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“Challenges in plastic recycling and its contribution on food waste reduction and sustainability”

“Ioannis Venizelos”

Supervisor: “Tsiotras Georgios”

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“Challenges in plastic recycling and its contribution on food waste reduction and sustainability”

Ioannis Venizelos

Supervisor*:*
Tsiotras Georgios

Co-Supervisor:
Adamidis Emannouil

Patras, Greece, May 2026

“Acknowledgements and / or Dedication”

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“Ioannis Venizelos”

Supervising Committee

Supervisor:	Co-Supervisor:
“Tsiotras Georgios”	“Adamidis Emannouil”
Hellenic Open University	Hellenic Open University

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Abstract

In this thesis we examine the challenges that plastic recycling faces and evaluates how plastic packaging contributes to food waste reduction and sustainability in the frame of the European Union's Packaging and Packaging Waste Regulation (PPWR). Using a realistic, mixed-methods design based on secondary research, the study gathers evidence from literature, institutional reporting and regulatory sources. The findings indicate that recycling performance is limited by material complexity (especially multilayer structures), contamination and polymer degradation, while economic barriers and infrastructure gaps hinder collection and high-quality recycling. For food-contact packaging, chemical safety requirements and the risk of contaminant migration further restrict circularity. At the same time, evidence shows that packaging plays a critical role in preserving quality and extending shelf life, meaning that packaging changes must be assessed alongside food waste impacts. PPWR introduces binding targets on recyclability, recycled content, labelling and substance restrictions, accelerating the need for design-for-recycling and improved recycling systems. The study concludes that meaningful sustainability gains require integrated action across packaging design, recycling infrastructure and governance, supported by life-cycle thinking that accounts for food waste prevention. Recommendations are proposed for packaging producers and brand owners to prioritize recyclable designs, improve data and compliance documentation, and collaborate across the value chain to strengthen collection, sorting and food-grade recycled material supply.

Keywords

Plastic Recycling, PPWR, food waste, sustainability

Περίληψη

Η παρούσα διατριβή εξετάζει τις προκλήσεις που αντιμετωπίζει η ανακύκλωση πλαστικών και αξιολογεί πώς οι πλαστικές συσκευασίες συμβάλλουν στη μείωση των απορριμμάτων τροφίμων και στη βιωσιμότητα στο πλαίσιο του Κανονισμού της Ευρωπαϊκής Ένωσης για τις Συσκευασίες και τα Απορρίμματα Συσκευασίας (PPWR). Χρησιμοποιώντας έναν ρεαλιστικό σχεδιασμό μικτών μεθόδων που βασίζεται σε δευτερογενή έρευνα, η μελέτη συγκεντρώνει στοιχεία από βιβλιογραφία με κριτές, θεσμικές αναφορές και ρυθμιστικές πηγές. Τα ευρήματα δείχνουν ότι οι επιδόσεις ανακύκλωσης περιορίζονται από την πολυπλοκότητα των υλικών (ιδίως πολυστρωματικές δομές), τη μόλυνση και την υποβάθμιση των πολυμερών, ενώ οι οικονομικοί φραγμοί και τα κενά στις υποδομές εμποδίζουν τη συλλογή και την ανακύκλωση υψηλής ποιότητας. Για τις συσκευασίες που έρχονται σε επαφή με τρόφιμα, οι απαιτήσεις χημικής ασφάλειας και ο κίνδυνος μετανάστευσης ρύπων περιορίζουν περαιτέρω την κυκλικότητα. Ταυτόχρονα, τα στοιχεία δείχνουν ότι η συσκευασία διαδραματίζει κρίσιμο ρόλο στη διατήρηση της ποιότητας και στην παράταση της διάρκειας ζωής, πράγμα που σημαίνει ότι οι αλλαγές στη συσκευασία πρέπει να αξιολογούνται παράλληλα με τις επιπτώσεις στη σπατάλη τροφίμων. Το PPWR εισάγει δεσμευτικούς στόχους για την ανακυκλωσιμότητα, το ανακυκλωμένο περιεχόμενο, την επισήμανση και τους περιορισμούς ουσιών, επιταχύνοντας την ανάγκη για σχεδιασμό για ανακύκλωση και βελτιωμένα συστήματα ανακύκλωσης. Η μελέτη καταλήγει στο συμπέρασμα ότι τα σημαντικά οφέλη βιωσιμότητας απαιτούν ολοκληρωμένη δράση σε όλο το σχεδιασμό συσκευασιών, την υποδομή ανακύκλωσης και τη διακυβέρνηση, υποστηριζόμενη από τη σκέψη του κύκλου ζωής που λαμβάνει υπόψη την πρόληψη της σπατάλης τροφίμων. Προτείνονται συστάσεις για τους παραγωγούς συσκευασιών και τους ιδιοκτήτες εμπορικών σημάτων να δώσουν προτεραιότητα στα ανακυκλώσιμα σχέδια, να βελτιώσουν τα δεδομένα και την τεκμηρίωση συμμόρφωσης και να συνεργαστούν σε όλη την αλυσίδα αξίας για την ενίσχυση της συλλογής, της διαλογής και της προμήθειας ανακυκλωμένων υλικών για τρόφιμα.

Λέξεις Κλειδιά

Ανακύκλωση πλαστικών, PPWR, απόβλητα τροφίμων, βιωσιμότητα

Summary

Purpose and scope

This study analyses the technical and systemic challenges that constrain plastic recycling and assesses how plastic packaging contributes to reducing food waste and supporting sustainability, with particular attention to PPWR obligations.

Method

A realistic, bibliography approach was applied to accomplish this Thesis, using secondary sources: peer-reviewed research on food packaging and post-consumer plastic waste management LCA synthesis evidence comparing plastics with alternative materials policy guidelines and finally reach the objective to apply reports linking packaging to food waste. (Dolci et al., 2025)

Key findings

(1) Recycling is constrained by material complexity, contamination and polymer degradation, particularly for flexible and multilayer food packaging (L. Operato et al., 2025)

(2) Food-contact recycling requires stringent chemical safety control due to potential contaminants and migration concerns.

(3) LCA evidence indicates that plastics are not uniformly worse than alternatives, quite the opposite. The results and assessments depend on weight, reuse, and end-of-life assumptions, and recycled content can improve performance (Dolci et al., 2025).

(4) PPWR accelerates redesign and systems change through binding requirements for recyclability, recycled content, labelling, minimisation and restrictions on substances of concern.

Implications

For the industry, compliance will require portfolio-level redesign and stronger alignment with real recycling infrastructure, while sector evaluation suggests a significant share of current packaging may require to be redesigned to meet PPWR requirements.

For sustainability, packaging optimisation must be evaluated alongside food waste prevention because packaging supports increased shelf life and food safety.

Recommendations

Prioritise design-for-recycling (promote mono-material usage where feasible), improve packaging data and technical documentation, strengthen collaboration with recyclers and waste management to increase high-quality collection and sorting, and apply LCA-based decision support that includes food waste impacts (European Commission, n.d.; Dolci et al., 2025).

Introduction

Plastic packaging occupies a key and increasingly contested role within modern food systems. On one hand, it is widely recognised as a critical enabler of food safety, quality preservation, and supply chain efficiency. On the other hand, its environmental consequences, particularly in the form of persistent plastic waste and low recycling rates, have positioned it at the forefront of sustainability debates. This duality has created a complex policy and confusing landscape, where the imperative to reduce environmental impact must be carefully balanced against the functional necessity of packaging in preventing food loss and waste.

Over the past decades, global plastic production has increased significantly, driven by its versatility, durability, and cost-effectiveness. Plastic materials have become deeply embedded in food packaging applications due to their ability to provide essential barrier properties, protecting products from oxygen, moisture, light, and microbial contamination. These characteristics are particularly important within increasingly globalised food supply chains, where products often travel long distances and are stored for extended periods before consumption. Consequently, plastic packaging is not simply a container, but a functional component that supports the integrity of the food chain.

Nevertheless, the environmental implications associated with plastic waste have become a growing concern. Despite advances in recycling technologies and waste management systems, a substantial proportion of plastic packaging remains unrecycled, either being incinerated, landfilled, or leaking into the environment. This inefficiency reflects a broader challenge, rather than purely a technological limitation. Issues such as material complexity, insufficient collection infrastructure, economic disincentives, and consumer mis-sorting all contribute to suboptimal recycling outcomes. Within this context, plastic packaging is frequently criticised as a key contributor to environmental degradation, particularly in discussions surrounding marine pollution and resource depletion.

Parallel to the plastic waste challenge, food waste has emerged as a critical global issue. A significant proportion of food produced for human consumption is lost or wasted across the supply chain, resulting in significant environmental, economic, and social consequences. From an environmental perspective, food waste represents a misuse of resources, including water, energy and land, while also contributing to greenhouse gas emissions. Economically, it leads to inefficiencies and financial losses across the food system, while socially it raises concerns in a world where food insecurity remains prevalent. As a result, reducing food waste has become a priority within sustainability agendas, including the United Nations Sustainable Development Goals.

A key interaction between plastic waste and food waste, lies in the role of packaging. Packaging can significantly extend shelf life, protect products from contamination and facilitate portion control, drastically reducing the chances of spoilage and waste. For perishable products such as meat, dairy and fresh produce, the protective function of packaging can result in suffice reductions in food waste volume. In many cases, the environmental impact associated with the packaging material is considerably lower than that of the food product itself, meaning that effective packaging can yield net environmental benefits when it prevents food loss.

Nevertheless, the relationship between packaging and food waste is not straightforward.

Both can be positively or negative affected by numerous factors, which make the correlation hard to be distinct. While packaging extends shelf life at a product level, its effectiveness in reducing food waste is influenced by broader behavioural and systemic factors. For instance, consumers may over-purchase food, misinterpret expiry dates, or fail to store products appropriately, thereby negating the benefits provided by packaging. In such cases, longer shelf life does not necessarily translate into reduced waste, highlighting the importance of considering consumer behaviour alongside technological solutions.

At the same time, efforts to reduce plastic use, often driven by policy initiatives or public pressure, may inadvertently lead to unintended consequences. Substituting plastic with alternative materials such as paper, glass or metal does not automatically result in improved environmental outcomes. These materials may have higher energy requirements during production, increased transportation emissions due to weight, or lower performance in preserving food quality. As such, sustainability assessments must move beyond simplistic material comparisons and adopt a life-cycle perspective that considers the full range of environmental impacts, including those associated with food waste.

In response to these challenges, policymakers have begun to adopt more comprehensive regulatory approaches. Within the European Union, the Packaging and Packaging Waste Regulation (PPWR) represents a significant step towards harmonising packaging requirements and promoting circular economy principles. The regulation aims to reduce packaging waste, improve recyclability, increase the use of recycled content, and enhance consumer information through labelling. At the same time, it introduces restrictions on hazardous substances and imposes stricter requirements for food-contact materials, reflecting the need to balance circularity objectives with safety considerations.

The introduction of PPWR signals a shift from voluntary sustainability initiatives toward binding regulatory obligations. For industry stakeholders, this transition presents both challenges and opportunities. On one hand, companies must redesign packaging portfolios, invest in compliance systems and adapt to evolving market conditions. On the other hand, the regulation provides a framework for innovation, encouraging the development of more sustainable packaging solutions and fostering greater alignment between design, infrastructure and policy objectives.

