MASTER

INNOVATION AND RESEARCH FOR SUSTAINABILITY

MASTER´S FINAL WORK

DISSERTATION

INNOVATIVE PATHWAYS TO SUSTAINABILITY IN INJECTION MOULDING: A MULTI-CRITERIA ANALYSIS FOR CHOOSING SUSTAINABLE PLASTICS

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TIAGO CAPELA LOURENÇO

MAY - 2025

ISEG Lisbon School of Economics & Management
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GLOSSARY

ABS	Acrylonitrile-Butadiene-Styrene
AK	Acrylic
Bio-PE	Bio-based polyethylene
Bio-PP	Bio-based polypropylene
CAGR	Compound Annual Growth Rate
CCF	Corporate carbon footprint
EPO	The European Patent Office
EPR	Extended Producer Responsibility
ESPR	Eco-design for Sustainable Products Regulation
EU	European Union
EVHO	Ethylene Vinyl Alcohol
HDPE	High-Density Polyethylene
HIPS	High-Impact Polystyrene
IPFs	Intellectual property filings
LCA	Life Cycle Assessment
LDPE	Low-Density Polyethylene
MAPP	Maleic Anhydride Polypropylene
PA	Polyamide
PA11	Polyamide A11
PA6	Polyamides A6
PA66	Polyamides A66
PBAT	Polybutylene Terephthalate
PBS	Polybutylene Succinate
PBT	Linear Polyester
PC	Polycarbonate
PCL	Polycaprolactone
PE	Polyethylene

PET	Polyethylene Terephthalate
PGA	Polyglycolide
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PLA	Polylactic Acid
PP	Polypropylene
PPC	Polypropylene Carbonate
PS	Polystyrene
PVC	Polyvinyl Chloride
rABS	Recycled ABS
rHDPE	Recycled HDPE
rPET	Recycled PET
SPI	Soybean Protein Isolate
TPS	Thermoplastic starch
UNFCCC	United Nations Framework Convention on Climate Change

ABSTRACT

Plastics play a vital role in modern society, but their widespread use poses significant sustainability challenges, particularly in the face of environmental degradation and climate change. Injection moulding, as a core manufacturing process, is central to shaping the future of sustainable plastics production. Innovation strategies, such as the integration of sustainable plastics into injection moulding processes are seen as key to reduce environmental impacts and comply with European sustainability regulations. This study presents a novel decision support framework that facilitates the adoption of sustainable plastic alternatives in injection moulding. A structured literature review informed the development of a multi-criteria analysis tool, which was subsequently applied and tested in the packaging, household appliances and automotive parts sectors. The multi-criteria analysis evaluated five types of alternative plastics based on material properties, sustainability criteria and industrial feasibility.

Key findings show that while bioplastics and recycled polymers offer significant environmental benefits, challenges such as data availability, performance trade-offs and infrastructure limitations remain, hindering the full potential of a plastic sustainability transition. The study highlights the need to advance recycling technologies, standardise sustainability assessment tools and foster collaboration between policy makers, scientists and industry leaders. The proposed framework serves as a practical guide for companies, helping them to evaluate plastic alternatives by balancing sustainability goals with technical feasibility. Future research should focus on improving material databases and investigating the economic impact of a transition to sustainable plastics.

KEYWORDS: Plastics; Injection Moulding; Sustainability plastics; EU Sustainability regulation; Muti-criteria Analysis, Sustainability transition

JEL Codes: L50; L65; L67; L52; Q56; Q53.

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INNOVATIVE PATHWAYS TO SUSTAINABILITY IN INJECTION MOULDING: A MULTI-CRITERIA ANALYSIS FOR CHOOSING SUSTAINABLE PLASTICS

By Ina Boeken

Plastics are indispensable yet challenging for the environment. This study presents a multi-criteria analysis to integrate sustainable plastics into injection moulding, evaluating alternatives in the packaging, household appliance and automotive sectors. Although bioplastics and recycled polymers offer advantages, data scarcity and performance trade-offs remain, requiring improved recycling methods and collaboration between scientists, policy makers and business leaders.

1. INTRODUCTION

1.1 Background

The challenges and socio-ecological implications of climate change have been around since the 1950s, initially discussed primarily within scientific communities.

In the 1970s, the global environmental agenda gained momentum, underlined by the 1972 Stockholm Conference, which emphasised the urgent need to intensify scientific research on environmental issues (Jordan & Rayner, 2010). This conference marked the beginning of a coordinated international effort to address environmental problems (Jordan & Rayner, 2010). The 1980s and early 1990s were a pivotal period in which climate change moved from being seen as a purely scientific problem to becoming an integral part of the political agenda (Jordan & Rayner, 2010). The European Union's (EU) participation in the 1992 United Nations Framework Convention on Climate Change (UNFCCC) marked another milestone, signalling the expansion of EU climate and environmental policies and reinforcing its commitment to sustainability at the international level (Jordan & Rayner, 2010). Throughout the 1990s and into the 2000s, EU climate policy became more comprehensive, highlighted by the establishment of the EU Climate Change Programme in 2000 (Jordan & Rayner, 2010). The program reflected the EU's proactive approach to align with broader global efforts and set ambitious targets to achieve climate neutrality by 2050 (Jordan & Rayner, 2010). While this regulatory framework is essential for environmental progress, it poses significant challenges for industries and manufacturing companies. Implementing these measures often requires significant changes to operations and supply chains, which can impact profitability. Historically, sustainability initiatives have been perceived as a drag on efficiency and profit margins (Nordin, Ashari, & Rajemi, 2014). Companies have faced the dilemma of balancing the need to reduce emissions with their economic sustainability. Nevertheless, the perception that sustainability is at conflict with profitability is gradually changing. Data from Dax 40 companies has shown that integrating sustainable practices can have a positive impact on the bottom line, demonstrating that environmental responsibility can be aligned with economic interests (Serhan Ili & Omar Abdelkafi, 2023). This shift is also being driven by increasing consumer awareness and demand for environmentally friendly products. The competitive landscape now requires companies to innovate and adopt sustainable practices to maintain their market position and respond to legislative and consumer pressure (Serhan Ili & Omar Abdelkafi, 2023).

This thesis focuses on the injection moulding industry, a key sector in modern manufacturing. Injection moulding is a process in which certain types of plastics are melted and injected into moulds to produce various products. Known for its design flexibility and cost effectiveness, the process is essential for mass production (Nitin Madiwale, 2021). Underscoring its importance, the global market for injection moulded plastics is expected to reach € 536.12 billion by 2032, at a Compound Annual Growth Rate (CAGR) of 4.2% (*Injection Molded Plastics Market Size | Global Report*, 2024). The growth of this industry is attributed to the demand for lightweight, durable and precisely moulded components in sectors such as automotive, packaging, construction and electronics (*Injection Molded Plastics Market 2024 - Global Insights, Growth, Trends & Forecast*, 2024). Despite its benefits, the injection moulding industry contributes significantly to global plastics production, which exceeds 400 million tonnes annually (Xu et al., 2024). The environmental impacts of such massive production volumes include waste generation and significant CO_2 emissions.

The environmental challenges posed by conventional plastics are well documented, and there is an urgent need for alternatives that reduce both waste and emissions. For example, the EU's Sustainable Packaging Strategy aims for all plastic packaging to be reusable or recyclable by 2030, representing a significant push towards a circular economy (Foschi & Bonoli, 2019). In addition to regulatory measures, the sustainable polymer market, which was valued at $5.82 billion in Europe in 2023, is forecast to grow at a CAGR of 18.3% to 2030, indicating a clear shift towards sustainable material solutions (*Europe Bioplastics Market Size, Share | Industry Report*, 2024).

1.2 Problem statement

Sustainability transitions are complex undertakings that require long term transformations of the established technical and societal systems, in their move towards more sustainable production and consumption modes (Markard et al., 2012). Plastic sector companies, for example, face many challenges such as determining the true sustainability of alternative plastics, overcoming supply chain constraints and meeting industry-specific regulatory requirements. For example, while bioplastics are marketed as environmentally friendly, their production and end-of-life processing must be evaluated to confirm their environmental benefits (Hanenkamp & Zipse, 2023). In addition, sustainability in manufacturing lacks a universally accepted definition, making it difficult for companies to adopt standardised practices. Nevertheless, there is broad agreement that sustainable manufacturing should balance economic, environmental and social considerations (Hanenkamp & Zipse, 2023). Effective strategies for sustainability, as evidenced by case studies, include the adoption of responsive product design, lean manufacturing practices, and the use of green materials (Nordin et al., 2014).

1.3 Research objective

This thesis aims to provide a comprehensive overview of sustainable alternatives to conventional plastics used in injection moulding, with a focus on assisting manufacturing companies in their transition to sustainability. It examines the key drivers for sustainability in the injection moulding industry, the commonly used plastics and their environmental impacts, and viable alternatives that companies can adopt. It also provides a critical view on the recent developments and the applicability of alternative plastics for companies.

1.4 Research questions

Four research questions guide the work of this thesis, namely:

1. *What are the key drivers of sustainability in the injection moulding industry?*
2. *Which are the main types of plastics used in injection moulding and what makes them difficult to replace?*

3. *What sustainable alternatives are available and how can companies integrate them into their processes?*
4. *What are the barriers to a wider adoption of sustainable plastics in injection moulding?*

This thesis aims to clarify currently available injection moulding plastic options and provide support to industry players that seek to evaluate potential changes. By giving an overview of the eligibility of conventional and alternative polymers, a practical multi-criteria analysis tool is developed to provide a quick overview of sustainable materials tailored to the packaging, household appliances and automotive parts sectors. While this study is primarily based on a literature review and does not address every product-specific requirement or regulatory challenge, it aims to facilitate informed decision-making and help plastic-centred companies position themselves in the transition to sustainability.

The thesis is divided into several chapters, each focusing on critical aspects of sustainability within the injection moulding industry. Chapter 1 introduces the background and challenges addressed in this study and states the objectives and research questions pursued in this thesis. In chapter 2, the methodology is described, detailing the research strategy followed and how data was collected and analysed. It additionally acknowledges the limitations of the study and provides some ethical considerations. Chapter 3 presents the current state-of-the-art and provides a comprehensive examination of the injection moulding process, detailing the current use of plastics and their environmental impact. Through a literature review, it also examines the drivers for sustainability within the industry and reviews emerging trends and advances in sustainable plastic alternatives. Chapter 4 outlines the key findings of the study, provides an overview of the available sustainable plastic options and assesses their feasibility for integration into existing manufacturing practices. This chapter also highlights the challenges that companies face in adopting these alternatives. Chapter 5 discusses the results of the application of the multi-criteria analysis, providing a deeper interpretation of the findings, while emphasizing their implications for the manufacturing sector. Finally, chapter 6 concludes by summarising key findings of the research and reflects upon the practical utility of the multi-criteria analysis as a tool for guiding companies towards sustainable practices.

2. METHODOLOGY

The following sections explain the choice of research methods, including research design, data collection and analysis, and some of the observed limitations.

The study integrates academic research with practical insights to provide an informative decision-making tool for industry stakeholders. The multi-criteria analysis synthesizes key findings to guide companies through the transition to sustainable practices and provide a realistic overview of today's opportunities and challenges.

