | 50 | 50 |
| Policy and regulations | 100 | 100 | 100 |
| *Score* | *40* | *30* | *30* |
| **Total** | **80** | **80** | **76** |

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**Criterion 1: Technical feasibility**

- *Suitable method*. The test case is a paper-based product, so all end-of-life options can be considered as suitable technologies for this material: paper can be mechanically recycled and biodegraded under aerobic (compost) and anaerobic (methanization) processes.
- *Result.* All end-of-life techniques were studied for this test case, obtaining the following results (Table 6).

*Table 6. End-of-life results of TC2 obtained for each technology.*

| Product | Mechanical recycling | Aerobic Biodegradation | Anaerobic Biodegradation |
|---|---|---|---|
| **Asendo POP** | The recyclability standard mill reached a score of 42, according to which this material can be considered as recyclable. **Score 100** | Disintegration degree for this material is 92.99%, which is above the standard requirement. Thus, it could be considered biodegradable. **Score 100** | Biodegradation percentage for this material is 60.41%, which is below the standard requirement. Thus, it could be considered partially biodegradable. **Score 50** |
| **Solide lucent POP** | The recyclability standard mill reached a score of - 69, according to which this material can be considered as non-recyclable. **Score 0** | Disintegration degree for this material is 92.03%, which is above the standard requirement. Thus, it could be considered biodegradable. **Score 100** | Biodegradation percentage for this material is 94.47%, which is above the standard requirement. Thus, it could be considered biodegradable. **Score 100** |

**Criterion 2: Life cycle and cost assessment**

- *Sustainability.* The mechanical recycling of paper products is currently the most sustainable approach (Score 100), followed by aerobic degradation (composting) (Score 50) and lastly anaerobic degradation (Score 30).
- *Cost.* The mechanical recycling of paper products is currently the most cost-effective approach (Score 100), followed by aerobic degradation (composting) (Score 50) and lastly anaerobic degradation (Score 30).

**Criterion 3: Current end-of-life scenario**

- *Collection, sorting and processing infrastructure*. Paper packages are collected and aggregated in a specific stream for recycling. For composting, the collection of organic waste is also managed and can include paper products. Anaerobic biodegradation could be performed on municipal waste or organic waste (depending on local directives and waste management schemes). So, for this Test Case, the collection sorting and processing is ensured for all end-of-life options. However, only the recycling technologies are readily available (Score 100), composting and methanization plants are more limited and some have difficulties accepting these materials as input, due to their effect on quality and yield (Score 50).

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- *Policy and regulations*: currently multiple EU regulations and standards exist for recycling paper packages[7,8], as well as for the composting[9,10] and methanization[11,12] of general organic and municipal waste, which includes paper as input (Score 100).

## 3.2 Test Case 3 (bio-based boxes)

Test Case 3 corresponds to foamed PLA (polylactic acid) for the production of boxes. The MCA was performed on the final foamed PLA demonstrator (without considering the 3D-printed insert). The results for the product are presented in Table 7, followed by the respective reasoning.

*Table 7. MCA for foamed PLA box (TC3)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 100 | 100 |
| Result | 100 | 100 | 100 |
| *Score* | *40* | *40* | *40* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 50 | 30 |
| Cost | 100 | 50 | 30 |
| *Score* | *20* | *10* | *6* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 50 | 50 | 50 |
| Policy and regulations | 100 | 100 | 100 |
| *Score* | *30* | *30* | *30* |
| **Total** | **90** | **80** | **76** |

**Criterion 1: Technical feasibility**

- *Suitable method*. The test case is a PLA foamed product, so all end-of-life options can be considered as suitable technologies for this material: PLA can be mechanically recycled and biodegraded under aerobic (compost) and anaerobic (methanization) processes.
- *Result.* All end-of-life techniques were studied for this test case, obtaining the following results in Table 8.