Despite the growing body of research on plastic recycling, food waste, and sustainable packaging, there is still a notable fragmentation in the bibliography. Recycling studies often focus on material flows and technological processes, while food waste research tends to emphasise behavioural and supply chain factors. As a result, integrated analyses that simultaneously consider packaging functionality, recycling systems and food waste dynamics remain limited. This gap is particularly relevant in the context of regulatory developments such as PPWR, which require a holistic understanding of the interactions between different elements of the packaging system.

Furthermore, existing research frequently adopts a descriptive approach, identifying challenges without fully exploring their organic interdependencies. There is need for more critical and analytical perspectives that examine the underlying drivers of inefficiency within recycling systems and evaluate the trade-offs associated with different sustainability strategies. In particular, the assumption that improving recyclability will automatically lead to better environmental outcomes requires closer scrutiny, especially when food waste implications are considered.

Against this background, we aim to provide a comprehensive and integrated analysis of the challenges associated with plastic recycling and the role of plastic packaging in reducing food waste and supporting sustainability. The study is based on secondary data analysis, drawing on bibliography, policy documents, and institutional reports. By synthesising evidence across different domains, the research seeks to develop a more holistic understanding of the packaging system and its sustainability implications.

The specific objectives of the dissertation are multiples. First, it seeks to identify and critically evaluate the technical, economic challenges that constrain plastic recycling. This includes an examination of issues such as material complexity, contamination and infrastructure limitations, as well as broader market dynamics that influence recycling performance. Second, the study aims to assess the role of plastic packaging in preventing food waste across different stages of the supply chain, with particular attention to the conditions under which packaging delivers measurable benefits. Third, the research evaluates the implications of the PPWR for packaging design, recycling systems and industry practices, considering both the opportunities and the constraints associated with implementation. Finally, we aim to develop strategic recommendations for industry stakeholders, informed by a life-cycle perspective that integrates environmental, economic and functional considerations.

1.1 Problem Statement

Recycling systems struggle with mixed materials, contamination and quality degradation, while new regulatory requirements increasingly demand recyclable packaging and higher recycled content. In parallel, the food system depends on packaging to avoid premature spoilage. The resulting trade-offs create complex sustainability decisions for policymakers and industry.

1.2 Background of the Study

Packaging is widely used across the food sector, yet packaging waste is growing and remains difficult to recycle at scale. Recent EU policy developments, particularly the Packaging and Packaging Waste Regulation (PPWR), have intensified the need to redesign packaging for circularity (European Commission, n.d.).

1.3 Research Aim and Objectives

Aim: To analyse challenges in plastic recycling and assess its contribution to food waste reduction and sustainability.

Objectives: (i) review key technical and economic constraints, (ii) examine the role of packaging in preventing food waste, (iii) assess PPWR implications, (iv) propose strategic recommendations.

1.4 Research Questions

In addressing these objectives, the study is guided by the following research questions:

- What are the dominant technical, economic and regulatory challenges limiting plastic recycling?
- How does plastic packaging contribute to food waste reduction across the supply chain?
- How does the PPWR influence packaging design and circular economy strategies?
- What strategic actions can support the transition toward sustainable packaging systems while maintaining food safety and performance?

To answer these questions, the research adopts a realistic point of view philosophy, recognising that complex sustainability challenges require flexible and problem-oriented approaches. By integrating insights from different sources and analytical perspectives, the study aims to generate findings that are both academically robust and practically relevant for industry decision-making.

Ultimately, achieving sustainability in packaging systems requires a shift from isolated interventions toward integrated system optimisation. Rather than viewing plastic packaging solely as an environmental problem or as a solution to food waste, it should be understood as part of a broader socio-technical system characterised by interdependent variables and trade-offs. Effective sustainability strategies must therefore balance multiple objectives, including resource efficiency, waste minimisation, food protection and regulatory compliance.

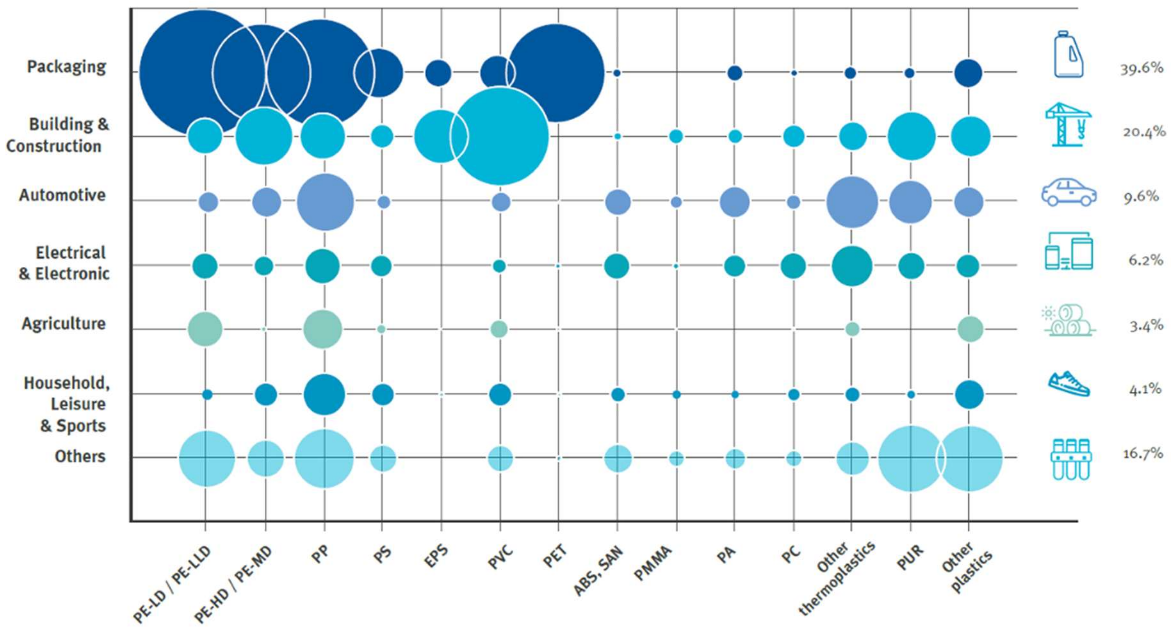
In conclusion, the study contributes to the existing literature by providing a more combined understanding of the relationship between plastic recycling, food waste and sustainability. It highlights the limitations of current approaches and proposes a more holistic framework for decision-making, aligned with both policy developments and industry realities. Through this integrated perspective, the research seeks to support the development of packaging systems that are not only more circular, but also more effective in delivering overall sustainability outcomes. (Saunders, 2022).

2. Literature Review

2.1 The History and Initiation of the Plastic Industry

The development of plastics as industrial materials represents one of the most transformative technological advancements of the twentieth century. Initially celebrated for their versatility, durability, and low cost, plastics rapidly became indispensable across multiple sectors, particularly in packaging.

Figure 2 Breakdown Plastic usage per sector



Source: Cabrera, G., Li, J., Maazouz, A. & Lamnawar, K. (2022)

Yet, the same characteristics that enabled their widespread adoption (persistence, resistance to degradation, and chemical stability) have also led to significant environmental challenges. Understanding the historical evolution of the plastic industry is therefore essential to contextualising current debates surrounding sustainability, recycling and regulatory intervention.

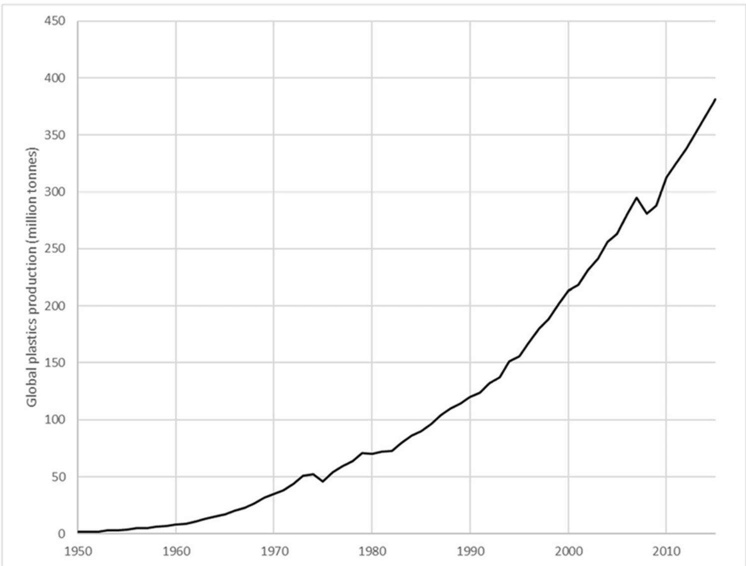
2.1.1 Early Development and Industrial Expansion

Synthetic plastics first appeared in the early twentieth century with the invention of Bakelite in 1907, often described as the first fully synthetic polymer. This marked a major shift in materials science, as manufacturers gained access to lightweight and durable alternatives to glass, metal and wood. During the following decades, advances in polymer chemistry led to the widespread use of materials such as polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET).

After the Second World War, demand for plastics grew rapidly because they were cheap, flexible and easy to produce at scale. Over time, plastics became essential in manufacturing, consumer goods and infrastructure. However, this growth was mainly driven by performance and cost, with little attention given to end-of-life management.

By the late twentieth century, packaging had become the main application of plastics. This was especially true in the food sector, where plastics offered strong barrier properties, hygiene and product protection. These advantages explain why plastics remain so widely used in food packaging today.

Figure 3 Global Plastic Production (mil tones)



Source : Hatem Alhazmi 1 ,Faris H. Almansour 2 and Zaid Aldhafeeri

2.1.2 Integration into Food Systems and Supply Chains

The integration of plastics into food systems is closely linked to broader transformations in production and distribution. As food supply chains became increasingly globalised, the need for materials capable of extending shelf life and maintaining product integrity became more critical. Plastics fulfilled this role through their ability to provide effective barriers against oxygen, moisture and microbial contamination.

In particular, the development of multilayer packaging technologies represented a significant innovation. By combining different materials, multilayer structures enabled manufacturers to optimise performance characteristics tailored to specific products. For example, layers may be designed to provide structural strength, oxygen barriers or moisture resistance, collectively enhancing food preservation. While these innovations improved functionality, they also introduced significant complexity at the end-of-life stage.

The multilayer packaging, despite its functional benefits, poses important recycling challenges due to its composite structure and strong interlayer adhesion. This illustrates a broader pattern in the evolution of the plastic industry: innovations driven by performance optimisation often generate unintended consequences for waste management and circularity. (Ciawi et al., 2025)

2.1.3 Emergence of Environmental Concerns

By the late twentieth and early twenty-first centuries, the environmental implications of plastic use became increasingly visible. Accumulation of plastic waste in landfills and natural environments, particularly in marine ecosystems, raised concerns about the long-term sustainability of plastic consumption patterns. At the same time, recycling rates remained relatively low, highlighting systemic inefficiencies in waste management.

Research indicates that less than 10% of global plastic waste has been effectively recycled, underscoring the scale of the challenge. This low recovery rate reflects a combination of technical constraints, economic barriers and behavioural factors, rather than a single point of failure. These challenges are deeply rooted in the historical evolution of plastics, where materials were designed primarily for performance and cost efficiency, with limited consideration for recyclability.

The environmental critique of plastics has therefore shifted from a focus on material properties to a broader systems perspective. It is increasingly recognised that the plastic waste problem cannot be addressed solely through technological improvements in recycling, but requires a fundamental rethinking of material design, consumption patterns, and waste management systems.

2.1.4 Transition Toward Circular Economy Thinking

The plastic industry has grown along trajectories shaped by decades of technological development, economic incentives, and consumer expectations. As a result, many of the current challenges, such as the prevalence of non-recyclable multilayer packaging, are not merely technical issues, but the legacy of past design choices.