2.1 Research design

This study follows a qualitative, multi-method approach, combining a structured literature review with a multi-criteria analysis using a specifically designed analytical framework. This method bridges academic knowledge and industry practice, making it well suited to address the research questions.

The literature review aim is to analyse the current state-of-the-art related to the sustainability of the plastic injection moulding industry, and identify trends, challenges possibilities in the adoption of sustainable plastics. Additionally, it provides the scope and content for the development of a novel multi-criteria decision support framework.

The developed framework objective is to provide guidance to strategic and operational decisions that seek a more sustainable adoption of alternative plastics in the plastic industry. Once developed, the framework will be applied and tested in the packaging, household appliance and automotive parts sectors, where plastic injection moulding is widely used.

2.2 Data collection

A structured search using databases such as Google Scholar[1], Elsevier[2], MDPI[3], Scispace[4] ensures that relevant studies are included. The multi criteria analysis then highlights practical implementations of sustainable plastic alternatives and associated

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[1] https://scholar.google.com

[2] https://www.elsevier.com

[3] https://www.mdpi.com

[4] https://typeset.io

barriers, providing a comprehensive perspective on sustainability efforts within the industry. The search strategy employs the use of specific industry terms in the above-mentioned knowledge databases. Initial results are assessed for relevance and refined as necessary. Articles are selected in two stages: (i) screening of titles and abstracts; and (ii) full text evaluation based on a set of pre-defined criterions.

Inclusion and exclusion criteria for the review was set, namely:

- *Inclusion: articles on back-knowledge such as the injection moulding process or historical data have no strict date limit, while studies on recent developments are select from 2020 onwards.*
- *Exclusion: Commercially Biased or Promotional Content.*

Collection, documentation and quality control protocols are applied, with all selected articles documented in Excel and analysed using MAXQDA[5] software, ensuring systematic organization and traceability. Referencing in the thesis is managed with the assistance of Mendeley[6]. Large scale language models like DeepL[7] were used to aid in the readability of the text.

2.3 Data analysis

The collected data is used to develop a multi-criteria analytical framework that synthesises literature findings (theoretical) and real-world industry studies (practical), to provide an overview of plastic alternatives for injection moulding. The methodology for data analysis consists of the following 6 steps:

1. **Identification of material requirements:** Material requirements are researched and compiled for each sector. Based on the literature review, three key sectors were selected: packaging, household appliances (a more specific part of the consumer goods sector) and automotive parts. These sectors cover a wide range of plastics applications and provide a diverse data set for analysis. Some of these requirements are clearly defined technical terms found in material databases, while others require further specification. To ensure consistency between

[5] https://www.maxqda.com/de/
[6] https://www.mendeley.com
[7] https://www.deepl.com

theoretical research and real-world applications, material properties are cross-referenced with the MATWeb database and industry websites. Non-standardised terms are refined and aligned with industry-recognised terminology.

2. **Identification of conventional and alternative plastics:** Conventional plastics commonly used for injection moulding in the selected sectors are identified and alternative plastics suitable for injection moulding are researched.
3. **Definition of sustainability criteria:** Sustainability criteria are identified through literature research also including requirements derived from EU legislations and cross-referenced with the IDEMAT database terminology. Some sustainability aspects are covered in the material requirements but require further specification. Only the sustainability criteria from the IDEMAT are used because of data access and because most of the other resources reviewed can only be applied to a very specific product.
4. **Development of the multi-criteria analysis framework**:A structured framework is developed to evaluate plastics based on material performance characteristics and Sustainability evaluation criteria. The framework uses data extracted from the Matweb[8], Materialdatacenter[9], DaKeBiku[10] and IDEMAT[11] databases. Data availability is assessed, and significant gaps are identified, particularly for alternative plastics. To allow a meaningful comparison, the framework is adapted to focus only on comparable requirements. To further simplify, plastic properties with insufficient data are exclude.
5. **Comparative analysis of material properties and sustainability*:*** The material properties of conventional and alternative plastics are compared. The values of conventional plastics are used as reference points. If the properties of an alternative plastic are significantly different (too high or too low), it is considered less suitable. The exception is material strength, where significantly higher values may indicate improved performance. Better performing alternative plastics on the material properties criteria are then evaluated against the sustainability criteria.

[8] https://www.matweb.com
[9] https://www.materialdatacenter.com/bo/
[10] https://dakebiku.ifbb-hannover.de/grades
[11] https://www.ecocostsvalue.com/data-tools-books/

The evaluation and scoring system used to rate eligibility and sustainability of alternative plastics compared to conventional plastics is as follows: Good = 6 points; Moderate = 3 points; Poor = 0 points. This scoring system provides a clear comparative ranking that makes differences between materials easily visible, by using colour coding (Good = Green; Moderate = Yellow; Poor = Red). Given the proximity of values within each criterion and sometimes across properties, the allocation of scores were based on expert judgment by the author.

6. **Selection of the most suitable alternative plastics:** Based on the evaluation, the best performing alternative plastics are identified. Due to data limitations, the framework is more of a pre-selection tool than a definitive assessment. The results support an initial decision-making process for material replacement.

The Multi-Criteria Analysis Framework provides a structured approach to evaluating conventional and alternative plastics, balancing material performance with sustainability issues. Despite data limitations, it aims to provide a transparent method for identifying potential plastic replacements in different industry sectors.

2.4 Study limitations

Some limitations to the study methodology must be acknowledged. Firstly, and despite the efforts to develop a comprehensive approach that is applied to three relevant sectors of the plastic industry (packaging, household appliances and automotive parts), the framework may not represent the plastic industry as a whole, given its complexities and context-specific parameters (e.g., industrial, infrastructural, processual). Secondly, results are affected by data limitations (e.g., information constrains on different types of plastics, especially alternative plastics), which in turn, may limit the actual use of the framework by companies. Finally, due to the reliance on databases, only a few sustainability factors could be analysed. To get a full overview, it is necessary to assess each product under development individually to ensure an accurate sustainability analysis. Therefore, the multicriteria itself can be used as a guide for analysis, but the results only give an overview of a small range of possibilities.

2.5 Ethical considerations

This study adheres to ethical research principles by ensuring credibility, proper citation and objectivity in the selection and interpretation of data. As it relies on secondary data, ethical concerns primarily relate to the responsible use and accurate reporting of sources.

3. LITERATURE REVIEW

3.1 Injection moulding: technologies, market and environmental impacts

Injection moulding is one of the most widely used plastics processing methods due to its many advantages. It is an economically viable manufacturing process that enables the mass production of a product. It also makes it possible to work with complex product shapes. The process uses high temperatures to melt a polymer charge and applies pressure to inject the molten material into a mould cavity where it solidifies into the desired shape (Nitin Madiwale, 2021). The technology has been widely used to produce polymer components in a variety of industries, including automotive, electronics, packaging and aerospace (Zhou & Hrymak, 2024). With the increasing demand for plastic products, manufacturers seek to improve production efficiency so they can maintain the balance between supply and demand (Nitin Madiwale, 2021).

The global market for injection moulded plastics is growing significantly. Valued at around $387.51 billion in 2023, it is forecast to reach $561.58 billion by 2032, at a CAGR of 4.2% (*Injection Molded Plastics Market Size | Global Report*, 2024). High demand is driven by applications in packaging, medical devices, automotive and consumer goods. The automotive industry is a major consumer, with its injection moulded parts market valued at $56.4 billion in 2022 and expected to reach $84.5 billion by 2032, growing at a CAGR of 4.8% (*Global Injection Molded Automotive Parts Market Size*, 2024). Food packaging is another key segment contributing significantly to market growth, although specific figures are limited.

A major challenge in the injection moulding industry is the reliance on fossil fuel-derived feedstocks, which require significant energy and contribute to greenhouse gas emissions. In 2019, plastics accounted for 3.3% of global emissions, a number that is expected to increase significantly by 2050 (Ritchie, 2023). Although injection moulding itself has a lower direct impact, associated factors such as raw material production, transportation and disposal increase the overall environmental footprint (Thiriez & Gutowski, n.d.). Electricity consumption is another key challenge, accounting for 62.6% of the industry's environmental impact (Elduque et al., 2015). In addition, plastic waste - both pre-consumer and post-consumer - exacerbates these environmental impacts. While pre-consumer waste can be reused with minimal processing, post-consumer waste requires extensive cleaning and reprocessing, making it difficult to recycle (Nguyen et al., 2024). In response to these concerns, companies are adopting sustainable practices that focus on energy efficiency, increased recycling, and life cycle assessment (LCA) practices to improve their environmental performance (Junior et al., 2019).

For example, most recent LCAs show that the greatest environmental impact of plastic products occurs during production, accounting for 91% of total emissions. The manufacturing phase alone contributes 60% of the global warming potential (GWP) over a 100-year period, compared to 35% from end-of-life disposal and just 5% from use (Mannheim & Simenfalvi, 2020). Additionally, plastic waste is a growing concern, with humans generating 2 billion tonnes of waste annually, 12% of which is plastic (Jambeck & Walker-Franklin, 2023). Most plastic waste comes from short-lived packaging and by 2015, 77% of all plastic produced had become waste. Alarmingly, only 9% is mechanically recycled, while 12% is burned, releasing CO_2 and other pollutants, and the majority is landfilled or pollutes natural ecosystems (Jambeck & Walker-Franklin, 2023). One result of this plastic waste is microplastics, which are omnipresent, persistent, highly mobile and almost impossible to capture once released into the environment, prompting the European Commission's Group of Chief Scientific Advisers in 2019 to recognise their potential risks and call for action to reduce and prevent further pollution (European Commission, 2023). Tackling these challenges require a full life-cycle approach, from production to disposal. Targets such as 90% landfill diversion or 'zero waste' are crucial to reducing the environmental impact of plastic (Jambeck & Walker-Franklin, 2023).

3.2 Plastic polymers: types and characteristics

Plastics are a special category of synthetic or semi-synthetic polymers made from molecules derived from oil, petroleum or bio-based materials. These molecules are combined to form different polymers, giving plastics their characteristic flexibility to be moulded, extruded or formed into solid objects of various shapes (*Definition of Polymers and Plastics*, n.d.).

Polymers are divided into conventional and bio-based polymers, with a further subdivision of the latter into biodegradable and non-biodegradable types (Figure 1).