[7] European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:01994L0062-20150526

[8] Confederation of European Paper Industries. https://www.cepi.org/

[9] Harrison, E., Richard, T. Municipal solid waste composting: Policy and regulation. Biomass and Bioenergy. 1992, 3, 3–4, pp. 127-143.

[10] Commission Regulation (EC) No 208/2006 of 7 February 2006 amending Annexes VI and VIII to Regulation (EC) No 1774/2002 of the European Parliament and of the Council as regards processing standards for biogas and composting plants and requirements for manure. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:036:0025:0031:EN:PDF

[11] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001&qid=1731062691039

[12] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32018L0851

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*Table 8. End-of-life results of TC3 obtained for each technology.*

| Product | Mechanical recycling | Aerobic Biodegradation | Anaerobic Biodegradation |
|---|---|---|---|
| **Foamed PLA** | The recyclability evaluation shows good processability and performance. Thus, it can be considered recyclable. **Score 100** | Disintegration degree for this material is 100%, which is above the standard requirement. Thus, it could be considered biodegradable. **Score 100** | Test were not performed within the project, but multiple studies show the potential of PLA for methanization in anaerobic conditions[13,14,15,16]. Thus, it could be considered biodegradable. **Score 100** |

**Criterion 2: Life cycle and cost assessment**

- *Sustainability.* The mechanical recycling of bioplastic packaging products is currently the most sustainable approach (Score 100), followed by aerobic degradation (composting) (Score 50) and lastly anaerobic degradation (Score 30).
- *Cost.* The mechanical recycling of bioplastic packaging products is currently the most cost-effective approach (Score 100), followed by aerobic degradation (composting) (Score 50) and lastly anaerobic degradation (Score 30).

**Criterion 3: Current end-of-life scenario**

- *Collection, sorting and processing infrastructure*. Foamed PLA packages are not currently considered under the plastic recycling schemes, nor have a specific stream for recycling, although they could be collected with general plastic packaging. For composting, the collection of organic waste is managed and could include plastic products. Anaerobic biodegradation could be performed on municipal waste (in which this type of product will most likely be discarded), or organic waste (depending on local directives and waste management schemes). So, for this Test Case, the collection is ensured for all end-of-life options, however, the sorting and processing of PLA in recycling plants are limited (mainly available for pre-consumer and close-loop recycling). Composting and methanization plants are also limited due to difficulties in accepting this material as input, due to its effect on quality and yield (Score 50).
- *Policy and regulations*: currently multiple EU regulations and standards exist for recycling bioplastic packages[17], as well as for the composting[18,19] and

[13] Krause, M. J. and Townsend T. G., Life-Cycle Assumptions of Landfilled Polylactic Acid Underpredict Methane Generation. Environmental Science & Technology Letters. 2016 3 (4), 166-169.

[14] Yagi, H. et al. Anaerobic biodegradation tests of poly(lactic acid) and polycaprolactone using new evaluation system for methane fermentation in anaerobic sludge. Polymer Degradation and Stability. 2009, 94, 9, p.p. 1397-1404.

[15] Tseng, H. et al. Biodegradability and methane fermentability of polylactic acid by thermophilic methane fermentation. Bioresource Technology Reports. 2019, 8, 100327.

[16] Mu, L. et al. Anaerobic Biodegradation of Pla at Mesophilic and Thermophilic Temperatures: Methanation Potential and Associated Microbial Community. SSRN. Pre-print. https://ssrn.com/abstract=4563055.

[17] European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:01994L0062-20150526

[18] Harrison, E., Richard, T. Municipal solid waste composting: Policy and regulation. Biomass and Bioenergy. 1992, 3, 3–4, pp. 127-143.

[19] COMMISSION REGULATION (EC) No 208/2006 of 7 February 2006 amending Annexes VI and VIII to Regulation (EC) No 1774/2002 of the European Parliament and of the Council as regards processing standards for biogas and composting plants and requirements for manure. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:036:0025:0031:EN:PDF

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methanization[20,21] of general organic and municipal waste, which includes biodegradable plastics as input.