This bond from the past creates structural barriers to change. For example, redesigning packaging to improve recyclability may require compromising in performance, cost, quality or supply chain compatibility. Similarly, transitioning to alternative materials may not always yield better environmental outcomes, as these materials often introduce their own limitations. This reinforces the need for systemic thinking, where solutions are evaluated in terms of their overall impact rather than isolated criteria.

In response to these challenges, the concept of the circular economy has emerged as a dominant framework for rethinking material use. Unlike traditional linear models of production and consumption, the circular economy emphasises resource efficiency, waste reduction and closed-loop systems. Within this framework, plastics are not viewed as waste, but as valuable resources that should be retained within the economic system for as long as possible.

Recycling plays a central role in this transition, but its effectiveness is contingent upon multiple factors, including material design, infrastructure availability, and market demand for recycled materials. As highlighted in reviews of plastic recycling technologies, different recycling methods exhibit distinct environmental and economic characteristics, with trade-offs between energy use, material quality and scalability. Mechanical recycling, for example, is widely deployed but sensitive to contamination and material degradation, while chemical recycling offers greater flexibility in feedstock but is often constrained by energy intensity and cost. (Dolci et al., 2025)

This diversity of recycling solutions reflects the complexity of achieving circularity in practice. It also highlights the limitations of relying on recycling alone as a solution to plastic waste. Instead, a more integrated approach is required, encompassing upstream design decisions, improved collection systems and supportive policy frameworks.

2.1.5 Implications for Sustainability and Policy

The historical evolution of plastics has important implications for contemporary sustainability strategies and policy development. Regulatory interventions such as the European Union's Packaging and Packaging Waste Regulation (PPWR) can be understood as attempts to correct systemic inefficiencies by redefining the rules governing packaging design and waste management.

Sustainability-related progress in the plastics sector remains limited. Only around 1% of innovation in plastics is considered environmentally significant, while bioplastics, although expanding, still account for only a very small share of total plastic production—approximately 0.5% to 1%. (OECD 2023)

Nevertheless, the success of such policies depends on their ability to address the underlying causes of the plastic waste problem, rather than its symptoms. This includes aligning incentives across the value chain, promoting design-for-recycling principles and ensuring that infrastructure capacity matches regulatory ambition. Without such alignment, there is a risk that policies may impose constraints without delivering the intended environmental benefits.

2.2 Overview of Plastic Recycling Processes and Systems

Plastic recycling is widely positioned as a central mechanism for achieving circularity within modern material systems. Despite significant technological innovation, recycling remains constrained by a combination of technical, economic, and systemic limitations. An in-depth understanding of recycling processes and their operational contexts is therefore essential to evaluate their effectiveness and their role in supporting sustainable packaging systems. This section critically examines the main recycling models (mechanical and chemical) alongside broader system-level considerations that influence performance outcomes.

2.2.1 Mechanical Recycling: Principles and Limitations

Mechanical recycling is the most established and widely implemented approach for processing post-consumer plastic waste. The process typically involves collection, sorting, washing, shredding, and reprocessing plastic materials into secondary raw materials, commonly in the form of pellets that can be reused in manufacturing. Its widespread deployment is largely due to its relatively low energy requirements and technological maturity compared to alternative recycling pathways.

The effectiveness of mechanical recycling is highly dependent on the quality and purity of input streams. Contamination from food residues, additives and non-target polymers can significantly reduce the efficiency of processing and the quality of the recycled output. Research consistently highlights that contamination represents one of the most significant barriers to high-quality recycling processes, as it can lead to material degradation and limits the applicability of recycled solutions in high-performance or food-contact applications.

Furthermore, polymer degradation presents an inherent limitation of mechanical recycling. During repeated processing cycles, the thermal and mechanical stresses applied to plastics result in a gradual reduction in material properties, such as tensile strength and barrier performance. This degradation often necessitates the blending of recycled polymers with virgin materials or limits their use to lower-value applications, commonly referred to as "downcycling." (Kaiser, K., Schmid, M. & Schlummer, M. 2018).

A critical implication of these limitations is that mechanical recycling does not inherently create a closed-loop system. Instead, it often operates as a cascade system, where materials move progressively toward lower value uses until they are ultimately disposed of. This challenges the assumption that recycling alone can achieve material circularity, particularly in high performance applications such as food packaging.

Figure 4 Existing Mechanical Recycling Loop

Source: UN News 2026

2.2.2 Chemical Recycling: Potential and Constraints

Chemical advanced recycling encompasses a range of technologies designed to break down plastic polymers into their constituent monomers or other chemical feedstocks. These processes include pyrolysis, gasification, depolymerisation and enzymatic recycling, each offering different directions for material recovery.

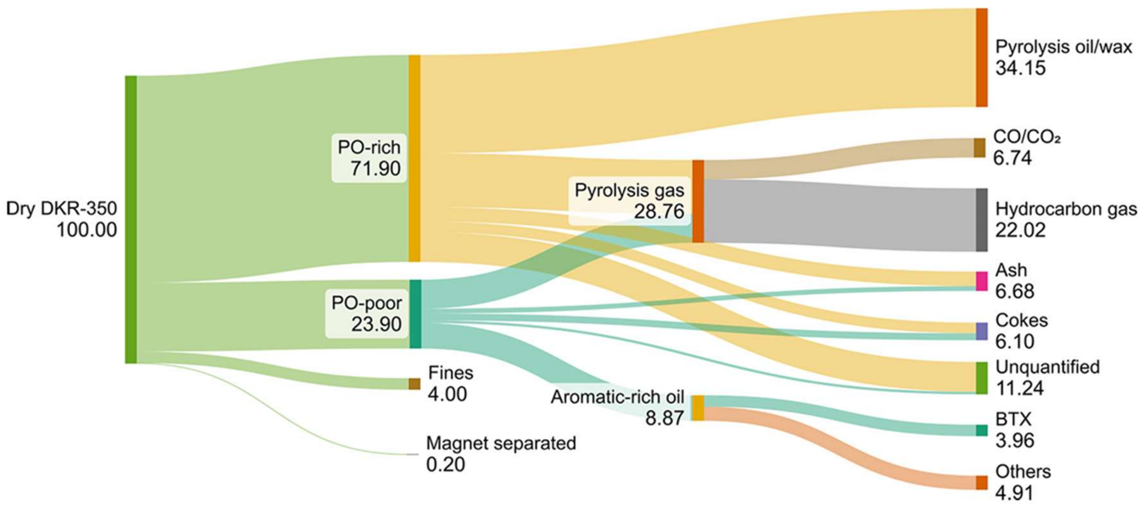
One of the primary advantages of chemical recycling is its ability to process more complex and contaminated plastic waste streams. Unlike mechanical recycling, which requires relatively clean and homogeneous materials, chemical processes can handle mixed or multilayer plastics, potentially expanding the range of materials that can be recycled. This is particularly relevant in the context of food packaging, where multilayer structures are prevalent due to their superior barrier properties.

In theory, chemical recycling offers the possibility of producing materials with properties equivalent to virgin polymers, enabling true closed-loop recycling. In practice though, significant challenges remain. Chemical recycling processes are often energy-intensive and associated with high operational costs, which can limit their economic viability.

Moreover, scalability remains a critical constraint. While pilot projects and industrial-scale facilities are emerging, chemical recycling technologies have yet to achieve widespread deployment comparable to mechanical recycling. This raises questions about their capacity to contribute meaningfully to large-scale circularity in the short to medium term.

Another important consideration is the environmental impact of chemical recycling itself. The high energy requirements associated with processes such as pyrolysis may offset some of the environmental benefits of recycling, particularly if energy sources are carbon intensive. This highlights the importance of evaluating recycling technologies through life-cycle assessment (LCA) methodologies, which consider the full range of environmental impacts rather than focusing solely on waste reduction. (ISPT, 2025)

Figure 4 Breakdown mixed plastic waste



Source: ISTP 2025

2.2.3 Multilayer Packaging as a Structural Challenge

The multilayer materials are engineered to provide high-performance barrier properties by combining multiple polymers, often bonded through adhesives or tie layers. While this design enhances functionality, it simultaneously complicates recycling processes.

The separation of different layers within multilayer packaging is technically complex and often economically unfeasible. As a result, such materials are frequently excluded from conventional recycling streams. Studies highlight that multilayer packaging lacks a universally viable recycling solution under current technological and economic conditions, despite ongoing research into innovative approaches such as selective dissolution and enzymatic degradation. (Cabrera et al., 2022)

This creates a fundamental tension between functionality and recyclability. Packaging systems optimised for food protection are often those least compatible with existing recycling infrastructure. This reinforces the need for design-for-recycling strategies, which seek to balance performance requirements with end-of-life considerations.

2.2.4 System-Level Constraints on Recycling Performance

Recycling performance depends not only on technology but also on wider system factors, including collection infrastructure, sorting capacity, economic incentives, and consumer behaviour.

Collection rates represent a critical determinant of recycling performance. Even the most advanced recycling technologies cannot operate effectively without sufficient feedstock. In many regions, inadequate collection systems and inconsistent waste segregation practices limit the availability of recyclable materials. Consumer behaviour, including incorrect sorting and contamination of recyclables, further exacerbates these challenges.

Sorting technologies also play a pivotal role in determining the quality of recycling streams. Automated sorting systems, such as near-infrared (NIR) technologies, have improved the ability to separate materials by polymer type. Their effectiveness is limited when dealing with complex or composite materials, such as multilayer packaging or heavily contaminated waste streams.

Economic factors further influence recycling outcomes. The cost of collecting, sorting, and processing plastic waste often exceeds the market value of the resulting recycled materials, particularly when oil prices are low and virgin plastics are relatively inexpensive. This creates a structural economic barrier to recycling, requiring policy interventions such as subsidies or extended producer responsibility (EPR).

Recycling thus, is not solely a technological challenge but a complex one. Improvements in recycling outcomes therefore require coordinated action across the entire value chain, including design, collection, processing and market development.

2.2.5 Critical Evaluation: Limits of Recycling as a Sustainability Strategy

While recycling is an essential component of circular economy strategies, its limitations must be critically acknowledged. A key issue is the widespread perception that increasing recycling rates alone will solve the plastic waste problem. This assumption overlooks the complexities and inefficiencies inherent in current recycling systems.

From a systems perspective, recycling should be viewed as one element within a broader hierarchy of waste management strategies, which also includes reduction, reuse and recovery. In many cases, upstream interventions, such as reducing material use or redesigning products for reuse, may offer more effective ways to sustainability than downstream recycling.

Moreover, the effectiveness of recycling must be evaluated in conjunction with its environmental impacts, rather than in isolation. As highlighted in LCA, different recycling technologies exhibit varying environmental profiles, and their benefits are highly context dependent. (Alhazmi et al., 2021)

Another critical limitation relates to the mismatch between design intentions and infrastructure capabilities. Packaging that is theoretically recyclable may not be recycled in practice if suitable collection and processing systems are not available. This distinction between “recyclable” and “actually recycled” is particularly important in the context of regulatory frameworks such as the PPWR, which emphasise design criteria but must also account for real world system performance.

2.3 Challenges in Plastic Recycling

Although recycling is often positioned as the primary pathway for improving plastic circularity, actual recycling performance is constrained by a set of interacting technical, economic, behavioural and regulatory factors. In practice, recycling outcomes are not determined by “recyclability” as a theoretical property of a material alone, but by system performance across the entire value chain, starting from packaging design and consumer use to collection, sorting, and reprocessing. This section composes the dominant challenges identified across the evidence base and critically evaluates why these barriers persist, particularly for food packaging applications.