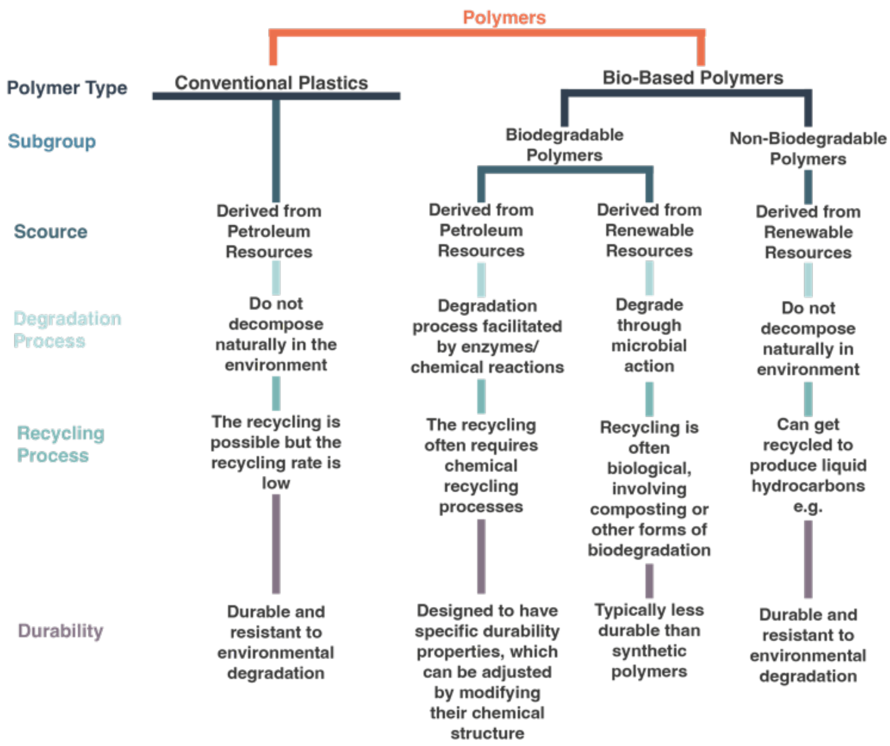

Figure 1 – Different types of plastic polymers and their main characteristics. Source: Own elaboration.

Conventional polymers are synthesised from petrochemicals using energy-intensive processes which contribute to greenhouse gas emissions (Kapa, 2023). These long-chain hydrocarbons provide strength, flexibility and chemical resistance. However, they are not biodegradable (Kapa, 2023). Their longevity makes recycling complex and economically challenging, leading to pollution (Kapa, 2023).

Biodegradable polymers derived from petroleum resources are synthetic polymers degrade by hydrolysis, sometimes assisted by enzymes or chemical reactions. Although they are more durable than natural polymers, they require specific conditions for degradation, making recycling complex (Vroman & Tighzert, 2009).

Biodegradable polymers from renewable resources are those derived from biological sources such as starch and cellulose, and that may be broken down by microbial action into natural by-products (Vroman & Tighzert, 2009). Although less durable, their properties can be enhanced through chemical modification. Unlike petroleum-based biodegradable polymers, they break down more readily in the environment, making them more sustainable (Vroman & Tighzert, 2009).

Non-biodegradable bioplastics are made from bio-based materials such as corn and sugar cane (Rahman & Bhoi, 2021). Although they are bio-based, they do not degrade naturally. Recycling methods may include catalytic pyrolysis or gasification (Rahman & Bhoi, 2021). Their durability makes them suitable for long-term use but also contributes to waste production.

3.3 Defining sustainability transitions in the plastic industry

Polymers are at the core of circular economy strategies, which seek to minimise waste and maximise resource efficiency. Bio-based plastics have the potential to reduce CO_2 emissions and even act as a carbon sink in long-life applications (The Circular Economy for Plastics A European Analysis, 2024). A polymer is considered sustainable if it minimises environmental impacts while maintaining an economic, environmental and social balance (De Souza Schaulet et al., 2024). The classification of sustainable polymers depends on two key criteria: the use of renewable raw materials and the ability to degrade or be recycled (Tarazona et al., 2022).

The market for sustainable plastics is evolving rapidly, driven by increasing environmental awareness, regulatory pressure and advances in materials. This shift, known as the plastics transition, reflects the global push towards greener materials and circular economy practices. Key developments include biodegradable, bio-based and recycled polymers, as well as improvements in recycling infrastructure and business models.

The global market for sustainable polymers, valued at $12.7 billion in 2023, is forecast to exceed $22.5 billion by 2032, growing at a CAGR of 6.5%. Growth will be driven by consumer demand for eco-friendly alternatives and stricter regulations targeting plastic waste and emissions (*Sustainable Polymer Market Research Report*, 2024). In comparison, the European sustainable polymer market, which was valued at $5.82 billion in 2023, is forecast to grow at a CAGR of 18.3% to 2030, indicating a clear shift towards sustainable material solutions (*Europe Bioplastics Market Size, Share | Industry Report*, 2024).

Europe leads in the adoption of circular plastics (focusing on recyclability and reusability), with significant achievements between 2018 and 2022. The use of recycled plastics increased by 70%, reaching 6.8 million tonnes in 2022, with circular plastics accounting for 19.7% of total European production. Recycling infrastructure saw a 57% increase in mechanical recycling, while investments in chemical recycling could add 2.8 million tonnes of recycled plastics per year by 2030. The uptake of circular plastics increased by 36.8%, with packaging and construction as the main sectors (The Circular Economy for Plastics A European Analysis, 2024). Despite progress, challenges remain to reach the EU target of 25% circular plastics by 2030. Further investment in recycling technology, policy support and waste management partnerships are critical in reaching that target (The Circular Economy for Plastics A European Analysis, 2024).

Asia Pacific leads the market of sustainable plastics (focusing on biodegradability or minimal impact after disposal) with a forecast CAGR of 7.2%, driven by manufacturing growth and environmental regulations in China and India. North America and Europe remain key players due to strong policy and consumer demand. Latin America and the Middle East and Africa are also on the rise due to increasing industrialisation and awareness (*Sustainable Polymer Market Research Report*, 2024).

Achieving long-term sustainability in plastics requires a tiered approach and three phases have been proposed by Plastics Europe (Plastics Europe, n.d.):

- 2023-2025: Data sharing, waste management partnerships and investment in green technologies.
- 2026-2027: Adoption of recyclable plastics, circular business models and renewable energy infrastructure.
- 2028-2030: Large-scale integration of biomass-based plastics, chemical recycling and carbon capture

3.4 Drivers of the plastic sustainability transition

Sustainability transition in the plastic sector, and therefor in the injection moulding industry, is driven by innovation, technological advances, consumer awareness, market pressures, corporate responsibility and regulatory frameworks.

Innovations in recycling technologies, alternative plastics and bioplastics are accelerating the shift towards sustainability. Europe and the US are leading this transition, accounting for 60% of global patent applications between 2010 and 2019 (Epo, 2021). The European Patent Office (EPO) highlights Europe and the US as the top innovators in plastics recycling and bioplastics, each contributing 30% of global patents. Within Europe, Germany leads the way (8% of global patents), followed by France, the UK, Italy and the Netherlands. Japan accounts for 18%, while South Korea and China each account for 5% (EPO, 2021). Chemical and biological recycling processes have seen the highest patent activity, with 9,000 Intellectual Property Filings (IPFs) between 2010 and 2019, more than double that of mechanical recycling. These innovations improve the quality of plastics and extend their recyclability (Epo, 2021). Bioplastics, including bio-based and biodegradable materials, are gaining traction to reduce fossil fuel dependency and emissions. The healthcare sector leads with more than 19,000 IPFs between 2010 and 2019, followed by packaging, electronics and textiles (Epo, 2021). Key developments include bio-derived monomers (e.g. bio-PE, bio-PET) that are equivalent to their fossil-based counterparts, allowing complete recycling and modified natural polymers (e.g. cellulose, polysaccharides) for reusable, biodegradable plastics (Epo, 2021). Several industries are driving the adoption of sustainable plastics. Packaging is moving towards biodegradable and bio-based alternatives, with brands looking to reduce their plastic footprint. The automotive sector is incorporating bio-based and recycled polymers to reduce vehicle weight and emissions. Construction and consumer goods industries are using sustainable materials to comply with regulations and meet consumer demand (*Sustainable Polymer Market Research Report*, 2024).

Increased environmental awareness is reshaping consumer behaviour, markets and corporate responsibility processes. Studies show that 87% of consumers now consider the environmental impact of their purchases (The Bioplastics Handbook for Injection Molders, n.d.). The biodegradable packaging market, valued at $452.7 billion in 2021, is expected to grow to $812.4 billion by 2030, driven by consumer demand and corporate initiatives (Petrenko et al., 2024). However, challenges such as material costs, production efficiency and recycling infrastructure remain critical barriers to widespread adoption. Nevertheless, companies are aligning themselves with the Sustainable Development Goals (SDGs) to meet the expectations of consumers and employees. Over 85% of Dax 40 companies are prioritizing climate action (Hatmanu et al., 2019), as neglecting sustainability risks alienating up to 70% of customers and 60% of employees, especially younger generations (Petrenko et al., 2024). A poor corporate carbon footprint (CCF) can lead to penalties, high costs and loss of consumer trust. Sustainable practices, on the other hand, reduce operating costs and attract environmentally conscious customers (Hatmanu et al., 2019).

Legislation is being adopted worldwide that aims to reduce plastic pollution, in turn driving additional pressure for corporate responsibility and market transformation. For example, the Plastic Waste Reduction and Recycling Act (2020) in the US and the European Green Deal (2019) both target waste reduction and improved recycling systems. However, regulatory inconsistencies challenge global harmonisation (Petrenko et al., 2024). In Europe, legislation has been one of the most effective drivers of the plastic transition. Since the turn of the century EU regulations, directives, strategies and action plans have shaped sustainability policies, particularly in the field of plastics. These policies affect industries such as automotive, consumer goods and packaging, and reflect the EU's commitment to waste reduction, innovation and environmental protection. A long list of EU legislation has been adopted in this field, namely: (i) regulations that are legally binding in all EU countries, ensuring uniform compliance (*Types of Legislation | European Union*, 2025); (ii) directives that set targets but allow national flexibility in implementation (*Types of Legislation | European Union*, 2025); and (iii) strategies and action plans, which are non-binding frameworks that guide future policy development (Strategy Documents - European Commission, 2025).

Figure 2 provides a comprehensive overview of this wealth of regulations, directives and strategies, acting as driving forces towards sustainability in the plastic industry, between 1994 and 2024. This figure shows three regulations, six directives and ten strategies. The results show that EU plastics legislation has evolved from waste management in 1994 to a push for a circular economy in the 2020s. In 2015, the Circular Economy Plan and in 2018 the Plastics Strategy accelerated action, leading to stricter bans and recycling obligations. More recent policies, such as the EU Green Deal and Eco-design Regulation, reflect a stronger focus on sustainability. This shift demonstrates the EU's growing commitment to sustainability and a circular economy.