## 3.3 Test Case 4 (bio-based tubes)

Test Case 4 corresponds to a paper/PHBV/PLA laminate for the production of cosmetic tubes. The MCA was performed on semi-finished demonstrators. The results for the product are presented in Table 9, followed by the respective reasoning.

*Table 9. MCA for bio-based tubes (TC4)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 100 | 100 |
| Result | 50 | 100 | 100 |
| *Score* | *30* | *40* | *40* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 50 | 30 |
| Cost | 100 | 50 | 30 |
| *Score* | *20* | *10* | *6* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 0 | 50 | 50 |
| Policy and regulations | 100 | 100 | 100 |
| *Score* | *20* | *30* | *30* |
| **Total** | **70** | **80** | **76** |

### Criterion 1: Technical feasibility

- *Suitable method*. The test case is a paper/PHBV/PLA laminate, so all end-of-life options can be considered as suitable technologies for this material: PLA/PHBV can be mechanically recycled and biodegraded under aerobic (compost) and anaerobic (methanization) processes.
- *Result.* All end-of-life techniques were studied for this test case, obtaining the following results presented in Table 10.

[20] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001&qid=1731062691039

[21] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32018L0851

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*Table 10. End-of-life results of TC4 obtained for each technology.*

| Product | Mechanical recycling | Aerobic Biodegradation | Anaerobic Biodegradation |
|---|---|---|---|
| **Bio-based tube** | The recyclability evaluation shows medium-low results on processability and performance. Thus, it can be considered for downgrade recycling. **Score 50** | Disintegration degree for this material is 93,73%, which is above the standard requirement. Thus, it could be considered biodegradable. **Score 100** | Test were not performed within the project, but multiple studies show the potential of paper, PLA and PHBV for methanization in anaerobic conditions[22,23,24]. Thus, it could be considered biodegradable. **Score 100** |

**Criterion 2: Life cycle and cost assessment**

- *Sustainability.* The mechanical recycling of plastic/paper packaging products is currently the most sustainable approach (Score 100), followed by aerobic degradation (composting) (Score 50) and lastly anaerobic degradation (Score 30).
- *Cost.* The mechanical recycling of plastic/paper packaging products is currently the most cost-effective approach (Score 100), followed by aerobic degradation (composting) (Score 50) and lastly anaerobic degradation (Score 30).

**Criterion 3: Current end-of-life scenario**

- *Collection, sorting and processing infrastructure*. Paper/PHBV/PLA laminate packages are not currently considered under the plastic recycling schemes, nor have a specific stream for recycling, although they could be collected with general plastic packaging. For composting, the collection of organic waste is managed and could include plastic products. Anaerobic biodegradation could be performed on municipal waste (in which this type of product will most likely be discarded), or organic waste (depending on local directives and waste management schemes). So, for this Test Case, the collection is ensured for all end-of-life options, however, the sorting and processing of paper/PHBV/PLA tubes in recycling plants does not exist (Score 0). Composting and methanization plants are also limited due to difficulties in accepting these materials as input, due to their effect on quality and yield (Score 50).
- *Policy and regulations*: currently multiple EU regulations and standards exist for recycling bioplastic packages, as well as for the composting and methanization of general organic and municipal waste, which includes biodegradable plastics as input (cited previously).

## 3.4 Test Case 5 (functional automotive component)

Test Case 5 corresponds to 3D printed automotive components, composed of PA10.10 (polyamide) + 5% Flax. The MCA was performed on the final demonstrators. The results for the product are presented in Table 11, followed by the respective reasoning.

[22] Lyshtva, P., et al. Degradation of a poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) compound in different environments, Heliyon, 2024, 10, 3, e24770.

[23] Derkenne, P., et al. Understanding the Biodegradation of PHBV/Cellulose Composites in Mesophilic Anaerobic Digestion. SSRN. Pre-print. https://ssrn.com/abstract=4951193.