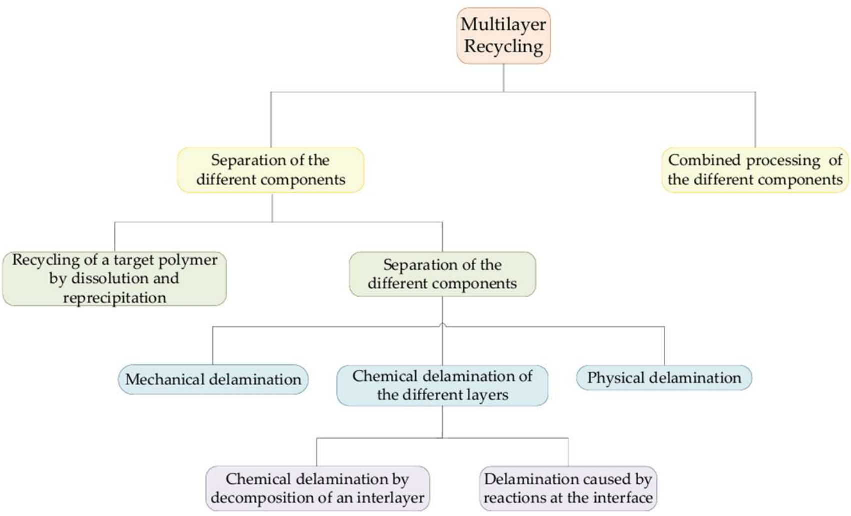
2.3.1 Material complexity and design incompatibility

One of the main barriers to high-quality recycling is the use of complex packaging, especially multi-material and multilayer formats. These structures are designed to give strong barrier performance against oxygen, moisture and light, but they are difficult to separate at the end of life. Multilayer films often combine different polymers, adhesives, coatings and sometimes non-plastic layers. This improves functionality but makes recycling much harder. As a result, flexible multilayer packaging is especially problematic because strong bonding between layers and mixed material chemistry reduce the quality and consistency of recycled output. (Cabrera et al., 2022)

Polymer incompatibility is another key issue. When different polymers are melted together in mechanical recycling, differences in melting point, viscosity and phase behaviour can weaken the final material. This reduces mechanical performance and limits where the recycled plastic can be used. In practice, composite packaging often faces higher rejection rates, lower reprocessing yields and more downcycling. These are not isolated problems. They reflect the fact that packaging has historically been designed for performance rather than compatibility with recycling systems.

In short, multilayer films remain difficult to recycle because functionality and circularity often pull in different directions. Proposed solutions such as delamination, selective dissolution-precipitation and chemical recycling show promise, but they are still limited by cost, environmental impacts and scale-up challenges. Even when they work in laboratory or pilot settings, applying them at industrial scale remains difficult. (Mahmoudi et al., 2025)

Figure 5 Schematic overview of the introduced recycling methods of multilayer



Source: MDPI, Recycling of Polymer-Based Multilayer Packaging

2.3.2 Contamination and feedstock quality constraints

A second major barrier is contamination, which affects both recycling efficiency and the quality and safety of recycled material. Contamination can come from food residues, inks, adhesives, labels, incompatible polymers and unwanted materials entering collection streams. Mechanical recycling is especially sensitive to these factors because they can cause discoloration, odour, weaker material performance and unstable processing. Reviews of recycling technologies consistently identify contamination and poor sorting and cleaning as major limits on both technical performance and economic viability.

Contamination is not just an operational problem. It shows how packaging is actually used and collected. In food packaging, contamination risks are higher because materials come into direct contact with food and often include complex printing and adhesive systems. This creates a persistent gap between design intent and system reality. In circular economy terms, it shows that packaging must be designed not only for performance, but also for realistic disposal and sorting conditions. (Mahmoudi et al., 2025)

Contamination also affects economics downstream. Heavily contaminated bales need more washing, sorting and processing, which raises costs and reduces profitability. This means that even when recycling is technically possible, it may still not be financially viable without policy support or stronger market incentives.

2.3.3 Polymer degradation and the limits of repeated mechanical recycling

Polymer degradation is widely reported as an inherent limitation of mechanical recycling. Reprocessing exposes plastics to heat, oxygen and shear stress, which can shorten polymer chains and alter molecular weight distribution. Over multiple cycles, this leads to measurable deterioration in mechanical properties (e.g., strength, elongation), optical clarity and barrier performance. These limitations contribute to “downcycling”, where recycled plastics are diverted toward less demanding applications, reducing the potential for closed-loop circularity, particularly in high-performance packaging uses. (L. Operato et al., 2025).

Degradation introduces a critical question for circular economy claims: even if collection and sorting improve, how many cycles can a polymer realistically undergo before performance loss makes it unsuitable for its original application? Stabilisers, additives, compatibilisers and blending strategies in general, can partially mitigate degradation, but these solutions add complexity and may introduce trade-offs (e.g., cost, additive safety considerations, or reduced recyclability in subsequent cycles). (Mahmoudi et al., 2025)

This reinforces the idea that recycling performance is shaped by system-wide design: material choices, additive systems, and product specifications define the feasible number of loops in practice. Consequently, policies and corporate sustainability targets that implicitly assume perpetual recycling may overstate achievable circularity, especially for demanding applications such as food-contact packaging.

2.3.4 Infrastructure constraints: collection, sorting

A consistent theme in the sources is that recycling outcomes are strongly determined by infrastructure capacity and consistency. Even when packaging is technically "recyclable", it may not be recycled if (i) it is not collected, (ii) sorting systems cannot reliably separate it, or (iii) re-processors do not have viable routes for that material stream. This creates a widely recognised distinction between "ready to recycle" and "actually recycled" packaging.

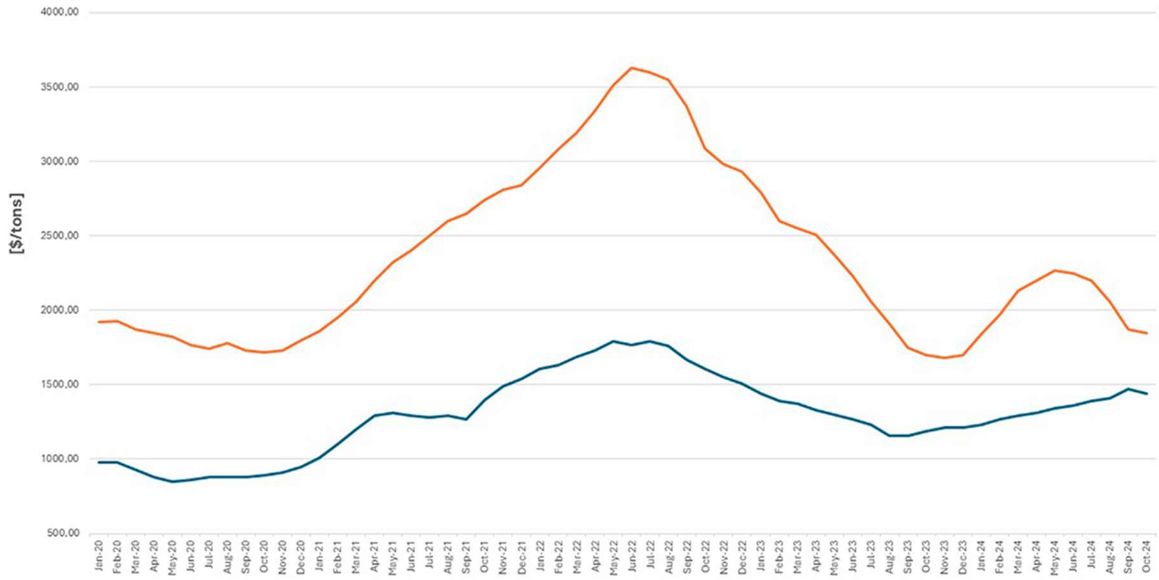
Sorting technology is a core bottleneck. Systems such as near-infrared (NIR) sorting can separate polymers effectively under certain conditions, yet performance drops for dark materials, complex composites and heavily contaminated items. When packaging formats are small, lightweight, or multi-component (e.g., films with closures, labels, or coatings), capture and sorting efficiency can decline substantially, leading to losses at material recovery facility (MRF) stage. This is treated as a structural limitation of existing infrastructure rather than a temporary gap, particularly for flexible packaging. (Mahmoudi et al., 2025).

In addition, recycling systems are geographically heterogeneous. Collection systems, sorting capabilities, and reprocessing capacity vary across regions, meaning that a packaging format may be recycled in one market but not in another. This has direct relevance for EU-wide harmonisation objectives and for PPWR's emphasis on recyclability requirements. Regulatory ambition must be aligned with actual system readiness to avoid "paper compliance" that does not translate into real circularity outcomes.

2.3.5 Economic barriers and weak market incentives for recycle

Economic constraints are repeatedly identified as a decisive barrier to scaling recycling, even where technical feasibility exists. Costs arise across the recycling chain (collection, transport, sorting, washing and reprocessing), while revenues depend on the market value of recycle and the stability of demand. When virgin polymer prices are low (often linked to fossil feedstock pricing), recycled materials struggle to compete on price, particularly if quality is variable due to contamination and mixed streams. Orderly reviews emphasise that mechanical recycling is often constrained by economic barriers driven by contamination and inefficiencies in sorting and cleaning.

Figure 6 EU Prices EU of APET vs R-PET (food grade)



Source: Food packaging use and post-consumer plastic waste management

A key insight is that recycling markets are not purely technological markets, they are institutional and policy-shaped markets. Without mechanisms that internalise externalities (e.g., EPR fees, recycled content mandates, landfill/incineration taxes, or procurement policies), recycling may remain under-scaled relative to sustainability ambitions. This is especially relevant for packaging formats that require significant infrastructure investment to become recyclable at scale (e.g., flexible packaging). (L. Operato et al., 2025)

In practical terms, this reinforces the importance of evaluating recycling through a system lens: the economics of recycling are influenced not only by process costs but by policy design, market governance, and the availability of stable, high-quality feedstock.

2.3.6 Food-contact safety challenges

Food-contact packaging introduces an additional layer of complexity that constrains circularity. Unlike many non-food applications, recycled plastics used in food-contact materials must meet strict safety standards due to the risk of contaminants migrating into food. Food packaging plastics can potentially contain thousands of substances used during manufacturing (e.g., stabilisers, pigments and plasticisers), and additional contaminants may enter during use and collection, creating migration and safety concerns. This risk may arise from previous use, cross-contamination from non-food plastic streams, or the presence of inks, adhesives, and non-intentionally added substances (NIAS). Therefore, recycled plastics for food contact require rigorous cleaning and regulatory review to achieve equivalence with virgin materials. (UN News) (FAO 2019). These constraints are explicitly highlighted in international and EU-focused discussions of recycled plastics for food use. (OECD, 2023).

Moreover, the food-contact constraint interacts with the earlier challenges: contamination, multilayer complexity and degradation, that all increase uncertainty regarding chemical composition and migration behaviour. Consequently, high-quality closed-loop recycling is most feasible where input streams are tightly controlled (e.g., well-managed PET bottle-to-bottle loops) and where decontamination efficacy can be demonstrated credibly. Is also important that traceability and process controls are implemented. (Adam et al., 2025),

Packaging has historically been engineered to optimise performance and cost under a linear economy logic (sell, use, dispose). Recycling systems in contrast, require standardisation, separability, and stable feedstock quality, conditions that are difficult to achieve when products are diverse, heavily branded, and used inconsistently across households and supply chains. (Mahmoudi et al., 2025)

Recycling performance is shaped by customization: the extent to which packaging designs are compatible with collection and sorting realities, and the extent to which market and policy structures support investment in high-quality recycling. This logic also clarifies why policy interventions such as the EU's PPWR explicitly aim to harmonise packaging standards, improve recyclability and strengthen system conditions for circularity.