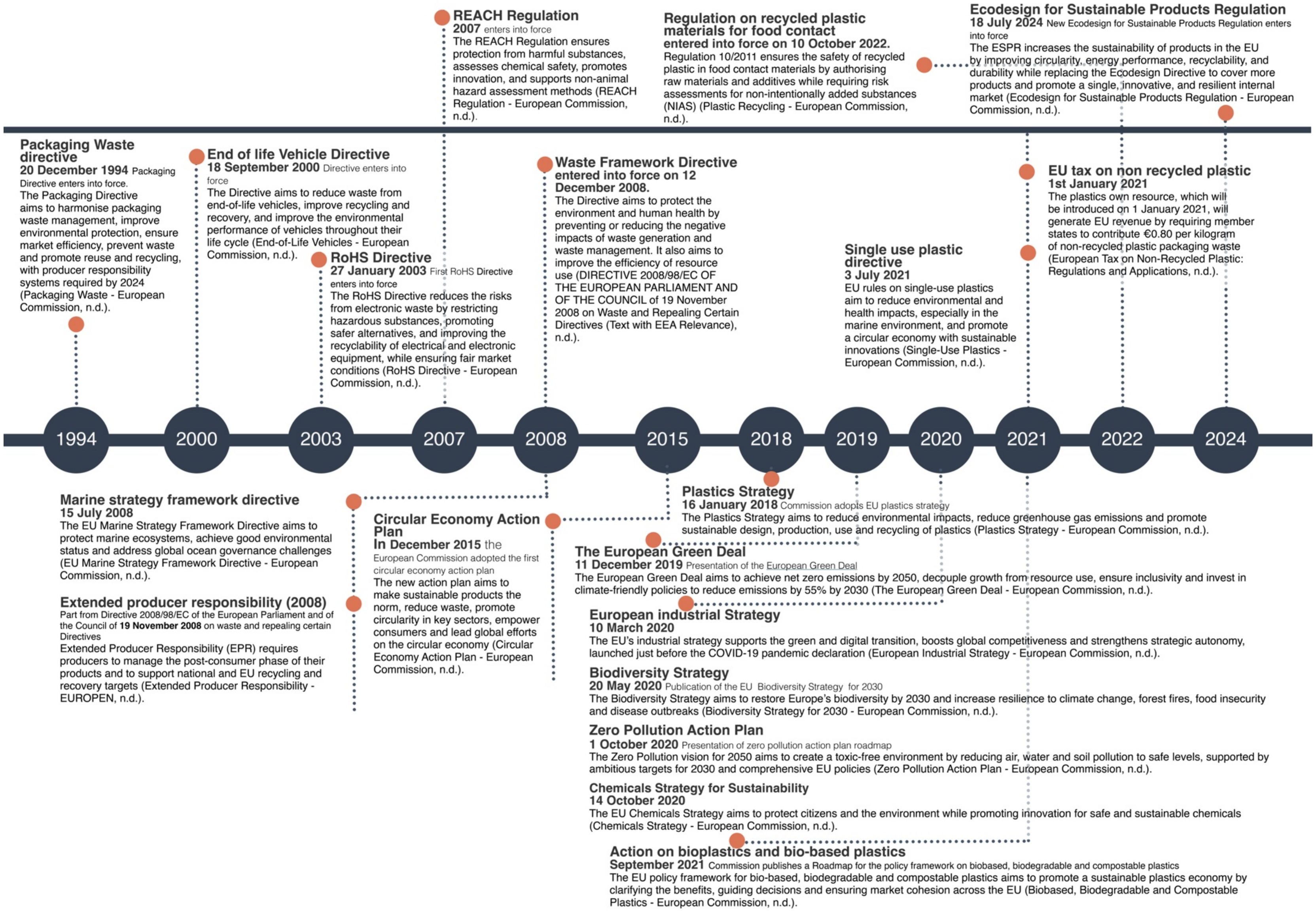

Figure 2 – An overview of EUs Regulations, Directives and Strategies as driving forces towards sustainability in the plastic industry (1994-2024). Source: Own elaboration.

4. RESULTS

This study evaluates the feasibility of introducing more sustainable plastics polymers in the injection moulding industry in three key sectors: packaging, household appliances and automotive parts. As part of that effort, a novel decision support framework that facilitates the adoption of sustainable plastic alternatives in injection moulding is developed. A structured literature review informed the development of a multi-criteria analysis tool based on material properties, sustainability criteria and industrial feasibility.

The analytical framework was applied and tested in these three sectors, that were selected based on the literature review results: while the packaging and automotive sectors are increasingly adopting sustainable plastics, the Household appliances sector remains less involved, making it an interesting case for potential improvement.

The following sections present the results of the development and application of the multi-criteria decision support framework for sustainable plastic use in injection moulding applications.

4.1 Identification of material requirements

The first step in developing the multi-criteria analysis framework is to identify the material requirements and key properties of the plastics polymers used in the three sectors. The objective is to define the standards that alternative plastics must meet.

Table 1 summarises 36 properties, their measurement methods and their relevance to each of the three sectors. A more detailed version of these results, including descriptions of the requirements, which requirements were included, and which weren't, and sources, can be found in Appendix 3. Table 16 and Appendices 4 and 5 online. To ensure consistency between theoretical research and real-world applications, material properties are cross-referenced with the MATWeb database and industry websites (see Appendix 3 and Appendences 1 and 2 online). Non-standardised terms are clarified and aligned with industry-recognised terminology, and synonyms are sorted (see Appendix 6 online).

TABLE 1

PLASTIC POLYMERS' MATERIAL PROPERTIES AS REQUIRED BY THE PACKAGING, HOUSEHOLD APPLIANCES AND AUTOMOTIVE SECTORS

General Properties (Literature)	Measured by (Matweb Databank)	Packaging	Household Appliances	Automotive Parts
Antibacterial Properties				
Barrier Properties includes Gas Permeability Resistance	Gas Barrier, Moisture Barrier, Light Barrier, Microbial Barrier			
Biodegradability and Compostability				
Chemical Resistance				
Corrosion and Solvent Resistance				
Cost-Effectiveness				
Dimensional Stability	Creep, Water absorption			
Durability				
Electrical Insulation	CTI (Comparative Tracking Index)			
Film-Forming Capability	Cooling rate			
Flame Retardancy				
Flexibility and Processability	Flexural Modoulus			
Flexural strength	Flexural Modulus, Modulus of Elasticity			
Heat Resistance				
High Specific Strength				
High Strength-to-Weight Ratio	Strength of an object divided by its mass or weight			
Impact resistance				
Impact Toughness	Analysing a stress-strain curve			
Insulating Properties	Thermal conductivity			
Lightweight / Density				
Material Strength, Strength, Tensile strength	Ultimate strength, yield strength			
Melting Point				
Modulus of Elasticity				

General Properties (Literature)	Measured by (Matweb Databank)	Packaging	Household Appliances	Automotive Parts
Moisture Resistance				
Non-Toxicity				
Optical Properties, Transparency	Haze , Gloss, Transmission, Visible			
Recyclability				
Resistance to Deformation	Elasticity and plasticity			
Scratch Resistance				
stiffness	Flexural modulus			
Temperature Resistance	Relative Thermal Index (RTI), Heat Deflection Temperature (HDT)			
Thermal Insulation	Thermal Conductivity			
Thermal Stability				
UV Resistance				
Versatility and Adaptability				
Water Vapor Barrier Properties	Water Vapor Transmission Rate, Oxygen Transmission Rate			

Source: Own elaboration

Results show that only five properties are common to all three sectors, with the majority being sector specific, reflecting the unique needs of different products and applications. The analysis identified four properties that are unique to packaging, four to household appliances and nine to automotive. In addition, certain characteristics are relevant to two sectors; the analysis identified four common characteristics for packaging and household appliances, two for packaging and automotive, and six for household appliances and automotive.

4.2 *Identification of conventional and alternative plastics*

The next step in developing the framework is to identify the main conventional plastic types used in the three sectors (Table 2). Their property values are later used as a guide to assess whether sustainable plastics can effectively replace them.

TABLE 2

LIST OF CONVENTIONAL PLASTIC POLYMERS TYPICALLY USED IN THE INJECTION MOULDING PROCESS, PER SECTOR

Conventional Plastics	Packaging	Household Appliances	Automotive Parts
Acrylic (AK)		■	
Acrylonitrile-Butadiene-Styrene (ABS)		■	■
Epoxy Resin			■
Ethylene Vinyl Alcohol (EVOH)	■		
High-Density Polyethylene (HDPE)	■	■	
High-Impact Polystyrene (HIPS)		■	
Linear Polyester (PBT and PES)			■
Low-Density Polyethylene (LDPE)	■	■	
Maleic Anhydride Polypropylene (MAPP)			■
Nylons		■	
Polyamide (PA)	■		
Polyamides (PA6 and PA66)			■
Polycarbonate (PC)		■	■
Polyethylene (PE)	■	■	
Polyethylene Terephthalate (PET)	■		
Polypropylene (PP)	■	■	■
Polystyrene (PS)	■	■	
Polyvinyl Chloride (PVC)	■	■	■
Unsaturated Polyester			■
Urethane Elastomers (TPE-U)			■

Source: Own elaboration

The results identify 20 types of conventional plastic polymers, of which nine are suitable for packaging, eleven for household appliances and ten for automotive parts. Three plastics are exclusive to packaging, three to household appliances and six to automotive. Four plastics can be used in both packaging and household appliances, while none is shared between packaging and automotive. Two plastics are suitable for both household appliances and automotive parts. Only two plastics can be used in all three sectors. A more detailed version of these results, with descriptions and sources, can be found in the Appendices 10, 11, 12 online.

Table 3 provides an overview list of alternative, more sustainable plastics that could potentially replace conventional materials in all three sectors analysed.

TABLE 3

LIST OF ALTERNATIVE PLASTIC POLYMERS TO BE POTENTIALLY USED IN THE INJECTION MOULDING PROCESS, PER SECTOR

Sustainable alternatives	Packaging	Household Appliances	Automotive Parts
Bio-based polyethylene (Bio-PE)		■	
Bio-based polypropylene (Bio-PP)		■	■
Bio-PE (Bio-based Polyethylene)	■		
Chitosan	■		
Gelatin	■		
PA11		■	■
Polybutylene Succinate (PBS)	■	■	■
Polybutylene Terephthalate (PBAT)	■		
Polycaprolactone (PCL)	■		
Polyglycolide (PGA)	■		
Polyhydroxyalkanoates (PHA)	■		
Polyhydroxybutyrate (PHB)	■		
Polylactic Acid (PLA)	■	■	■
Polypropylene Carbonate (PPC)	■		
Recycled ABS		■	■
Recycled HDPE (rHDPE)		■	■
Recycled PET (rPET)	■		■
Soybean Protein Isolate (SPI)	■		
Starch-Based Materials	■		
Thermoplastic starch (TPS)	■		

Source: Own elaboration

The results identified 20 alternative plastics suitable for the three sectors: 15 for packaging, 7 for white goods and 7 for automotive parts. In contrast to conventional plastics, alternative plastics are more concentrated in the packaging sector, which has significantly more options supporting the findings in the literature review. Twelve plastics are specific to packaging, while only one is specific to household appliances. One plastic can be used in both packaging and automotive, and four are suitable for both automotive and household appliances. Two plastics can be used in all sectors. A more detailed version of these results, with descriptions and sources, can be found in Appendices 13, 14, 15 online.

4.3 Definition of sustainability criteria

As the EU introduces more stringent sustainability regulations and directives for the manufacturing industry (see Figure 2 in the literature review), it is crucial to examine the resulting product requirements. Table 4 details the EU regulatory requirements for each sector.