[24] Hernández-García, E., et al. Biodegradation of PLA-PHBV Blend Films as Affected by the Incorporation of Different Phenolic Acids. Foods 2022, 11, 243.

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*Table 11. MCA for functional automotive component (TC5)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 0 | 0 |
| Result | 100 | 0 | 0 |
| *Score* | *40* | *0* | *0* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 0 | 0 |
| Cost | 100 | 0 | 0 |
| *Score* | *20* | *0* | *0* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 100 | 0 | 0 |
| Policy and regulations | 100 | 0 | 0 |
| *Score* | *40* | *0* | *0* |
| **Total** | **100** | **0** | **0** |

### Criterion 1: Technical feasibility

- *Suitable method*. The test case is a 3D-printed part composed of PA10.10 + 5% Flax, so the only suitable technology for this material is mechanical recycling since PA10.10 is not considered biodegradable.
- *Result.* The recyclability evaluation shows good processability and performance. Thus, it can be considered recyclable (Score 100).

### Criterion 2: Life cycle and cost assessment

- *Sustainability.* The mechanical recycling of plastic automotive products is currently the most sustainable approach (Score 100), aerobic degradation (composting) and anaerobic degradation can't be applied for this material (Score 0).

- *Cost.* The mechanical recycling of plastic automotive parts is currently the most cost-effective approach (Score 100), aerobic degradation (composting) and anaerobic degradation can not be applied to this material (Score 0).

### Criterion 3: Current end-of-life scenario

- *Collection, sorting and processing infrastructure*. Automotive components are collected as part of the full vehicle and then separated when possible. In general, polyamides are not currently considered in automotive recycling schemes, due to low volumes recovered, however pre-consumer/close-loop recycling is performed on these materials [25,26,27,28] (Score 50).

[25] Recycled Polyamide (PA6, PA66, PA12). https://www.cirplus.com/materials/R-PA

[26] Vanden. https://www.vandenrecycling.com/en/what-we-do/buy-and-sell-plastic/pa/

[27] Kondo, M. Y., et al. Recent advances in the use of Polyamide-based materials for the automotive industry. Polímeros. 2022, 32, 2.

[28] Plastics recycling in the strategies of well-known automotive brands. https://knaufautomotive.com/recycled-plastics-in-the-automotive-industry/

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- *Policy and regulations*: currently multiple EU regulations and directives are in force, which contemplates the end-of-life of vehicles [29,30,31]. In addition, a new regulation for EoL of vehicles is being proposed[32].

## 3.5 Test Case 6 (structural/aesthetic components)

Test Case 6 corresponds to injection moulded structural/aesthetic automotive parts composed of black PHBV (Poly(3-Hydroxybutyrate-co-3-Hydroxyvalerate)). The MCA was performed on the final composition used for demonstrators. The results for the product are presented in Table 12, followed by the respective reasoning.

*Table 12. MCA for structural/aesthetic components automotive component (TC6)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 0 | 0 |
| Result | 50 | 0 | 0 |
| *Score* | *30* | *0* | *0* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 0 | 0 |
| Cost | 100 | 0 | 0 |
| *Score* | *20* | *0* | *0* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 0 | 0 | 0 |
| Policy and regulations | 100 | 0 | 0 |
| *Score* | *20* | *0* | *0* |
| **Total** | **70** | **0** | **0** |

### Criterion 1: Technical feasibility

- *Suitable method*. The test case is an injection moulded part composed of PHBV, so the only suitable technology for this material is mechanical recycling, since even though PHBV is considered biodegradable, injection moulded parts from the automotive sector are not considered as such, due to high thickness and application sector.
- *Result.* The recyclability evaluation shows medium-low results on processability and performance. Thus, it can be considered for downgrade recycling (Score 50).