2.3.7 Transition to the next section

These recycling limits matter because they affect the real sustainability performance of packaging systems. If a packaging format is theoretically recyclable but is not actually collected, sorted, or turned into usable recycled material, claims about circularity and environmental benefits may be exaggerated. At the same time, if better recycling depends on energy-intensive processes or high solvent use, new environmental trade-offs can arise. This leads directly to the next section, which explores how Life Cycle Assessment (LCA) is used to evaluate sustainability and why methodological choices can strongly influence packaging comparisons.

2.4 The Role of Plastic Recycling in Sustainability and LCA

Life Cycle Assessment (LCA) is one of the most widely used tools for evaluating the environmental implications of packaging systems and plastic recycling. LCA adopts a life-cycle perspective by accounting for impacts across stages such as raw material extraction, polymer production, conversion, distribution, use, and end-of-life management. This perspective is particularly relevant to plastics because the sustainability debate is frequently shaped by narrow end-of-life narratives (e.g., litter, landfilling, incineration), while outstanding impacts may occur upstream (e.g., fossil feedstock extraction and polymer manufacturing) or downstream through replacement materials and waste-management counterfactuals. A major review of plastics' life-cycle environmental impacts highlights that life-cycle approaches have, become instrumental in revealing previously underappreciated impacts and trade-offs across the plastics value chain. (ISPT, n.d.).

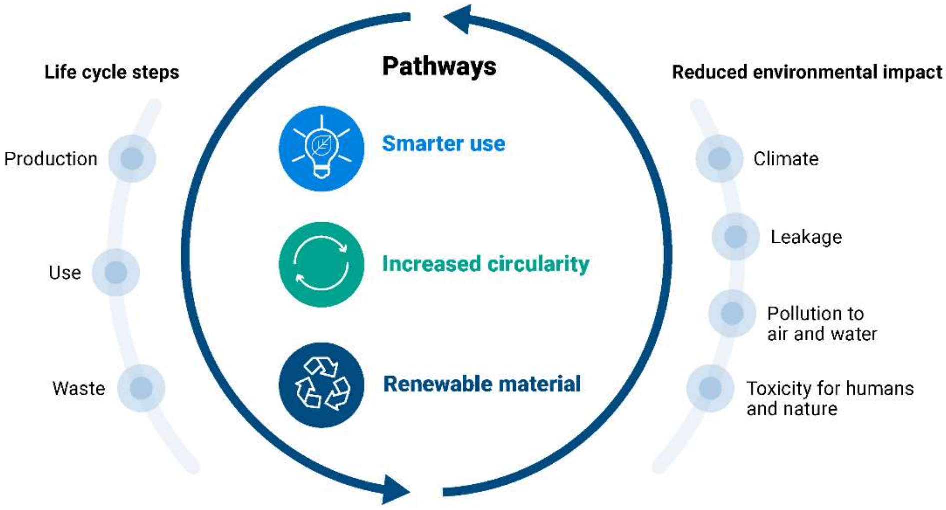


Figure 7 :Pathways towards sustainable and circular plastics

Source: Pathways towards circular plastics in Europe (by the EEA and the ETC/CE)

2.4.1 Why LCA is central to packaging sustainability decisions

Packaging is a system intervention rather than a stand-alone product: it exists to protect, preserve, portion, and communicate. Accordingly, the environmental performance of packaging cannot be evaluated solely by mass, material type, or recyclability label. LCA is valuable because it can compare alternative packaging options on a consistent functional basis (e.g., delivery of a defined quantity of food in a safe condition), while accounting for trade-offs such as transport weight, material intensity, energy use and end-of-life performance. Packaging LCAs have found that conventional plastics are not uniformly the poorest option: outcomes vary by material type, weight, reuse patterns, and end-of-life assumptions. In many cases, heavier alternatives (e.g., glass) can incur transport-related burdens, and reuse assumptions can dominate outcomes.

Within this framing, plastic recycling is important not only because it diverts waste from disposal but because it may reduce demand for virgin polymer production. The increasing recycled polymer content can significantly improve the environmental performance of plastic packaging (Dolci et al., 2025). If recycled polymers can substitute for primary materials at meaningful ratios, the avoided upstream burdens can be significant. The magnitude of this benefit depends on quality, feasible substitution, and whether recycling is modelled as closed-loop (replacing the same material/function) or open-loop (replacing a different material/function). These modelling choices explain why LCA conclusions sometimes conflict across studies and why “recycling is better” cannot be asserted without context. A review of plastic waste-management LCAs emphasises that results vary widely because studies differ in key methodological parameters, including goals and scope, functional units, impact categories, system boundaries, geographical context, and uncertainty analysis.

2.4.2 Core LCA design choices that shape conclusions about recycling

Functional unit. The functional unit defines what is being delivered (the service), and it can fundamentally change what "better" means. In plastics recycling, an influential perspective argues that assessing recycling systems per "tonne of waste managed" can produce different conclusions from assessing them per "tonne of recycled product yielded." The implication for packaging is direct: an LCA focusing on waste diversion may favour options that handle mixed waste volumes, whereas an LCA focusing on high-quality recycled output may favour options that deliver higher-purity recycled raw materials, even if they divert less total mass.

System boundaries and counterfactuals. LCA results are highly sensitive to what is included and what is assumed to happen otherwise (the counterfactual). For example, recycling benefits are often calculated relative to landfilling or incineration. Yet the counterfactual can differ across geographies and infrastructures, and excluding or including transport, sorting losses, contamination treatment, or energy recovery can alter outcomes. Reviews of plastic waste-management LCAs highlight that boundary choices (including transport and other factors) can materially shift results, which reinforces the need for transparent scope definition and scenario testing.

Allocation and substitution Many LCAs assign recycling benefits via avoided virgin production (substitution). This requires defensible assumptions about what the recycled material replaces. If recycling is downcycled into lower-grade applications, substitution may be partial rather than one-to-one. This issue is central to plastic recycling because mechanical recycling can suffer from polymer degradation and contamination that reduce performance and narrow applications. Consequently, substitution ratios and the choice between closed-loop and open-loop modelling are not technical details; they are decisive drivers of results.

End-of-life leakage and broader impact metrics. A further methodological concern is that many LCAs focus heavily on climate impacts (e.g. greenhouse gases) while underrepresenting other relevant outcomes such as plastic pollution and fossil carbon accounting. The LCA recommendations perspective argues for expanding plastics-recycling LCAs beyond greenhouse gases and including additional metrics such as fossil carbon balances, net diversion from landfill, and avoided release of plastic waste to the environment. This is particularly relevant for packaging debates, where public concern often centres on litter and environmental leakage rather than climate impacts alone.

2.4.3 Comparing recycling through LCA: mechanical vs chemical recycling

LCA is frequently used to compare mechanical and chemical recycling routes, but conclusions are often conditional. Evidence on plastic recycling technologies indicates that different methods present distinct environmental and economic characteristics: mechanical recycling can encounter economic barriers due to contamination and inefficiencies in sorting and cleaning, while thermolysis/chemical routes are constrained by high energy demands and operational costs; chemical and biological approaches also face scalability and cost limitations. These characteristics translate directly into LCA profiles: higher energy intensity tends to increase climate impacts unless offset by effective avoidance of virgin polymer production or powered by low-carbon energy.

The assumption that chemical recycling automatically delivers superior environmental outcomes simply because it can process more heterogeneous feedstocks, is not correct. The energy requirements and process yields become central: if yields are low or energy demand is high, benefits may diminish. Conversely, if chemical recycling produces outputs that substitute virgin feedstocks at high rates, it may deliver meaningful upstream savings—again underscoring that substitution assumptions and functional units must be explicit. The continuous review of plastic recycling highlights that research increasingly seeks lower-energy routes (including improved pretreatment and emerging techniques), indicating that current performance constraints are recognised and actively targeted.

2.4.4 Packaging LCAs and the plastics alternatives

Packaging sustainability debates often reduce to a perceived hierarchy of materials (e.g. “paper good, plastic bad”). LCA philosophy rejects such simplification because outcomes depend on product system design, weight, reuse, and end-of-life realities, where concludes that plastics are not consistently the worst-performing option and that heavier materials (such as glass) can incur transport burdens. It also points that reuse strategies can be decisive in reducing impacts and supports the major argument that sustainability cannot be assessed from material identity alone; it must be evaluated as a system delivering a defined service.

Additionally, LCA indicates that increasing recycled polymer content can improve environmental performance of plastic packaging, which aligns with policy directions that emphasise recycled content targets. The extent of improvement depends on actual recycled content quality, availability, and the impacts of collection and reprocessing. Therefore, the sustainability benefit of recycled content cannot be treated as a constant, it is contingent on the recycling system's efficiency and the degree to which recycled content displaces virgin production.

2.4.5 Integrating food waste into packaging LCAs

A major conceptual limitation of many packaging LCAs is that they assess packaging impacts without fully integrating the environmental burden of food waste. Packaging exists primarily to protect food. If packaging changes increase spoilage or reduce shelf life, the overall environmental outcome can worsen even if packaging impacts decrease. Your dissertation already foregrounds this point by noting that packaging decisions should be assessed alongside food waste impacts because packaging can protect food and extend shelf life, and food loss can carry an environmental footprint that exceeds packaging production and end-of-life.

From an LCA perspective, integrating food waste requires explicit modelling of: (i) the baseline spoilage rate, (ii) the change in spoilage attributable to packaging design changes, and (iii) the life-cycle impacts of the wasted food itself. This integration is methodologically challenging but necessary for credible conclusions in food packaging. It also reframes "recycling" as only one lever among several: a packaging format that is marginally less recyclable but substantially reduces food waste could outperform an alternative that is easier to recycle but increases spoilage. This is consistent with the broader LCA critique that research questions and functional units must reflect the actual service delivered (food preservation and delivery), not merely the management of packaging waste.

2.4.6 Critical appraisal: what LCA can and cannot decide

LCA is powerful, but it is not a mechanical "truth machine." It produces structured comparisons under specified assumptions, and it is most informative when paired with sensitivity analysis and transparent reporting. Reviews of LCA studies in plastic waste management stress that methodological variation is widespread and can materially influence conclusions. Accordingly, uncertainty analysis and scenario testing are central to responsible interpretation.

A balanced position is to treat LCA as (i) essential for avoiding intuitive but misleading material narratives, and (ii) constrained by modelling choices that should be explicitly justified. The most defensible way to use LCA in packaging strategy is therefore comparative and scenario-based: evaluate plausible end-of-life routes, realistic substitution ratios for recycling and the effect of packaging on food waste, rather than relying on single-point estimates.

2.4.7 Implications for industry strategy and regulatory alignment

Recycling-oriented sustainability strategies should prioritise not only "can it be recycled?" but also to "will it be collected, sorted, and reprocessed into a product that credibly displaces virgin material?" This distinction aligns the challenges identified in plastic recycling reviews (contamination, sorting inefficiencies, economic barriers, and energy intensity for advanced routes). It also aligns with the LCA recommendations that emphasise choosing functional units that reflect recycled product yield and incorporating broader metrics beyond climate alone.