TABLE 4

PRODUCT REQUIREMENTS RESULTING FROM EU SUSTAINABILITY REGULATIONS AND DDIRECTIVES, PER SECTOR

Sector	Product requirements
Packaging sector	<u>Recyclable and reusable packaging:</u> packaging needs to meet recyclability standards, incorporates recycled content and provides reusable options where feasible. <u>Sustainable alternatives for disposable items:</u> Redesigning single-use plastic products with biodegradable or reusable materials.
Household Appliances	<u>Eco-design compliance:</u> Designing products to meet standards for durability, repairability and resource efficiency, using recycled materials where possible. <u>Chemical safety:</u> Elimination of substances of very high concern and ensuring complete chemical registration dossiers.
Automotive parts sector	<u>Reduction of hazardous substances:</u> Elimination of restricted substances in vehicle components and electronics to comply with ELV and RoHS directives. <u>Circular design:</u> Designing vehicles to optimise reuse and recycling. Sustainable materials use: Incorporation of recycled materials into vehicle production to meet environmental targets.

Source: Own elaboration

The results show that recyclability is essential in all sectors. In the packaging sector, where products are used only for a short time, priority should be given to biodegradable and reusable materials. Due to strong regulatory pressure, sustainability requirements have already been incorporated into the general properties for the packaging and automotive sectors (see Table 1). A more detailed version of these results, with descriptions and sources, can be found in Appendix 9 online.

To establish a more precise sustainability criteria, the literature search was cross-referenced with the IDEMAT database terminology. Due to data limitations, only sustainability criteria from the IDEMAT database were used, as many criteria from the literature only apply to specific products at the development stage. Table 5 reflects the choice and definition of the sustainability criteria.

TABLE 5

LIST OF SUSTAINABILITY CRITERIA AND DEFINITIONS, SELECTED FOR INCLUSION IN THE MULTI-CRITERIA ANALYSIS FRAMEWORK

Criteria	Definition
Biodegradability	This criterion shows whether the polymer can degrade or not.
CED Total (MJ)	CED is the total primary energy consumed during the life cycle of a product or service. It helps to assess the environmental impact and sustainability of products and services (Amor et al., 2010).
Total Eco-Costs €	Representation of the marginal cost of reducing pollution and material consumption. It reflects the financial risk of non-compliance with future government regulations (Eco-Costs Concept and Structure - Sustainability Impact Metrics, n.d.).
ReCiPe endpoint	ReCiPe is a Life Cycle Impact Assessment (LCIA) methodology it converts Life Cycle Inventory results into indicator scores. It measures the relative importance of environmental impact categories (ReCiPe - PRé Sustainability, n.d.).
EF Total	The EF is a tool for assessing sustainable consumption. It measures how fast humanity consumes resources compared to their regeneration rate (Schaefer et al., n.d.).

Source: Own elaboration

Selected criteria include the biodegradability of the plastic, its energy consumption over its life cycle, the associated eco-costs to reduce pollution and material use, the overall environmental impact summarised by the ReCiPe endpoint, and the comparison between plastic consumption and regeneration rates. A more detailed version of these results, with descriptions and sources, can be found in Appendices 7 and 8.

4.4 *Development of a multi-criteria analysis framework*

Based on the above results a multi-criteria analysis framework was developed. Tables 6, 7 and 8 present the final list of metrics selected for this decision support tool, tailored to each of the three specific sectors under analysis.

To ensure comparability and applicability to companies, the final property definitions were identified using the MatWeb (*MatWeb*, n.d.), IDEMAT (*Idemat,Tools,Books - Sustainability Impact Metrics*, n.d.) and MaterialCenter (*Biopolymer*, n.d.) databases.

A detailed version of these tables including all data and sources, can be found in the Appendices 16 to 21 online.

TABLE 6

MULTI-CRITERIA ANALYSIS FRAMEWORK FOR THE PACKAGING SECTOR

Criteria	Criterions	Properties defined by
Mechanical Properties	Material Strength / Tensile Strength	Tensile Strength, Ultimate Mpa
		Tensile Strength, Yield Mpa
	Flexibility/ Versatility and Adaptability	Flexural Modulus Gpa
	Resistance to Deformation	Modulus of Elasticity Gpa
Barrier Properties/ Physical Properties	One part of Mass calculation	Density
	Gas Permeability Resistance	Oxygen Transmission cc-mm/m²-24hr-atm
		Carbon Dioxide Transmission
		Nitrogen Transmission
	Water Vapor Barrier	Moisture Vapor Transmission
		Water Vapor Transmission g/m²/day
Thermal Properties	Melting Point °C	
	Heat Resistance	Maximum Service Temperature, Air
		Continuous Use Temperature
		Relative Thermal Index (RTI) °C
		Relative Thermal Index (RTI) °C
	Film-Forming Capability	Cooling rate
		crystallization
		brittleness

Criteria	Criterions	Properties defined by
Processing Properties	Processability	Processing Temperature
		Nozzle Temperature
		Melt Temperature
		Mold Temperature
		Injection Velocity
		Drying Temperature
		Injection Pressure
Aesthetic Properties	Transparency	Transmission, Visibility
Functional and Safety Properties	Durability/ Impact resistance	
	Non-Toxicity	
	Antibacterial Properties	
Environmental and Sustainability Properties	Biodegradability	
	Total Eco-Costs €	
	Carbon Dioxide kgCO_2e	
	CED Total (MJ)	
	EF Total	
	ReCiPe endpoint	
Economic Viability	Average material price (EUR/kg)	

Source: Own elaboration

TABLE 7

MULTI-CRITERIA ANALYSIS FRAMEWORK FOR THE HOUSEHOLD APPLIANCES SECTOR

Criteria	Criterions	Properties defined by
Mechanical Properties	Material Strength / Tensile Strength	Tensile Strength, Ultimate
		Tensile Strength, Yield
	High Specific Strength	
	Flexibility/ Versatility and Adaptability	Flexural Modulus
	Resistance to Deformation	Modulus of Elasticity
Chemical Properties	Corrosion and Solvent Resistance/ Chemical Resistance	
	Flame Retardancy	

Criteria	Criterions	Properties defined by
	UV Resistance	
Electrical Properties	Electrical Insulation	CTI (Comparative Tracking Index)
Physical Properties	Mass	Density
Thermal Properties	Thermal Insulation	Thermal Conductivity
Processing Properties	Processability	Processing Temperature
		Nozzle Temperature
		Melt Temperature
		Mold Temperature
		Injection Velocity
		Drying Temperature
		Injection Pressure
Aesthetic Properties	Haze	
	Gloss	
	Transmission, Visible	
Environmental and Sustainability Properties	Biodegradability	
	Total Eco-Costs €	
	Carbon Dioxide $kgCO_2e$	
	CED Total (MJ)	
	EF Total	
	ReCiPe endpoint	
Functional and Safety Properties	Durability/ Impact resistance	
	Antibacterial Properties	
Economic Viability	Average material price (EUR/kg)	

Source: Own elaboration

TABLE 8

MULTI-CRITERIA ANALYSIS FRAMEWORK FOR THE AUTOMOTIVE SECTOR

Criteria	Criterions	Properties defined by
Mechanical Properties	Material Strength / Tensile Strength	Tensile Strength, Ultimate
		Tensile Strength, Yield
	High Specific Strength	
	Flexibility/ Versatility and Adaptability	Flexural Modulus
		Flexural strength
	Resistance to Deformation	Modulus of Elasticity
	Impact Toughness	

Criteria	Criterions	Properties defined by
Chemical Properties	UV Resistance	
	Corrosion and Solvent Resistance/ Chemical Resistance	
Electrical Properties	Electrical Insulation	CTI (Comparative Tracking Index)
Thermal Properties	Thermal Insulation	Thermal Conductivity
		Relative Thermal Index (RTI)/ UL RTI, Electrical
		Heat Deflection Temperature (HDT)
		Distortion
		Vicat softening
Processing Properties	Processability	Processing Temperature
		Nozzle Temperature
		Melt Temperature
		Mold Temperature
		Injection Velocity
		Drying Temperature
		Injection Pressure
Aesthetic Properties	Haze	
	Gloss	
	Transmission, Visible	
Environmental and Sustainability Properties	Biodegradability	
	Total Eco-Costs €	
	Carbon Dioxide $kgCO_2e$	
	CED Total	
	EF Total	
	ReCiPe endpoint	
Barrier Properties/ Physical Properties	Gas Permeability Resistance	Oxygen Transmission
		Carbon Dioxide Transmission
		Nitrogen Transmission
	Water Vapor Barrier	Moisture Vapor Transmission
		Water Vapor Transmission
		Water absorption
	Mass	Density
Functional and Safety Properties	Durability/ Impact resistance	
	Dimensional Stability	Linear thermal expansion
		Creep
	Scratch Resistance	
Economic Viability	Average material price (EUR/kg)	

Source: Own elaboration

Collecting comprehensive data, particularly for alternative plastics, is challenging but essential to make meaningful comparisons. Data availability is assessed, and significant gaps are identified, particularly for alternative plastics (see Appendices 17, 19, 21 online). To allow a meaningful comparison, the framework is adapted to focus only on comparable requirements. To further simplify, plastic properties with insufficient data are excluded. As a result, the multi-criteria analysis framework is adapted to focus on mechanical, physical, processing and environmental properties. A more detailed version of these tables and the final adapted framework, with descriptions and sources, can be found in Appendices 22 to 27 online.

4.5 Comparative analysis of material properties and sustainability criteria

Using the adapted final multi-criteria analysis framework presented above, a comparison of material properties was performed to ensure that alternative plastics meet product requirements, using conventional plastics as a benchmark. Given the proximity of values within each criterion and across properties, the allocation of scores were based on expert judgment by the author.

For plastics those that meet material requirements, sustainability criteria are then used to evaluate the environmental benefits of these alternatives. Plastics without sufficient data for comparison were excluded, as were conventional plastics with advanced properties that could not be matched to any alternative. For conventional plastics, average values are used to represent the full range of options across manufacturers. For alternative plastics, values from specific manufacturers are selected as no averages are available.

As an example, tables 9 and 10 present the results of the application of the final framework to the Packaging sector. Similarly, the results of the analysis for the Household Appliances and Automotive sectors are presented in Appendices 1 and 2.