[29] Regulation (EE) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/2007 and (EC) No 595/2009 and repealing Directive 2007/46/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018R0858

[30] Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32000L0053

[31] Directive 2005/64/EC of the European Parliament and of the Council of 26 October 2005 on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability and amending Council Directive 70/156/EEC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32005L0064

[32] BRIEFING - EU Legislation in Progress. Circularity requirements for vehicle design and management of end-of-life vehicles.
https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/754627/EPRS_BRI(2023)754627_EN.pdf

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**Criterion 2: Life cycle and cost assessment**

- *Sustainability.* The mechanical recycling of plastic automotive products is currently the most sustainable approach (Score 100), aerobic degradation (composting) and anaerobic degradation are not considered for this type of application (Score 0).
- *Cost.* The mechanical recycling of plastic automotive parts is currently the most cost-effective approach (Score 100), aerobic degradation (composting) and anaerobic degradation are not considered for this type of application (Score 0).

**Criterion 3: Current end-of-life scenario**

- *Collection, sorting and processing infrastructure*. Automotive components are collected as part of the full vehicle and then separated when possible. However, PHAs are not considered in automotive recycling schemes, due to their very low use in such applications (Score 0).
- *Policy and regulations*. Currently, multiple EU regulations and directives are in force, which contemplate the end-of-life for vehicles as well as a new proposed regulation for the EoL of vehicles (previously cited).

## 3.6 Test Case 7 (ultracapacitors)

Test Case 7 corresponds to ultracapacitors, composed of, among other components, aluminium and activated carbon. The MCA was performed on the final demonstrators. The results for the product are presented in Table 9Table 13, followed by the respective reasoning.

*Table 13. MCA for ultracapacitors (TC7)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 0 | 0 |
| Result | 100 | 0 | 0 |
| *Score* | *40* | *0* | *0* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 0 | 0 |
| Cost | 100 | 0 | 0 |
| *Score* | *20* | *0* | *0* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 100 | 0 | 0 |
| Policy and regulations | 100 | 0 | 0 |
| *Score* | *40* | *0* | *0* |
| **Total** | **100** | **0** | **0** |

**Criterion 1: Technical feasibility**

- *Suitable method*. The test case is an ultracapacitor composed mainly of aluminium and carbon, so the only suitable technology for this material is mechanical recycling since metal and carbon are not considered biodegradable.
- *Result.* The recyclability evaluation shows good processability and performance for both the aluminium (for closed-loop) and activated carbon (for other applications). Thus, it can be considered recyclable (Score 100).

**Criterion 2: Life cycle and cost assessment**

- *Sustainability.* The mechanical recycling of ultracapacitors and other types of energy-storage systems is currently the most sustainable approach (Score 100), aerobic

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degradation (composting) and anaerobic degradation can not be applied for this material (Score 0).

- *Cost.* The mechanical recycling of ultracapacitors and other types of energy-storage systems is currently the most cost-effective approach (Score 100), aerobic degradation (composting) and anaerobic degradation can not be applied for this material (Score 0).

**Criterion 3: Current end-of-life scenario**

- *Collection, sorting and processing infrastructure*. Ultracapacitors are considered as electronic devices (not batteries). These are collected, sorted and recycled under the electric and electronic waste management system[33] (Score 100).
- *Policy and regulations*. Currently, multiple EU regulations and directives are in force, which contemplate the end-of-life of electric and electronic devices[34,35]. In addition, a new regulation for batteries is being proposed, that could indirectly be applied to ultracapacitors[36].

## 3.7 Test Case 8 (shoe sole)

Test Case 8 corresponds to the 3D-printed shoe soles, composed of bio-based TPU (thermoplastic polyurethane) + 5% Hemp. The MCA was performed on the final demonstrators. The results for the product are presented in Table 14, followed by the respective reasoning.