For packaging portfolios under tightening policy constraints (including PPWR's emphasis on recyclability and recycled content), LCA can support prioritisation decisions by identifying where recycled content delivers meaningful net benefit, where redesign improves real-world circularity, and where food waste prevention dominates the environmental outcome. This argument acts as a bridge from technical recycling challenges to PPWR-driven strategic choices.

2.5 Overview of the Packaging and Packaging Waste Regulation (PPWR)

The European Union’s Packaging and Packaging Waste Regulation (PPWR) represents a significant transition in the governance of packaging systems, shifting from a directive-based framework toward a directly applicable regulation with harmonised requirements across all Member States. This regulatory evolution reflects a broader policy ambition to accelerate the transition toward a circular economy by addressing inefficiencies in packaging design, waste management, and material recovery. Although PPWR introduces a comprehensive set of measures targeting sustainability, recyclability, and waste reduction, its effectiveness depends on its alignment with technical feasibility and system-level realities identified in the preceding sections.

2.5.1 From Directive to Regulation:

Before the Packaging and Packaging Waste Directive (PPWD), the EU members followed individual paths on recyclability, driven by national legislations. This approach resulted in fragmented implementation, varying standards, and inconsistent enforcement across countries. PPWR replaces this system with a directly applicable regulation, thereby eliminating the need for national transposition and aiming to ensure uniform compliance across the EU market.

This structural shift is particularly important for industry stakeholders operating across multiple jurisdictions, as it reduces regulatory complexity and creates a more predictable compliance environment. At the same time, it increases the level of obligation, as non-compliance with a regulation carries direct legal and market consequences, including restrictions on placing non-compliant packaging on the EU market. (OECD, 2023)

Expanding this to a global level, we can easily conclude, that heterogeneity among continents and nations on the legal frame is enormous.

2.5.2 Core Objectives of PPWR

PPWR is designed around several interrelated objectives that reflect circular economy principles:

- Reduction of packaging waste
- Improved recyclability of all packaging

- Increased use of recycled content
- Promotion of reuse and refill systems
- Harmonisation of labelling and consumer information
- Restriction of substances of concern (e.g., PFAS)

The regulation emphasises lifecycle thinking, extending regulatory oversight across production, use, and end-of-life stages. By targeting both upstream design and downstream waste management, PPWR seeks to address systemic inefficiencies that have historically limited recycling performance.

2.5.3 Recyclability Requirements and Mono Materials

One of the most significant provisions of PPWR is the requirement that all packaging placed on the EU market must be recyclable by 2030.

This requirement is further operationalised through recyclability performance criteria, including Quantitative thresholds for recyclability (e.g. percentage of material that can be effectively recovered), classification systems (e.g. recyclability grades), potential restrictions on packaging that falls below minimum performance levels.

From a theoretical perspective, this marks a shift from voluntary design-for-recycling principles toward mandatory compliance. The critical question now is the feasibility. Many packaging formats, particularly multilayer and flexible structures, are inherently difficult to recycle due to material incompatibility and infrastructure limitations. The regulation therefore exposes a tendency: it assumes that packaging can be redesigned to meet recyclability criteria, while existing evidence suggests that technical constraints may limit this transition in practice.

This trend highlights that designed recyclability on packaging, under ideal conditions may not be effectively achieved in real-world systems, due to collection gaps, sorting limitations, and economic constraints.

Skipping the complexity of the individual polymers, promoting trends towards Mono-Material Packaging are increasing. Consortiums such as Ceflex and RecyClass creating further efforts to increase recyclability from the perspective of the producers. In coordination with the actual recycling infrastructures these efforts aiming to maximize content of recyclable components in the structures and avoidance of hazardous materials or non-recyclables. (Camila Tavora de M.S, 2020)

2.5.4 Recycled Content Targets and Market Dynamics

In addition to design requirements, PPWR introduces mandatory minimum recycled content targets for plastic packaging, to be phased in over time. These targets are intended to stimulate demand for recycled plastics, encourage investment in recycling infrastructure and reduce reliance on virgin fossil-based materials.

The effectiveness of recycled content mandates depends on the availability of high-quality recycling. Recycling streams currently face significant constraints related to contamination, degradation, and feedstock variability. These factors limit the supply of food-grade recycled materials, particularly for sensitive applications such as food-contact packaging.

A further complexity arises from competition for high-quality recycling, especially for materials like PET, where closed-loop recycling (e.g., bottle-to-bottle) is already well established. If demand for recycled materials drastically increases without a proportional increase in supply, recycled content targets may lead to market distortions, higher material costs, or reliance on imports. For instance, fossil crisis in the past has increased on the spot the demand for Recycled Polyester which consequently drive to higher prices than virgin material.

From an LCA perspective, this raises important questions about substitution: if recycled content displaces virgin production, environmental benefits may be significant. If supply constraints limit substitution or lead to indirect effects (e.g., shifting recycling between sectors), net benefits may be reduced. (OECD, 2023)

2.5.5 Labelling, Consumer Behaviour, and Recycling streams

PPWR also introduces harmonised labelling requirements designed to improve consumer understanding and participation in waste sorting. Packaging must provide clear, standardised information regarding material composition and disposal solutions.

This measure reflects an important recognition that consumer behaviour plays a critical role in recycling performance. Contamination at the household level is a key barrier to high-quality recycling. Improved labelling aims to reduce mis-sorting and increase the quality of collected materials.

It is evident that the effectiveness of labelling depends on broader system conditions. Even if consumers correctly sort packaging, the impact remains limited if collection systems are inconsistent, sorting infrastructure is inadequate and reprocessing capacity is insufficient.

This reinforces a systems perspective: behavioural interventions must be aligned with infrastructure capabilities to deliver meaningful outcomes.

2.5.6 Restrictions on Hazardous Substances and Food-Contact Packaging

A particularly challenging aspect of PPWR relates to restrictions on substances of concern, including the regulation of chemicals used in food-contact packaging (e.g., PFAS).

These provisions reflect growing concerns regarding chemical safety and the potential risks associated with recycled materials. Recycled plastics may contain contaminants originating from previous use, additives, or degradation processes. Regulatory frameworks therefore require that recycled materials meet strict safety standards equivalent to virgin materials.

This creates a fundamental trade-off between circularity and safety: Increasing recycled content may introduce variability and contamination risks, while ensuring safety may limit the use of recycled materials in certain applications.

Closed-loop systems with controlled input streams (e.g., PET bottles) are more compatible with food-contact requirements, while open-loop systems or mixed waste streams face greater regulatory barriers. This implies that PPWR's circularity objectives must be implemented selectively, with consideration of material-specific and application-specific constraints.

2.5.7 Ambition and Implementation of PPWR

PPWR can be understood as a response to existing failures in the packaging system, aiming to realign incentives and create regulatory pressure for innovation. The success of the regulation depends on its ability to address the underlying drivers of inefficiency rather than imposing design constraints in isolation, where the challenges are formed:

- Technical constraints: Not all packaging formats can be easily redesigned for recyclability

- Infrastructure gaps: Collection and sorting systems are not uniformly developed across the EU
- Economic barriers: Recycling may remain uncompetitive without strong policy support
- Safety limitations: Food-contact applications impose strict constraints on recycled materials

These challenges highlighting the risk of policy versus practice misalignment, where regulatory requirements outpace system readiness. In such cases, compliance may be achieved formally (e.g., redesigning packaging to meet recyclability criteria) without delivering actual improvements in recycling rates or environmental outcomes.

At the same time, PPWR should not be interpreted solely as a constraint. It also creates opportunities for innovation in material design (e.g., mono-material solutions), investment in recycling technologies and infrastructure, development of new business models (e.g., reuse and refill systems), improved transparency and accountability in packaging systems.

The interpretation of PPWR has a central role on the evaluation, as poses significant step towards improvements. Sustainability in packaging cannot be achieved through isolated interventions but requires integrated system transformation. The regulation attempts to operationalise circular economy principles by targeting multiple stages of the packaging lifecycle, yet its effectiveness depends on alignment with technological capabilities, market conditions, and behavioural factors:

- Designing for recyclability may conflict with packaging performance and food protection
- Increasing recycled content may conflict with safety requirements
- Reducing packaging material may increase food waste under certain conditions

These interdependencies highlighting the need for decision-making frameworks that integrate recycling, food waste, and regulatory compliance into a coherent strategy.

The EU Packaging and Packaging Waste Regulation (PPWR) represents a policy shift toward harmonised, binding requirements across all members. The European Commission describes PPWR as targeting less wasteful, more recyclable and clearly labelled packaging, including measures such as recycled content requirements, improved labelling, minimisation of unnecessary packaging, and restrictions on hazardous substances like PFAS in food-contact packaging.

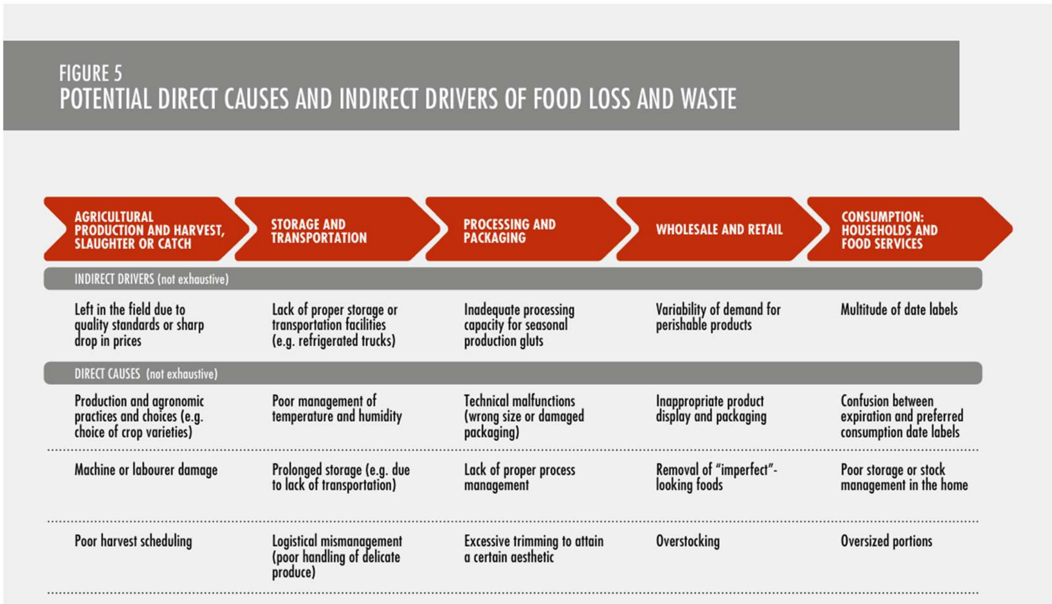
The PPWR regulation entered into force on the 11th of February 2025, and the provision is to be implemented from 12 August 2026, with further obligations phased in. It additionally notes that all packaging must be recyclable by 2030, that packaging will be classified within recyclability levels, and that chemical safety restrictions (including PFAS-related measures) are relevant for food-contact packaging. PPWR is characterised as a dynamic framework likely to require redesign of a substantial share of current packaging solutions and highlights major topic clusters such as waste reduction targets, recyclability requirements, recycled content targets, and labelling and EPR mechanisms.

For packaging producers and food brands, PPWR implies stronger alignment between design-for-recycling principles and the capabilities of real recycling infrastructure. It also implies an increased demand for high-quality post-consumer recycled materials, which may intensify competition for compliant recycled and place pressure on supply chains.