TABLE 9

APPLICATION OF THE MULTI-CRITERIA FRAMEWORK TO THE COMPARISON OF MATERIAL PROPERTIES OF PLASTIC POLYMERS FOR THE PACKAGING SECTOR

	Mechanical properties			Physical properties	
	Material Strength		Flexibility		
Plastic type [a]	Tensile Strength, Ultimate (Mpa)	Tensile Strength, Yield (Mpa)	Flexural Modulus (Gpa)	Density (g/cc)	Eligibility score [b]
HDPE (C)	22.0	26.2	1.14	0.95	
PBAT (A)	18			1.30	Moderate
LDPE (C)	10.8	11	0,26	0.92	
PBAT (A)	18			1.30	Moderate
PP (C)	29.5	31.5	1.43	0.93	
PBAT (A)	18			1.30	Poor
PS (C)	41.0	32.3	2.68	0.98	
PBAT (A)	18			1.30	Poor
HDPE (C)	22.0	26.2	1.14	0.95	
PHB (A)	18			1.20	Good
LDPE (C)	10.8	11	0,26	0.92	
PHB (A)	18			1.20	Good
PP (C)	29.5	31.5	1.43	0.93	
PHB (A)	18			1.20	Moderate
PS (C)	41.0	32.3	2.68	0.98	
PHB (A)	18			1.20	Poor

	Mechanical properties			Physical properties	
	Material Strength		Flexibility		
Plastic type [a]	Tensile Strength, Ultimate (Mpa)	Tensile Strength, Yield (Mpa)	Flexural Modulus (Gpa)	Density (g/cc)	Eligibility score [b]
HDPE (C)	22.0	26.2	1.14	0.95	
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Moderate - poor
LDPE (C)	10.8	11	0,26	0.92	
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Poor
PP (C)	29.5	31.5	1.43	0.93	
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Moderate - poor
PS (C)	41.0	32.3	2.68	0.98	
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Good

[a] Plastic type	[b] Eligibility score
(C) Conventional plastic	Good
(A) Alternative plastic	Moderate
	Poor

Source: Own elaboration

Results suggest that PP could potentially be well replaced by rPET, considering the difference in flexural modulus, which could be either an advantage or a disadvantage, and the density value, which would only be an advantage if it were lower. Conventional plastics that are more suitable for replacement include PS (replaced by rPET), HDPE (replaced by PHB) and LDPE (replaced by PHB). However, it is important to note that there is a significant lack of data, particularly for the transition between HDPE and PHB, LDPE to PHB, PP to PHB and PS to PHB, so complete potential replacement cannot be guaranteed. Plastics that should not be replaced are PP by PBAT, PS by PBAT, PS by PHB and LDPE by rPET as the values do not match well. Based on these results six 'pairs' of plastics are selected to advance to the comparative evaluation of environmental and sustainability properties. The results of this second-tier analysis are reflected in Table 10.

TABLE 10

APPLICATION OF THE MULTI-CRITERIA FRAMEWORK TO THE COMPARISON OF ENVIRONMENTAL AND SUSTAINABILITY PROPERTIES OF PLASTIC POLYMERS FOR THE PACKAGING SECTOR

	Environmental and Sustainability Properties							
Plastic type[a]	Biodegradability	Contains renewable resources	Total Eco-Costs (€)	Carbon Dioxide ($kgCO_2$ e)	CED Total (MJ)	EF Total	ReCiPe endpoint	Final sustainability score [b]
HDPE (C)	No	Yes	1.10	1.8	84.7	0.00018	0.051	**21**
PBAT (A)	Yes		0.68	4.1	107.2	0.00024	0.094	**15**
LDPE (C)	No	No	1.19	1.9	87.7	0.00021	0.058	**21**
PBAT (A)	Yes		0.68	4.1	107.2	0.00024	0.094	**15**
HDPE (C)	No	Yes	1.10	1.8	84.7	0.00018	0.051	**24**
PHB (A)	Yes	Yes	0.43	2.6	68.7	0.00013	0.051	**39**
LDPE (C)	No	No	1.19	1.87	87.7	0.00021	0.058	**12**
PHB (A)	Yes	No	0.43	2.6	68.7	0.00013	0.052	**27**
PP (C)	No	No	1.19	1,6	82,3	0,00021	0,055	**15**
PHB (A)	Yes	Yes	0.43	2.6	68.7	0.00013	0.051	**27**
PS (C)	No		1.19	2.2	88.6	0.00018	0.044	**3**
rPET (A)	No		0.10	0.6	8.9	0.000028	0.011	**30**

[a] Plastic type	**[b] Sustainability score**
(C) Conventional plastic	Good (6 pts)
(A) Alternative plastic	Moderate (3 pts)
	Poor (0 pts)

Source: Own elaboration

Results show that all the alternative plastics are significantly more sustainable than conventional plastics, with the exception of PBAT. PBAT has a lower score than the conventional polymer LDPE and HDPE, so its replacement is not recommended.

4.5.1 Evaluation of alternatives for the household appliances sector

Table 12 in Appendix 1 shows that Bio-PP is the best substitute for PS, HDPE and PP in the household appliances sector. ABS can be replaced not only by Bio-PP but also by rPET. Bio-PP has excellent tensile strength, even higher than conventional options, which is a significant advantage in meeting product requirements. The same advantage is seen with rPET in terms of tensile strength and yield value.

Table 13 in Appendix 1 presents the results of the sustainability assessment and shows that all alternative plastics score significantly higher than conventional plastics. For ABS, which can be replaced by either rPET or Bio-PP, rPET is the more sustainable option.

4.5.2 Evaluation of alternatives for the Automotive Parts sector

Table 14 in Appendix 2 shows that in the automotive sector, as in the household appliances sector shown in Table 11, ABS is best replaced by Bio-PP and rPET, while PP is best replaced by Bio-PP and PBS. The alternative plastics have superior material strength compared to conventional plastics. In addition, Bio-PP has excellent density, making it ideal for lightweight applications.

Table 15 in Appendix 2 shows that ABS has a significantly higher negative environmental impact compared to Bio-PP and rPET and is therefore strongly recommended as a replacement. Although the material properties of PP are closer to those of Bio-PP, rPET is the preferred option from a sustainability perspective. PBS is not the most sustainable option.

4.6 Selection of the most suitable alternative plastics

Packaging plastics must resist bacteria, protect food by blocking moisture, gases and contaminants, and be cost effective. They also need to be biodegradable, flexible, durable, able to withstand heat, impact and deformation, while being light, strong and non-toxic (see Appendix 3).

Household plastics need to be antibacterial, chemical and corrosion resistant and cost effective. They must be durable (impact, scratch and deformation resistant), offer excellent electrical/thermal insulation, flame retardancy and UV resistance, while remaining lightweight, strong and recyclable (see Appendix 4 online).

Automotive plastics must resist chemicals, corrosion and moisture, while retaining their shape and electrical insulation. They need to be lightweight but have high tensile, flexural and impact strength, as well as resistance to shock, heat, UV and weathering. Design flexibility and recyclability are also essential (see appendix 5 online).

Due to data limitations, very limited criteria could be assessed. However, tensile strength (ultimate and yield) is particularly important and are prioritised for evaluation. Table 11 summarises the evaluation of the potential replacement of conventional plastics by alternatives, in injection moulding and for the three sectors analysed. These alternatives may be relevant for several sectors depending on specific product requirements - for example, ABS in the household appliances sector could be replaced by either rPET or Bio-PP, providing additional flexibility in material selection.

TABLE 11

SUMMARY TABLE OF THE APPLICATION OF THE MULTI-CRITERIA ANALYSIS, PER SECTOR.

Sector	Conventional Plastic	Alternative Plastic	Eligibility (material properties)	Sustainability score	Best option replacement
Packaging	HDPE	PHB	Good	+15	HDPE -> PHB
		PBAT	Moderate	-6	
	LDPE	PHB	Good	+15	LDPE -> PHB
		PBAT	Moderate	-6	
	PS	rPET	Good	+27	PS-> rPET
	PP	PHB	Moderate	+12	PP->PHB
Household Appliances	PS	Bio-PP	Good	+33	PS- >Bio-PP
	ABS	Bio-PP	Good	+21	ABS-> rPET
		rPET	Good	+30	
	HDPE	Bio-PP	Good	+21	HDPE -> Bio-PP
	PP	Bio-PP	Good	+30	PP-> Bio-PP
Automotive Parts	ABS	Bio-PP	Good	+21	ABS-> rPET
		rPET	Good	+30	
	PP	Bio-PP	Good	+12	PP-> Bio-PP

Sector	Conventional Plastic	Alternative Plastic	Eligibility (material properties)	Sustainability score	Best option replacement
		rPET	Moderate	+27	
		PBS	Good	+9	

Source: Own elaboration

Results highlight the differences in scores between conventional and alternative plastics. Best option replacements are chosen on the basis of the combined results of eligibility (material proprieties) and sustainability scores. The results show that HDPE should not be replaced by PBAT and PP should not be replaced by rPET. Although ABS can be replaced by Bio-PP, rPET offers a better sustainability profile. Replacing PP with PBS is feasible based on material properties but is not recommended from a sustainability perspective. Other possible replacements include HDPE with PHB, LDPE with PHB, PS with rPET or Bio-PP, ABS with rPET, HDPE with Bio-PP and PP with Bio-PP.

5. DISCUSSION

The results of this study highlight the complex and multifaceted nature of sustainability in the injection moulding industry. The main drivers of sustainability are regulatory pressure, growing consumer awareness, financial considerations and technological innovation. Regulatory bodies, particularly in Europe, have set stringent policies to reduce plastic waste and emissions, forcing companies to seek sustainable alternatives. However, despite these pressures, the widespread adoption of sustainable plastics remains a challenge.

The types of plastics used in injection moulding are largely conventional polymers derived from petrochemical sources, which are preferred for their durability and chemical resistance. However, this durability makes them particularly difficult to replace with sustainable alternatives. The environmental impact of these conventional plastics is significant, as 77% of the 8.3 billion tonnes of plastic ever produced has become waste, with only 9% mechanically recycled (Jambeck & Walker-Franklin, 2023). Furthermore, the injection moulding process itself is energy intensive, with electricity consumption accounting for approximately 62.6% of the environmental impact (Elduque et al., 2015).

Several sustainable alternatives have emerged, including biodegradable polymers and non-biodegradable bioplastics. Biodegradable polymers, whether petroleum-based or derived from renewable resources, offer potential benefits but also present performance trade-offs, particularly in terms of durability (Vroman & Tighzert, 2009). While non-biodegradable bioplastics offer a more robust alternative, they still require specialised end-of-life solutions (Rahman & Bhoi, 2021). The packaging and automotive industries have led the adoption of these materials, and the global market for sustainable polymers is growing rapidly (*Sustainable Polymer Market Research Report*, 2024).

Despite these developments, there are several barriers to the wider adoption of sustainable plastics in injection moulding. High production costs are a major challenge, making bioplastics initially less economically viable than conventional plastics. However, regulatory frameworks are now imposing financial penalties for non-compliance with sustainability strategies. A comprehensive economic assessment must therefore consider all associated costs. This broader perspective may ultimately reveal that alternative plastics are potentially more cost effective than traditional plastics in the near future. In addition, recycling infrastructure limitations and the lack of a standardised data framework complicate efforts to integrate these alternatives into manufacturing processes. Consumer and industry hesitancy is further slowing the transition as companies remain uncertain about the long-term performance and economics of these materials.

Looking at the results of the multi-criteria analysis developed in this study, it is evident that simple replacement is challenging due to the complex and broad material requirements. However, there is still significant potential. For example, consideration of Bio-PP shows that superior performance can be achieved compared to conventional materials in certain properties, underlining the potential for a material transition. In contrast, the conventional polymer ABS performs very poorly in terms of sustainability, highlighting the urgent need for its replacement. However, it is crucial to approach any replacement carefully, as not all alternatives offer improved sustainability. For example, PBS has not been shown to be a more sustainable option when compared to HDPE and LDPE. Therefore, replacing conventional materials should be carefully evaluated to avoid compromising overall material performance.

5.1 Study limitations and challenges with data availability

A major limitation identified in this study is the lack of comprehensive data on sustainable plastics. Existing databases such as MatWeb do not provide sufficient information, making it difficult to systematically compare material properties. This lack of transparency forces companies to rely solely on data provided by material manufacturers, which may not always be standardised. In addition, because material properties must first meet functional requirements before sustainability considerations can be prioritised, companies are often unable to make an immediate switch to greener alternatives. A notable example is LEGO, which attempted to switch to sustainable polymers but found that the available options did not meet its high level of product requirements (*Lego Abandons Effort to Make Bricks from Recycled Plastic Bottles | Lego | The Guardian*, n.d.). Given the current state-of-the-art, it is probably safe to infer that other, less notable companies, are currently struggling with the same challenges and implications.