*Table 14. MCA for Shoe soles (TC8)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 0 | 0 |
| Result | 100 | 0 | 0 |
| *Score* | *40* | *0* | *0* |
| **LCA & LCC** | | | |
| Environmental impact | 30 | 0 | 0 |
| Cost | 30 | 0 | 0 |
| *Score* | *6* | *0* | *0* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 50 | 0 | 0 |
| Policy and regulations | 0 | 0 | 0 |
| *Score* | *10* | *0* | *0* |
| **Total** | **56** | **0** | **0** |

[33] Waste from Electrical and Electronic Equipment (WEEE). https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

[34] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02012L0019-20180704

[35] Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02011L0065-20160715

[36] Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798

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**Criterion 1: Technical feasibility**

- *Suitable method*. The test case is a shoe sole composed of TPU + 5% Hemp, so the only suitable technology for this material is mechanical recycling since TPU is not considered biodegradable.
- *Result.* The recyclability evaluation shows good processability and performance, obtaining again a rubbery material, possibly not suitable for 3D printing, but for injection moulding applications (Score 100)

**Criterion 2: Life cycle and cost assessment**

- *Sustainability.* Although the mechanical recycling of the shoe soles is expected to have high sustainability, currently the recycling of footwear (full shoe), is not considered very sustainable and most parts are sent to landfills or incineration (Score 30)[37]. Aerobic degradation (composting) and anaerobic degradation can not be applied to this material (Score 0).

- *Cost.* The mechanical recycling of footwear is a difficult process, requiring complex sorting techniques and multiple dismantling steps, and usually, the recovered materials are mixed and have low quality[38] (Score 30). Aerobic degradation (composting) and anaerobic degradation can not be applied to this material (Score 0).

**Criterion 3: Current end-of-life scenario**

- *Collection, sorting and processing infrastructure*. Currently, several collection routes exist for post-consumer footwear, usually collected together with post-consumer textiles or via specific store or brand's return systems[39]. However, few sorting and recycling facilities exist, and these are usually private initiatives (usually funded), and operate at a low scale[40] (Score 50).
- *Policy and regulations*. Currently, some specific regulations exist concerning footwear but they are mainly focused on labelling and the packaging material[41]. No current regulation contemplates the design for recycling of footwear or its end-of-life (Score 0).

[37] Footwear Sustainability: Embracing Recycling to Tread Lightly on Earth. https://recyclinginside.com/textile-recycling/footwear-sustainability-embracing-recycling-to-tread-lightly-on-earth/

[38] Van Rensburg, M. et al. Life cycle and End-of-Life management options in the footwear industry: A review. Waste Management & Research. 2020, 38, 0734242X2090893.

[39] Can we recycle shoes? https://sustainability.decathlon.com/can-we-recycle-shoes

[40] Life Re-Shoes Project: a way to give new life to used footwear. https://world.scarpa.com/post/life-re-shoes-project.html

[41] Footwear legislation – end of life responsibility. https://www.satra.com/bulletin/article.php?id=3154

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## 3.8 Test Case 9 (sports goods)

Test Case 9 corresponds to sports goods, composed of foamed biopolymers with antimicrobial coating. The MCA was performed on preliminary demonstrators. The results for the product are presented in Table 15, followed by the respective reasoning.

*Table 15. MCA for sports goods (TC9)*

| Criteria | Option A | Option B | Option C |
|---|---|---|---|
| **Technical feasibility** | | | |
| Suitable method | 100 | 100 | 0 |
| Result | 50 | 0 | 0 |
| *Score* | *30* | *20* | *0* |
| **LCA & LCC** | | | |
| Environmental impact | 100 | 50 | 0 |
| Cost | 100 | 50 | 0 |
| *Score* | *20* | *10* | *0* |
| **Current end-of-life** | | | |
| Collection and infrastructure | 50 | 50 | 0 |
| Policy and regulations | 0 | 0 | 0 |
| *Score* | *10* | *10* | *0* |
| **Total** | **60** | **40** | **0** |

**Criterion 1: Technical feasibility**

- *Suitable method*. The test case is a sports good, composed of foamed biopolymers with antimicrobial coating, so the main suitable technology for this material is mechanical recycling. Since this biopolymer is considered biodegradable, this EoL method is also suitable, although the fact that the part contains an antimicrobial treatment could make it unsuitable.
- *Result.* The recyclability evaluation showed a loss of processability and performance, obtaining brittle material, although it will be possible to use it in applications with lower requirements (Score 50).