2.6 Plastic Packaging and Food Waste Reduction

When we talk about food, most of us think about meals, nutrition, and the joy of eating, without considering how much of this food never even reaches our plates. Food waste is a global problem, which direct or indirect affects households, restaurants, farms and retailers.

Figure 8 Potential Direct causes of Food Lost & Waste



Source: FAO report 2019, The state of Food and Agriculture

To understand the scale of this loss every day, 1 billion meals are thrown away, water that could have nourished crops is wasted, and greenhouse gas emissions increase because discarded food ends up rotting in landfills. While countries spend billions of dollars producing food that never gets eaten, at the same time millions of people around the world remain hungry. This isn't just an environmental issue anymore; it's an economic drain, a social problem, and an ethical challenge for the society.

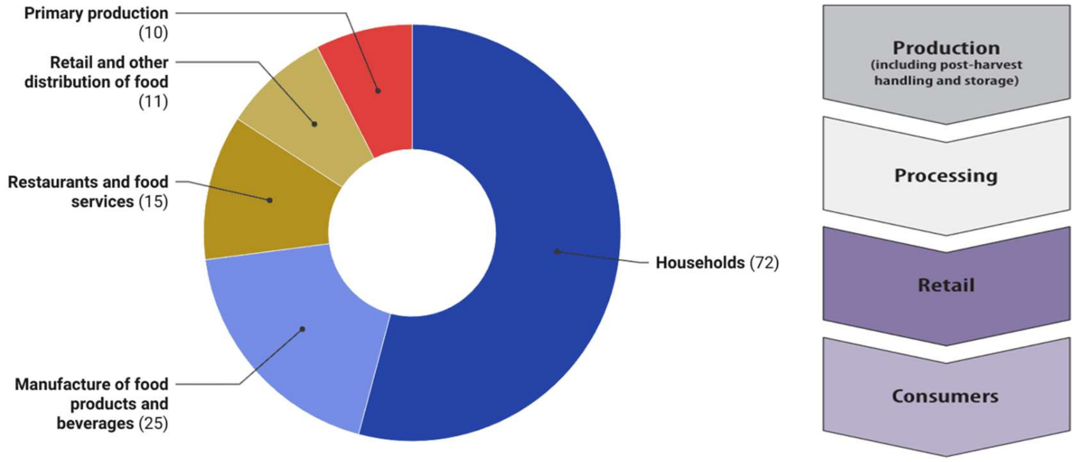
Figure 9

(Source: statista.com)

2.6.1 Plastic Packaging and Food Waste Reduction

The terms of food waste and food loss are quite recent, therefore statistics and bibliography cannot monitor the full extent of the problem and the precise size of it. Approximately 1.05 billion tonnes of food are wasted each year, valued at around $1 trillion. A common assumption in food packaging research is that extending shelf life inherently reduces food waste. While longer shelf life increases the window for consumption, this does not necessarily lead into reduced food waste particularly in households where overstocks is a common practice. In such cases, packaging delays spoilage, but not disposal.

Figure 10 Food Waste in the EU, by main economic sectors (2022) – Kgr/habitant



Source: Sci-Tech Today

To better understand the distribution of food waste and food loss we limit our research on European Union. Households generate more than half of the total food waste (72%) in the EU. The remaining 40% was waste generated upwards in the food supply chain, with main contributor with 25% the manufactures of food products and beverages.

The relationship between plastic packaging and food waste reduction is one of the most critical and contested dimensions within the broader sustainability debate on packaging. While plastic packaging is frequently criticised for its environmental burden, a growing trend emphasises its role in preserving food quality, extending shelf life and engaging efficiently supply chains. This relationship though is not linear, nor universally beneficial. It is rather mediated by behavioural, technological and systemic factors. This section critically evaluates the role of plastic packaging in reducing food waste, integrating insights from life-cycle thinking, consumer behaviour research and system-level analysis.

2.6.2 Packaging as a Functional Enabler of Food Preservation

Plastic packaging plays a fundamental role in modern food systems by protecting products from external factors such as oxygen, moisture, light and microbial contamination. These barrier properties are particularly important for perishable goods, where even minor deterioration can lead to spoilage. By extending shelf life, packaging increases the time available for consumption, thereby reducing the likelihood of premature disposal.

Evidence consistently supports the view that packaging contributes to food waste reduction at multiple stages of the supply chain, including transportation, retail, and household consumption. Packaging allows food to be transported over long distances while maintaining quality, facilitates storage in retail environments, and helps consumers manage consumption over time. This protective function is widely recognised as essential to modern global food distribution systems.

While packaging provides the potential to reduce food waste, this benefit is inherently conditional. It depends not only on packaging performance but also on how food is handled, stored and consumed within the supply chain. As such, packaging should be understood as an enabler, rather than a guarantee of food waste reduction.

2.6.3 The Environmental Trade-Off: Packaging vs Food Waste

The environmental impact of food products often exceeds that of their packaging. This has important implications for sustainability decision-making. If packaging prevents food waste, even a small reduction in spoilage may offset the environmental burden associated with packaging production and disposal.

From a life-cycle perspective, food waste represents a loss of all upstream resources, including water, energy, land and labour. When food is discarded, these embedded impacts are effectively wasted. Therefore, strategies that reduce food waste may yield greater environmental benefits than those that focus solely on minimizing packaging material.

This trade-off challenges the assumption that reducing packaging is inherently beneficial. In some cases, reducing packaging (especially for vulnerable products) may increase food waste, resulting in higher overall environmental impacts. This reinforces the need for integrated LCA approaches that evaluate packaging and food systems together, rather than in isolation.

2.6.4 Behavioural Factors and the Limits of Packaging Effectiveness

Despite its technical capabilities, packaging does not operate in a behavioural vacuum. Consumer practices play a decisive role in determining whether extended shelf life translates into reduced food waste. Research highlights that consumer behaviour is a critical leverage point in food waste reduction and that packaging interacts with behavioural patterns in complex ways.

Several behavioural factors limit the effectiveness of packaging:

- Over-purchasing: Consumers often buy more food than they can consume within the available time, regardless of packaging shelf-life extension.
- Misinterpretation of expiry labels: Confusion between "use by" and "best before" dates lead to premature disposal.
- Improper storage practices: Failure to store food correctly reduces actual shelf life, undermining packaging benefits.
- Low awareness of packaging functionality: Consumers may not fully utilise features such as reseal-ability or portioning.

In addition, research suggests that specific packaging features can influence consumer behaviour, sometimes in unintended ways. For example, attributes such as packaging transparency may affect perceptions of freshness and monitoring behaviour, potentially reducing or increasing food waste depending on context.

These findings underscore a critical point: the effectiveness of packaging in reducing food waste is mediated by how consumers interact with it. Therefore, technical improvements in packaging must be complemented by behavioural interventions, such as improved labelling, education, and user-centred design.

2.6.5 Packaging Design and Food Waste Outcomes

Packaging design plays a significant role in shaping food waste outcomes. Features such as portion size, re-sealable, ease of opening, and transparency can influence how consumers use and manage food products. We observe though a misalignment between packaging design priorities and consumer needs.

A recent scoping review indicates that packaging attributes perceived as important by consumers -such as usability, dispensing mechanisms, and ergonomic design are often under-represented in research and development efforts. This suggests that packaging is frequently designed with a focus on production efficiency, branding, or shelf appeal, rather than on facilitating effective consumption and reducing waste.

Furthermore, certain design choices may have conflicting effects. For instance:

- Large package sizes may reduce packaging material per unit but increase the risk of food spoilage at household level
- Small, portioned packaging may reduce waste but increase packaging material use
- High-barrier multilayer packaging improves shelf life but reduces recyclability

These trade-offs illustrate the multi-dimensional nature of packaging design decisions, where performance, sustainability, and usability must be balanced.

2.6.6 System-Level Perspective: Where Packaging Adds Value

A distinction-level understanding requires identifying where packaging delivers the greatest value in reducing food waste across the supply chain. Packaging is particularly effective in protecting highly perishable products (e.g., meat, dairy, fresh produce), supporting long-distance transportation and distribution, enabling portion control and extended consumption at household level.

Conversely, packaging may provide limited value in contexts where products are consumed quickly and locally, consumer behaviour dominates waste outcomes (e.g., over-purchasing) and packaging functions are poorly aligned with actual usage patterns.

This perspective aligns with system-based approaches that emphasise context-specific optimisation. Rather than applying uniform packaging reduction strategies, it is more effective to evaluate the role of packaging for each product category and usage context.

2.6.7 Packaging Reduction vs Sustainability

The common idea that less plastic packaging always means more sustainability needs to be reconsidered. Reducing packaging is important, but not if it increases food spoilage or waste. Looking only at the amount of packaging can lead to the wrong conclusion. Less packaging can increase spoilage and food waste, while increased packaging can add environmental impact without offering real benefits. The best approach is not simply to use less or more packaging, but to use the right amount for the right purpose.

This argument supports a shift from material substitution (e.g., replacing plastic with alternative materials) toward systems optimisation frameworks which should integrate:

- Packaging performance
- Food waste prevention
- Recycling feasibility
- Consumer behaviour
- Regulatory requirements

2.6.8 Link to Dissertation Argument

The plastic packaging sustainability and the food waste reduction cannot be evaluated separately, but require a combined perspective:

- Packaging contributes significantly to food waste reduction, but only under certain conditions
- Behavioural and system factors often limit the realisation of packaging benefits
- Environmental trade-offs between packaging and food waste are context-dependent
- Design decisions must balance functionality, circularity, and usability

These insights are directly relevant to the evaluation of plastic recycling and PPWR requirements. As regulatory pressure increases to improve recyclability and reduce packaging waste, it is essential that such measures do not increase food waste or compromise food safety.

Packaging, particularly in retail and distribution level plays a key role for reducing food loss and waste along with preserving quality and extending shelf life. Addressing both food and packaging waste requires system redesign rather than simple material substitution. Sustainability strategies must consider where packaging adds measurable shelf-life value and where it does not. Over-reduction of packaging can increase food waste if protective functions are compromised, while over-packaging can add environmental burden with limited benefits. Therefore, packaging optimisation requires a careful evaluation of product-specific spoilage dynamics and the end-of-life feasibility of the selected packaging format.

2.7 Research Gaps

Despite the expanding body of publications examining plastic recycling, sustainable packaging, and food waste, significant gaps remain that limit scientific understanding and practical application. These gaps are not simply areas of incomplete knowledge, but reflect deeper fragmentation across research domains, methodological inconsistencies, and the emerging nature of regulatory frameworks such as the Packaging and Packaging Waste Regulation (PPWR).

2.7.1 Fragmentation between Recycling and Food Waste Research

One of the most prominent gaps in the bibliography is the lack of integration between plastic recycling studies and food waste research. Existing research tends to focus on these topics in isolation:

- Recycling studies primarily analyse material flows, process efficiencies, and technological innovations.
- Food waste research focuses on consumer behaviour, supply chain inefficiencies, and resource loss.

While both fields contribute valuable insights, their separation results in an incomplete understanding of packaging sustainability. As highlighted in earlier sections, packaging plays a dual role: it contributes to environmental burden through waste generation while simultaneously preventing food losses whose impacts may be significantly higher.

This creates an important limitation. Current decision-making frameworks often do not fully capture the trade-offs between packaging and food waste at the system level. As a result, strategies that aim to improve recyclability or reduce plastic use may unintentionally increase food waste and weaken overall sustainability outcomes.