The complexity of biopolymers and their sustainability profile presents additional challenges. While biopolymers are often marketed as sustainable solutions, their actual environmental benefits depend heavily on simultaneous developments in recycling systems and infrastructure. Simply replacing conventional plastics with bioplastics will not address issues such as overconsumption and inefficiencies in waste management (Di Bartolo et al., 2021). Instead, effective policies and technological advances are needed to optimise biodegradability, recyclability and overall sustainability.

5.2 Future directions and industry implications

This research highlights the importance of education, data accessibility, and regulatory clarity to facilitate a realistic and effective transition to sustainable plastics. Given the rapid pace of sustainability-driven developments since 2018 (see figure 2), the industry is struggling to keep up due to data limitations, economic constraints, and technical challenges. While the initial assumption was that replacing conventional plastics with sustainable ones would be the most effective strategy, the findings suggest that improving recycling technologies and optimising production machinery may be a more impactful first step. In addition, academia, policy makers and industry stakeholders need to work together to develop a unified approach to sustainability. Standardised material databases, improved recycling infrastructures and economic incentives for sustainable plastics could encourage wider adoption. Until these systemic improvements are realised, the transition to sustainable plastics is likely to remain slow and uneven. Based on the Plastics Europe Sustainability Transition Plan presented in the literature review, this study supports the plan's recommendation to start by sharing data. In line with this plan, the multi-criteria analysis framework proposed here could become increasingly important between 2026 and 2030 and, after further refinement, could eventually be adopted by companies to facilitate the transition to recyclable plastics and bioplastics since it is, to our knowledge, one of the first attempts at developing a framework that combines theoretical approaches with industrial applicability, for the plastic polymer injection moulding industry. Other, more specific studies exist, but these are typically framed by companies' specific requirements and conventional use of plastics, therefore lacking the wider applicability that was targeted with the multi-criteria analysis framework developed in this thesis.

6. CONCLUSION

This study provides a comprehensive overview of the current landscape of sustainable plastic alternatives in injection moulding and highlights the many challenges and opportunities in this area, namely in the Packaging, Household appliances and Automotive parts sectors. The research shows that regulatory pressure, increasing consumer awareness, financial factors and technological innovation are key drivers pushing the industry towards sustainability. However, the widespread reliance on conventional petrochemical-based plastics - with their inherent durability and significant environmental impact - remains a significant challenge.

The multi-criteria analysis framework developed in this study has proven to be a potentially valuable tool in guiding companies towards more sustainable practices in the future. By systematically evaluating a wide range of environmental and operational factors, the analysis showed that while certain sustainable alternatives, such as Bio-PP, can achieve superior performance in certain properties, others, such as PBS, may not deliver the expected improvements. These findings emphasise that straightforward replacement of conventional plastics is not feasible without careful consideration of the overall material performance and sustainability trade-offs.

A critical limitation identified in this research is the lack of comprehensive, standardised data on sustainable plastics. This data gap hinders the effective comparison of material properties and complicates the decision-making process, as companies often must rely on information provided by manufacturers. Further research is therefore needed to improve data accessibility, refine the multi-criteria analysis framework and explore complementary strategies - such as advances in recycling technologies and process optimisation - to support the transition to sustainable manufacturing.

This research provides a comprehensive overview of the current landscape of sustainable plastic alternatives in injection moulding and the challenges associated with their adoption. While progress is evident, numerous technological, economic and infrastructural barriers continue to hinder widespread implementation. The findings suggest that a multi-sectoral approach - combining material innovation, recycling advances and regulatory cooperation - is essential to achieve meaningful progress in sustainability.

Ultimately, while sustainable plastics offer promising alternatives, their success will depend on their integration into a well-structured circular economy. Rather than approaching sustainable plastics as a one-off solution, the industry should adopt a holistic strategy that balances material development with improvements in recycling, education and policy frameworks. Only through such a coordinated effort can the industry move towards a truly sustainable future.

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8. APPENDICES

Appendix 1

TABLE 12

COMPARISON OF THE MATERIAL PROPERTIES OF THE POLYMERS FOR THE HOUSEHOLD APPLIANCES SECTOR

	Mechanical Properties				
	Material Strength			Flexibility	
Plastic Type	Tensile Strength, Ultimate (MPa)	Tensile Strength, Yield (MPa)	Flexural Modulus (GPa)	Density (g/cc)	**Eligibility Score**
ABS (C)	41.0	44.8	2.33	1.07	
Bio-PP (A)	49			0.98	Good
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Good
HDPE (C)	22.0	26.2	1.14	0.95	
Bio-PP (A)	49			0.98	Good
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Moderate - bad
PP (C)	29.5	31.5	1.43	0.93	
Bio-PP (A)	49			0.98	Good
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Moderate - bad
PS (C)	41.0	32.3	2.68	0.98	
Bio-PP (A)	49			0,98	Good
rPET (A)		48.26 - 55.16	2.07 - 2.41	1.33	Moderate - bad

[a] **Plastic type**	[b] **Eligibility score**
(C) Conventional plastic	Good
(A) Alternative plastic	Moderate
	Poor

Source: Own elaboration

TABLE 13

COMPARISON OF THE ENVIRONMENTAL PROPERTIES OF THE POLYMERS FOR THE HOUSEHOLD APPLIANCES SECTOR

Environmental and Sustainability Properties								
Plastic Type	Biodegradability	Contains renewable resources	Total Eco-Costs (€)	Carbon Dioxide ($kgCO_2e$)	CED Total (MJ)	EF Total	ReCiPe endpoint	Final sustainability Score
ABS (C)	No	No	1.33	2.69	97.2	0.00023	0.054	6
Bio-PP (A)	No	Yes	1.08	1.26	72.7	0.0000607	0.032	27
rPET (A)	No	No	0.10	0.552	8.9	0.0000284	0.011	36
HDPE (C)	No	No	1.10	1.8	84.7	0.00018	0,051	12
Bio-PP (A)	No	Yes	1.08	1.3	72.7	0.000061	0,032	33
PP (C)	No	No	1.19	1.63	82.3	0.00021	0.055	6
Bio-PP (A)	No	Yes	1.08	1.26	72.7	0.000061	0.032	36
PS (C)	No	No	1.19	2.16	88.6	0.00018	0.044	3
Bio-PP (A)	No	Yes	1.08	1.26	72.7	0.000061	0.032	36

[a] Plastic type	[b] Sustainability score
(C) Conventional plastic	Good (6 pts)
(A) Alternative plastic	Moderate (3 pts)
	Poor (0 pts)

Source: Own elaboration

Appendix 2

TABLE 14

COMPARISON OF THE MATERIAL PROPERTIES OF THE POLYMERS FOR THE AUTOMOTIVE PARTS SECTOR

	Mechanical Properties				
	Material Strength / Tensile Strength			Flexibility	
Plastic Type	Tensile Strength, Ultimate (MPa)	Tensile Strength, Yield (MPa)	Density (g/cc)	Flexural Modulus (GPa)	**Eligibility Score**
ABS (C)	41.0	44.8	1.07	2.33	
Bio-PP (A)	49		0.98		Good
rPET (A)		48.26 - 55.16	1.33	2.07 - 2.41	Good
PBS (A)	36		1.3		Moderate
PP (C)	29.5	31.5	0.931	1.43	
Bio-PP (A)	49		0.98		Good
rPET (A)		48.26 - 55.16	1.3	2.07 - 2.41	Moderate
PBS (A)	36		1,3		Good

[a] **Plastic type**	[b] **Eligibility score**
(C) Conventional plastic	Good
(A) Alternative plastic	Moderate
	Poor

TABLE 15

COMPARISON OF THE ENVIRONMENTAL PROPERTIES OF THE POLYMERS FOR THE AUTOMOTIVE PARTS SECTOR

	Environmental and Sustainability Properties							
Plastic Type	Biodegradability	Contains renewable resources	Total Eco-Costs (€)	Carbon Dioxide ($kgCO_2e$)	CED Total	EF Total	ReCiPe endpoint	Final sustainability Score
ABS (C)	No	No	1.33	2.69	97.2	0.000231	0.054	0
Bio-PP (A)	No	Yes	1.08	1.26	72.7	0.0000607	0.032	21
rPET (A)	No	No	0.10	0.552	8.9	0.0000284	0.011	30
PP (C)	No	No	1.19	1.63	82.3	0.000207	0.055	9
Bio-PP (A)	No	Yes	1.08	1.26	72.7	0.0000607	0.032	21
rPET (A)	No	Yes	0.10	0.552	8.9	0.0000284	0.011	36
PBS (A)	Yes	Yes	0.65	3.753	125.5	0.000264	0.088	18

[a] **Plastic type**	[b] **Sustainability score**
(C) Conventional plastic	Good (6 pts)
(A) Alternative plastic	Moderate (3 pts)
	Poor (0 pts)

Appendix 3

TABLE 16

GENERAL PROPRIETIES FOR PACKAGING

General Properties for Packaging Products				
Requirements on Plastic out of the Literature	Description	Standardized more specific terms out of Industry websites	Databank Terms	Included in the framework
Antibacterial Properties	The material should have antibacterial properties to prevent bacterial growth, extending food shelf life (Zhao, 2024).	Sometimes tables are available	Not in Databank included	Yes
Barrier Properties	Barrier properties are crucial to make sure the material preserves food moisture and prevent contamination, ensuring freshness and safety (Mahajan et al., 2024)	Gas Barrier: Prevents oxygen permeation to slow spoilage and preserve freshness. Moisture Barrier: Blocks moisture to prevent degradation, mold, and spoilage. Light Barrier: Shields against UV and visible light to maintain product stability. Microbial Barrier: Protects against contamination, ensuring sterility in food, pharmaceuticals, and medical devices.	Oxygen Transmission, Carbon Dioxide Transmission , Nitrogen Transmission , Moisture Vapor Transmission , Water Vapor Transmission	Yes
Biodegradability and Compostability	Biodegradable polymers decompose naturally, reducing waste, while compostable ones turn into compost, aiding sustainability (Mahajan et al., 2024)	no further specification needed	Biodegradability	Yes
Cost-Effectiveness	Packaging materials should be low-cost for economic viability, especially for single-use applications (Mahajan et al., 2024)	Material Costs	Not in Databank included	Yes
Environmental Impact	Packaging materials should minimize environmental impact from production to disposal (Mahajan et al., 2024)			Yes
Film-Forming Capability	The ability to form films is crucial for packaging applications (Zhao, 2024)	Temperature: Higher temperatures lower viscosity and reduce molecular orientation (thermoforming). Cooling Rate: Faster cooling decreases crystallinity, creating more amorphous regions (quenching). Draw Ratio: Higher ratios improve molecular orientation and mechanical properties (stretch blow molding).	Cooling Rate	Yes
Flexibility and Durability	Packaging materials should be flexible enough to accommodate different shapes and sizes while being durable to protect the contents (Ponnusamy & Mani, 2022)	Flexibility: Flexural Modulus	Flexural Modulus	Yes