**Criterion 2: Life cycle and cost assessment**

- *Sustainability.* The mechanical recycling of mono-material sports goods is currently the most sustainable approach (Score 100), aerobic degradation (composting) and anaerobic degradation should not be considered for this type of application due to the presence of antimicrobial coating (Score 0).
- *Cost.* The mechanical recycling of mono-material sports goods is currently the most cost-effective approach (Score 100), aerobic degradation (composting) and anaerobic degradation should not be considered for this type of application due to the presence of antimicrobial coating (Score 0).

**Criterion 3: Current end-of-life scenario**

- *Collection, sorting and processing infrastructure*. Currently, several collection routes exist for post-consumer sports goods, usually via specific stores' or brands' return

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systems[42]. However, few sorting and recycling facilities exist, and these are usually initiatives (usually funded), and operate at a low scale[43] (Score 50).

- *Policy and regulations.* Currently, some specific/local regulations exist concerning sport equipment but are mainly focused on labelling, extended producer responsibility and packaging material[44]. No current regulation contemplates the design for recycling of sports goods or their end-of-life (Score 0).

## 3.9 MCA Global view

The final scores for all the test cases analysed, under each of the end-of-life options, are summarised in Table 16.

*Table 16. Summary of the final scores obtained for each test case.*

| Test Case | Description | Mechanical Recycling | Anaerobic degradation | Aerobic degradation |
|---|---|---|---|---|
| 2 | A POP | 100 | 80 | 66 |
| 2 | S POP | 80 | 80 | 76 |
| 3 | Bio-Based boxes | 90 | 80 | 76 |
| 4 | Bio-based tubes | 70 | 80 | 76 |
| 5 | Functional automotive component | 100 | 0 | 0 |
| 6 | Structural/aesthetic components | 70 | 0 | 0 |
| 7 | Ultracapacitors | 100 | 0 | 0 |
| 8 | Shoe sole | 56 | 0 | 0 |
| 9 | Sports goods | 60 | 40 | 0 |

From Table 16, it is possible to identify a clear end-of-life option for some test cases (green shades), but for others, the low performance, lack of collection schemes or existing policies, make any EoL option complicated (yellow-orange shades). Depending on the material and application, some end-of-life choices are not suitable (red shades).

According to the results of the MCA,

- For TC2, TC3, TC5 and TC7 the preferred end-of-life choice is the mechanical recycling over biodegradation technologies.
- For TC4, the preferred EoL option is aerobic degradation.
- For TC6, TC8 and TC9, mechanical recycling will be the only alternative, but currently, a lot of challenges limit the effectiveness of recycling.

[42] Going circular - Transition towards a circular economy. https://sustainability.decathlon.com/going-circular-transition-towards-a-circular-economy.

[43] Life Re-Shoes Project: a way to give new life to used footwear. https://world.scarpa.com/post/life-re-shoes-project.html

[44] 5 Regulatory Issues Your Sporting Goods Company can't Afford to Overlook. https://www.complianceandrisks.com/blog/5-regulatory-issues-your-sporting-goods-company-cant-afford-to-overlook/

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# 4 Challenges and enablers

The main challenges and enablers detected during the Multi-criteria analysis of all test cases are the following:

1. **Waste collection and sorting.**

The first step to ensure the end-of-life approach for any product is that suitable collection schemes exist, that could be handled by either public or private organisations. For most of the test cases analysed, these collection schemes are available at some level, regardless of the composition of the product (e.g., biomaterials). However, once the post-consumer products are taken into the respective waste management facility, the sorting process could be a challenge.

In the case of biobased packaging (e.g. PLA- and PHA-based), the main issue related to the sorting is that, currently, there is no recycling stream for these materials, thus they end up being discarded and sent to landfills or incineration.

For automotive plastic parts, the main difficulty encountered is the variety of materials and the complexity of parts present in a vehicle. This makes the dismantling and sorting process very complicated, resulting in many different small-volume streams, which most times are not cost-effective to recycle, regardless the high value of the materials. Thus, they end up being discarded and sent to landfills or incineration.

The footwear and sports goods products are the most complex to collect and sort, and their main collection routes are via return schemes. However, due to complexity (mainly regarding footwear), sorting into specific streams usually is not possible. Thus, they end up being discarded and sent to landfills or incineration.

So, in this context, to overcome these barriers, the main focus should be put on updating the sorting technologies/plants, to recover the biobased materials, as well as improve citizen awareness of correct disposal of the products after their end of life (applicable to all test cases). And additional effort should also be made by the brand owners regarding the eco-design of their products, to ensure that they can be dismantled and sorted correctly at their end-of-life.

2. **Treatment infrastructures.**

Even if all the products are collected and sorted properly, a processing facility that accepts this wasted stream must exist, otherwise, the sorted products will be sent to landfills or incineration.

For bioplastic products, such as PLA and PHBV, a very low number of processing facilities exists, in comparison to the ones existing for conventional plastics (e.g., PE, PP, PS, ABS, PA, etc.), which most of them work only with closed-loop waste, coming from packaging applications (for automotive components, foot-wear or sport goods made from biobased plastics, these facilities are even more limited or non-existing). The lack of processing infrastructure limits the possibility to successfully recycle the bioplastics cost-effectively.

In the case of biodegradation facilities (composting or methanization), these materials are usually rejected as input, due to having longer biodegradation times than organic matter, causing lower compost quality.

To overcome this issue, it must be demonstrated that there is enough volume of a specific material stream, to ensure that the treatment (e.g. mechanical recycling) will be cost-effective. To ensure this, first, the efficient sorting of the individual bio-plastic streams must be assessed (whether they come from packaging, automotive, or other products), to ensure a high-purity stream, which will result in a high-quality recyclate.

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### 3. Policy support.

The main lack of policies and directives detected are related to footwear and sports goods, for which only labelling regulations exist. For biodegradable packaging, the current regulations (i.e., SUP and PPWR), limit the end-of-life options, making it difficult to select the best waste management approach. In addition, recycling associations do not recognise these bio-materials as a specific recycling stream (most are currently considered as not-recyclable), which holds back the investment in technology for efficient sorting and recycling. The modification of current regulations and policies will be directly related to the volume of the biomaterials in the market, to ensure a correct end-of-life management.

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# 5 Conclusion and perspectives

In task 8.5, a Multi-criteria Analysis of the different test cases was performed, to select the most suitable end-of-life option, and to detect the current challenges and enablers of each TC to be effectively treated by the selected choice.

According to the results of the MCA, mechanical recycling is the main choice for TC2, TC3, TC5 and TC7, the aerobic degradation is the optimal choice for TC4, and for TC6, TC8 and TC9, mechanical recycling will be the only alternative, but currently a lot of challenges limit the effective recycling.

The main challenges detected were the lack of sorting facilities or limited technologies to effectively treat some of the test cases, and for which specific recycling steam is currently not contemplated (e.g. bio-based packaging). The composition and complex design of some products also affect the possibility for recycling at scale (e.g., footwear, sports goods, and automotive parts), and finally, there is a lack of policy concerning the end-of-life of some products (e.g., footwear and sports good), or it exists and limits the selection of sustainable end-of-life choices, such as recycling or biodegradation (e.g. bio-based packaging), and force their disposal to landfills or treatment via incineration.

It should be expected that if the volume of these materials increases in the market (in any of the studied applications), there should be an overall interest in recovering and recycling them, which will imply improving the current collection, sorting and recycling technologies, followed by the proposal of new or updated regulations.

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