General Properties for Packaging Products				
Requirements on Plastic out of the Literature	Description	Standardized more specific terms out of Industry websites	Databank Terms	Included in the framework
Flexibility and Processability	The plastic should be easy to process and mold into various packaging forms (Zhao, 2024)		Flexural Modulus, Modulus of Elasticity, Processing Properties	Yes
Gas Permeability Resistance	The ability to resist gas permeability is crucial for maintaining the freshness and quality of food products. This property helps in preventing the ingress of oxygen, which can lead to oxidation and spoilage of food (Sin & Tueen, 2023a)		Oxygen Transmission, Carbon Dioxide Transmission , Nitrogen Transmission	Yes
Heat Resistance	Heat resistance is necessary for certain packaging applications that involve exposure to higher temperatures (Zhao, 2024)	Discribed by: Maximum Service Temperature, Continuous Use Temperature, and Relative Thermal Index (RTI)	Maximum Service Temperature Air, Continuous Use Temperature, Relative Thermal Index (RTI) °C	Yes
impact resistance	Impact resistance stands for robustness and durability (Sin & Tueen, 2023a)		Tensile Strength ultimate, Tensile Strength, Yield, Flexural Modulus, Modulus of Elasticity	Yes
Lightweight	Plastics are often chosen for packaging because they are lightweight, which reduces transportation costs and energy use (Lata Meena et al., 2017)		Density	Yes
Material Strength	Plastics used in packaging need to maintain structural integrity and strength throughout their use. This ensures that the packaging can withstand handling and transportation without breaking or leaking (Lata Meena et al., 2017)	no further specification needed	Tensile Strength ultimate, Tensile Strength, Yield	Yes
Melting Point	A high melting point prevents packaging deformation, ensuring protection under various temperatures (Mahajan et al., 2024)	no further specification needed	Melting Point	Yes
Non-Toxicity	Food packaging must be non-toxic to prevent contamination and ensure consumer safety (Mahajan et al., 2024)	Sometimes tables are available	Not in Databank included	Yes
Regulatory Compliance	While not a physical property, regulatory compliance is critical to ensure that the packaging does not leach harmful chemicals into the food. This involves adhering to food safety standards and regulations set		No: Regulatory compliance cannot be described by a specific material property. The standards depend on the	No

General Properties for Packaging Products				
Requirements on Plastic out of the Literature	Description	Standardized more specific terms out of Industry websites	Databank Terms	Included in the framework
	by authorities in different countries (Sin & Tueen, 2023a)		manufacturer of the plastic.	
Tensile Strength	Packaging materials need to have good tensile strength to withstand mechanical stresses during handling and transportation (Ponnusamy & Mani, 2022)	no further specification needed	Tensile Strength	Yes
Transparency	Transparency allows consumers to see the product inside the packaging, which is important for marketing and consumer trust (Sin & Tueen, 2023b)		Aesthetic Properties: Transparency -> Transmission, Visiblity	Yes
Versatility and Adaptability	Packaging needs to be versatile to accommodate different types of products and adaptable to various shapes and sizes (Lata Meena et al., 2017)		Flexural Modulus	Yes
Water Vapor Barrier	A strong water vapor barrier is essential to protect food from moisture, which can cause spoilage or degradation. (Sin & Tueen, 2023a)		Moisture Vapor Transmission , Water Vapor Transmission	Yes
Water Vapor Barrier Properties	Effective packaging materials should prevent moisture from penetrating, which is crucial for preserving the contents (Ponnusamy & Mani, 2022)	Discribed by: Water Vapor Transmission Rate (WVTR)The Oxygen Transmission Rate (OTR)	Water Vapor Transmission, Oxygen Transmission	Yes

The online Appendices can be found here:
https://1drv.ms/x/c/6fc58b6e7e8e0100/ERAl0WoC7y1HpvJJmThLiD0BAQ88WTfDxmcBWClBfamlwg?e=coy3DI

Online-Appendix: Appendix 4

TABLE 17

GENERAL PROPERTIES FOR HOUSEHOLD APPLIANCES

Scources:

(Tuteja et al., 2024)

(Liu Shichao, 2017)

(Sercer & Raos, n.d.)

Online-Appendix: Appendix 5

TABLE 18

GENERAL PROPERTIES FOR AUTOMOTIVE PARTS

Scources:

(Fitri et al., 2021)

(Gerdroudbari et al., 2015)

(Strumberger et al., 2005)

(Uzoma et al., 2023)

(Volpe et al., 2019)

Online-Appendix: Appendix 6

TABLE 19

TERMS WITH THE SAME MEANING IN THE GENERAL PROPERTIES

Online-Appendix: Appendix 6

TABLE 20

EVALUATION CRITERIA FOR SUSTAINABILITY

Sources:

(Lima et al., 2024)

(Keith et al., 2024)

(Torkelis et al., 2024)

(Di Bartolo et al., 2021)

(Shamsuddoha & Kashem, 2024)

(Fagnani et al., 2022)

(Torres-Alba et al., 2023)

(Keith et al., 2024)
(Tarazona et al., 2022)

Online-Appendix: Appendix 8

TABLE 21

SORTING AND CHOOSING THE EVALUATION CRITERIA FOR SUSTAINABILITY FOR THE FRAMEWORK

Sources:
(Schaefer et al., n.d.)
(*Eco-Costs Concept and Structure - Sustainability Impact Metrics*, n.d.)
(Amor et al., 2010)
(*ReCiPe - PRé Sustainability*, n.d.)

Online-Appendix: Appendix 9

TABLE 22

PRODUCT REQUIREMENTS THROUGH EU REGULATIONS

Sources:
(*REACH Regulation - European Commission*, n.d.)
(Office of the European Union L- & Luxembourg, n.d.)
(*RoHS Directive - European Commission*, n.d.)
(*End-of-Life Vehicles - European Commission*, n.d.)
(Ragonnaud, n.d.)
(*Single-Use Plastics - European Commission*, n.d.)
(*Waste Framework Directive - European Commission*, 2023)

Online-Appendix: Appendix 10

TABLE 23

CONVENTIONAL PLASTICS FOR PACKAGING

Sources:
(Sin & Tueen, 2023a)
(Foltynowicz, 2020)
(Ponnusamy & Mani, 2022)
(Vermeulen et al., 2018)

Online-Appendix: Appendix 11

TABLE 24

CONVENTIONAL PLASTICS FOR HOUSEHOLD APPLIANCES

Source:

(Menchaca-Campos et al., 2014)

(Der et al., 2022)

(Tuteja et al., 2024)

Online-Appendix: Appendix 12

TABLE 25

CONVENTIONAL PLASTICS FOR AUTOMOTIVE

Source:

(Strumberger et al., 2005)

(Volpe et al., 2019)

(Der et al., 2022)

Online-Appendix: Appendix 13

TABLE 26

SUSTAINABLE PLASTIC ALTERNATIVES FOR PACKAGING

Scources:

(Zhao, 2024)

(Ponnusamy & Mani, 2022)

(Sin & Tueen, 2023)

(Mahajan et al., 2024)

Online-Appendix: Appendix 14

TABLE 27

SUSTAINABLE PLASTIC ALTERNATIVES FOR HOUSEHOLD APPLIANCES

Sources:

(*Beologic Beobase PE RTM186 Rotomolding*, n.d.)

(*Bio-Based Polypropylene Market Size & Share | Report [2032]*, n.d.)

(*Polybutylene Succinate (PBS) | Reverdia*, n.d.)

(*The Ultimate Guide To Compostable PLA Plastic Tableware*, n.d.)

(Loultcheva et al., 1997)

(*Recycled ABS: Materials Explained: Process, Applications and Pros & Cons - Monday Merch*, n.d.)

(*Visionary Market Analytics - Polyamide 11 PA 11 Market By Application*, n.d.)

Online-Appendix: Appendix 15

TABLE 28

SUSTAINABLE PLASTIC ALTERNATIVES FOR AUTOMOTIVE

Sources:

(*Bio-Based Polypropylene Market Size & Share | Report [2032]*, n.d.)

(*Polybutylene Succinate (PBS) | Reverdia*, n.d.)

(Sintac, 2023)

(*Emerging Applications of RPET - Jbrpet*, n.d.)

(*Sustainable Innovations: Exploring the Versatile Uses of Recycled ABS Resins – Mid Continent Plastics, Inc. Blog*, n.d.)

(*Applications of Polylactic Acid*, n.d.)

(*Visionary Market Analytics - Polyamide 11 PA 11 Market By Application*, n.d.)

Scources fort he multi-criteria framework:

(*Raw Materials & Prices*, 2025)

(*DaKeBiKu*, n.d.)

(*MatWeb*, n.d.)

(*Biopolymer*, n.d.)

Online-Appendix: Appendix 16

TABLE 29

FULL MULTI CRITICAL ANALYSIS – CONVENTIONAL PLASTICS (PACKAGING)

Online-Appendix: Appendix 17

TABLE 30

FULL MULTI CRITICAL ANALYSIS – ALTERNATIVE PLASTICS (PACKAGING)

Online-Appendix: Appendix 18

TABLE 31

FULL MULTI CRITICAL ANALYSIS – CONVENTIONAL PLASTICS (HOUSEHOLD APPLIANCES)

Online-Appendix: Appendix 19

TABLE 32

FULL MULTI CRITICAL ANALYSIS – ALTERNATIVE PLASTICS (HOUSEHOLD APPLIANCES)

Online-Appendix: Appendix 20

TABLE 33

FULL MULTI CRITICAL ANALYSIS – CONVENTIONAL PLASTICS (AUTOMOTIVE PARTS)

Online-Appendix: Appendix 21

TABLE 34

FULL MULTI CRITICAL ANALYSIS ALTERNATIVE PLASTICS (AUTOMOTIVE PARTS)

Online-Appendix: Appendix 22

TABLE 35

ADAPTED MULTI-CRITERIA ANALYSIS FOR COMPARING -PACKAGING (CONVENTIONAL PLASTIC)

Online-Appendix: Appendix 23

TABLE 36

ADAPTED MULTI-CRITERIA ANALYSIS FOR COMPARING -PACKAGING (ALTERNATIVE PLASTIC)

Online-Appendix: Appendix 24

TABLE 37

ADAPTED MULTI-CRITERIA ANALYSIS FOR COMPARING – HOUSEHOLD APPLIANCES (CONVENTIONAL PLASTIC)

Online-Appendix: Appendix 25

TABLE 38

ADAPTED MULTI-CRITERIA ANALYSIS FOR COMPARING – HOUSEHOLD APPLIANCES (ALTERNATIVE PLASTIC)

Online-Appendix: Appendix 26

TABLE 39

ADAPTED MULTI-CRITERIA ANALYSIS FOR COMPARING – AUTOMOTIVE PARTS (CONVENTIONAL PLASTIC)

Online-Appendix: Appendix 27

TABLE 40

ADAPTED MULTI-CRITERIA ANALYSIS FOR COMPARING – AUTOMOTIVE PARTS (ALTERNATIVE PLASTIC)