2.7.2 Limited Evidence on PPWR Implementation

A significant gap relates to the limited evidence on the real-world impacts of PPWR, which remains a relatively new regulatory framework. While the frame and the industry reports outline the expected effects of the regulation, there is currently a lack of:

- Data on actual compliance across different packaging formats
- Data on the effectiveness of recyclability criteria in practice

- Assessment of how recycled content targets influence market dynamics
- Evaluation of unintended consequences (e.g., design trade-offs, cost impacts)

This lack of empirical data is particularly relevant for complex packaging applications, such as multilayer flexible films, where technical and economic constraints are most pronounced. These structures involve significant challenges for both recyclability and compliance but remain widely used due to their functional performance.

Consequently, there is a need for research and development that bridges the gap between regulatory ambition and operational reality, providing proved insights into how PPWR requirements translate into practical design and business decisions.

2.7.3 Methodological Limitations in Life Cycle Assessment Studies

Although LCA is widely used to evaluate packaging sustainability, there is significant methodological variability that constrain comparability and reliability of findings, with most important limitations:

- Differences in functional units (e.g., packaging mass vs product protection)
- Variation in system boundaries and inclusion/exclusion of lifecycle stages
- Inconsistent treatment of recycling processes and substitution assumptions
- Limited integration of food waste impacts into LCA models

These choices can significantly change conclusions about how plastics compare with alternative materials. If food waste impacts are left out or given too little attention, packaging assessments remain incomplete. Therefore, a key research gap lies in the development of more consistent, transparent, and integrated LCA frameworks that can account for both packaging and food system interactions. (Molina-Besch, K., Wikström, F. & Williams, H., 2019)

2.7.4 Insufficient Focus on Behavioural and Systemic Interactions

While consumer behaviour is widely recognised as a major driver of food waste, its interaction with packaging design and recycling systems remains underexplored. Existing studies often analyse:

- Consumer behaviour independently of packaging design
- Packaging performance independently of user interaction

Nevertheless, as demonstrated in Section 2.6, the effectiveness of packaging in reducing food waste is highly dependent on how consumers use, interpret, and manage packaged products. A recent review highlights that consumer behaviour remains a critical leverage point in food waste reduction, while is often insufficiently integrated into packaging design research.

This creates a gap in understanding how:

- Packaging features influence real-world consumer behaviour
- Behavioural patterns affect recycling outcomes (e.g., contamination)
- System-level interventions (e.g., labelling, education) can be optimised

Addressing this gap requires a more interdisciplinary approach that combines engineering, behavioural science, and policy analysis.

2.7.5 Lack of Decision-Support Tools for Industry

From a practical perspective, a significant gap exists in translating academic research into actionable guidance for industry stakeholders. Companies must navigate complex and often conflicting requirements, including:

- Achieving recyclability under PPWR
- Incorporating recycled content
- Maintaining food safety and product performance
- Minimising overall environmental impact

Tthe sources provide limited structured frameworks that integrate these dimensions into decision-making processes. Instead, research tends to focus on individual aspects (e.g., material selection, recycling technologies, or consumer behaviour) without offering a comprehensive approach.

This gap is particularly relevant in the context of packaging innovation, where decisions must balance technical feasibility, regulatory compliance, cost, and sustainability performance. As a result, there is a clear need for integrated decision-support models that can guide industry practitioners in optimising packaging systems under multiple constraints.

2.7.6 Synthesis of Research Gaps

The gaps identified above can be summarized into three major themes:

Lack of Integration

- Separation between recycling, food waste, and behavioural research
- Limited system-level analysis of packaging sustainability

Limited Empirical and Methodological Consistency

- Insufficient real-world cases on PPWR implementation
- Variability in LCA methodologies and assumptions

Gap between Theory and Practice

- Lack of actionable frameworks for industry decision-making
- Limited translation of research into operational strategies

2.7.7 Contribution of This Dissertation

In response to these gaps, we aim to provide a more integrated and practical analysis by:

- Combining insights from recycling systems, food waste dynamics, and regulatory frameworks
- Critically evaluating sustainability trade-offs using an LCA-informed perspective
- Assessing PPWR implications in relation to real-world constraints
- Proposing strategic recommendations and frameworks for industry application

By bridging the divide between scientific research and industry needs, the study contributes to a more holistic understanding of packaging sustainability and supports the development of solutions that are both environmentally effective and operationally feasible.

3. Research Methodology

3.1 Introduction

This chapter outlines the methodological framework adopted to investigate the challenges associated with plastic recycling and to evaluate the role of plastic packaging in reducing food waste within a sustainability and regulatory context. In particular, the research is positioned against the evolving requirements of the European Union's Packaging and Packaging Waste Regulation (PPWR), which introduces significant structural changes to packaging design and waste management systems.

The methodology is designed to address the research gaps, particularly the fragmentation between recycling and food waste literature, the limited empirical proofs on regulatory implementation, and the lack of integrated decision-making frameworks for industry. In response, the study adopts an approach that combines theoretical depth with applied relevance, enabling a comprehensive examination of the interdependencies between packaging systems, consumer behaviour and environmental outcomes.

Given the complexity of the research topic, which spans technical, behavioural, environmental and regulatory dimensions, the study does not rely on a single methodological tradition. Instead, it adopts a flexible and integrative design that allows for the form of multiple forms of acknowledgment and the development of a system-level understanding.

3.2 Research Structure

This study follows a pragmatist approach because the topic is complex and needs a flexible method. It combines existing theories such as circular economy and life cycle assessment, while the bibliography is also used to identify new themes and patterns. Based its facts on secondary sources, including scientific studies, policy documents and institutional reports, aim to produce solid analysis and practical recommendations. Conclusions from previous studies provide support and context for generating meaningful insights.

Rather than relying on primary data collection, the study focuses on the integration and critical evaluation of existing knowledge across multiple domains. This format allows the research focus on main targets and objectives and the extraction of high-quality academic, institutional, and policy results.

3.3 Data Collection

Data are drawn from three main categories.

(1) Policy and regulatory sources: EU institutional materials (e.g., European Commission explanations of PPWR) and sector guidance documents outlining PPWR timelines and requirements relevant to food packaging.

(2) Research papers: Acknowledgment from scientific papers on recycling systems, packaging functions, and LCA-based comparisons of packaging materials.

(3) Institutional reports: reports that addressing food waste and packaging, including publications that link packaging decisions to retail food waste dynamics.

3.4 Data Analysis

The analysis is primarily based on thematic settlement, which allows for the coherent organisation and interpretation of complex qualitative data. Through this process, the literature is analysed to identify recurring patterns and relationships, which are then grouped into key thematic categories aligned with the research questions.

The analysis focuses on four overarching themes: technical challenges in plastic recycling, systemic and economic constraints, the role of packaging in food waste reduction, and the influence of regulatory frameworks such as PPWR. These themes are not treated independently but are examined in relation to one another, reflecting the interconnected nature of the packaging system.

In addition to thematic analysis, the study incorporates comparative evaluation based on findings from LCA research. This enables the assessment of environmental trade-offs between different packaging solutions and highlights the influence of methodological choices on sustainability outcomes.

Triangulation is used to enhance the robustness of the analysis. By comparing findings from different types of sources, academic papers, policy documents, and institutional reports, the study ensures that conclusions are not based on a single perspective. Where multiple sources converge on a particular finding, this is interpreted as strengthening the validity of the result.

3.5 Reliability and Validity

The reliability of the research is supported by the usage of high-quality, peer-reviewed, and institutional sources, as well as by the transparent documentation of the data collection and analysis process. Consistency is maintained through the application of a structured analytical framework across all sections of the study.

Validity is addressed through the alignment between the research objectives, methodology, and analytical approach. The use of multiple data sources allows for cross-verification of findings, while the critical evaluation of assumptions particularly in relation to LCA and policy analysis, ensures that conclusions are grounded in evidence.

It is important to acknowledge that the reliance on secondary data introduces certain limitations. The researcher does not have control over data generation, and the availability of up-to-date empirical information (particularly in relation to PPWR) is limited. These constraints are addressed through cautious interpretation and by emphasising patterns and trends rather than precise quantification.

3.6 Ethical Considerations

As the study is based entirely on secondary data, it does not involve human participants or sensitive personal information. Consequently, ethical considerations are primarily related to the responsible use of sources.

All sources are accurately cited and represented, ensuring that original authors' findings are not misinterpreted or taken out of context. The research presents solid outcomes, avoiding plagiarism and maintaining transparency in the presentation of data and interpretation of findings.

Content relies on publicly available secondary sources and does not collect personal data. Ethical practice therefore focuses on accurate representation of sources, and transparent reporting of assumptions.

Limitations include dependence on secondary data (which may not be updated to current market developments) and limited availability of metrics across studies and countries. Additionally, PPWR implementation is ongoing, so presumptions on its full effects is emerging rather than mature.

3.7 Methodological Limitations

While the chosen methodology enables a comprehensive and integrative analysis, it also has inherent limitations. The absence of primary data collection means that the study cannot provide direct empirical validation of its findings, particularly in relation to industry practices or consumer behaviour.

In addition, the reliance on existing publications may introduce biases linked to the focus areas of previous research. For example, recycling studies may prioritise technical aspects, while behavioural studies may emphasise consumer perspectives, potentially limiting full integration.

Finally, the complexity of the research topic makes it challenging to quantify certain trade-offs, particularly those between packaging reduction and food waste. These limitations are acknowledged as part of the research design and do not detract from the value of the study, which lies in its integrative and analytical approach.

4. Findings

4.1 Introduction to the Findings

This chapter presents the outcome derived from the careful analysis of secondary data sources, including academic bibliography, policy documents, and institutional reports. The aim is not merely to report observations, but to interpret patterns across the evidence pool and identify the structural mechanisms shaping plastic recycling performance and its relationship to food waste reduction.

Plastic recycling remains constrained by a combination of technical limitations, economic factors, safety requirements for food-contact applications, and misalignment between packaging design and recycling infrastructure (L. Operato et al., 2025).

The conclusions are organised around seven key themes that emerged consistently across the literature:
(1) material complexity and design incompatibility,
(2) contamination and recycling efficiency,
(3) polymer degradation and downcycling dynamics,
(4) food-contact safety constraints,
(5) sustainability trade-offs and LCA,
(6) packaging as a lever for food waste reduction, and
(7) PPWR as a system-level driver of change

These themes are not independent. They interact within a broader system, shaping real-world sustainability outcomes.

4.2.1 Material Complexity and Design Incompatibility

The analysis confirms that packaging design represents a primary determinant of recycling outcomes. In particular, the widespread use of multi-material and multilayer packaging introduces structural incompatibilities within current recycling systems. Primary packaging can be more complex than secondary or tertiary packaging, and these complex combinations can hinder sorting and reprocessing, limiting recyclability (L. Operato et al., 2025).

Multilayer packaging, while functionally advantageous, poses critical challenges for recycling processes due to the difficulty of separating bonded materials and the incompatibility of mixed polymers during reprocessing. This leads to reduced recycled quality and increased rejection rates.

From a systems perspective, this finding reveals a deeper structural issue: packaging design decisions are historically optimised for performance, not for end-of-life recovery. As a result, recycling systems must handle materials that were never designed to be circular, creating persistent inefficiencies.

Moreover, attempts to address this issue through design-for-recycling approaches face inherent barriers. Simplifying material structures (e.g., moving toward mono-material packaging) may improve recyclability but can reduce barrier performance, potentially affecting product shelf life. This reinforces the argument that packaging design cannot be optimised along a single dimension.

4.2.2 Contamination and Recycling Efficiency

A second dominant finding concerns the role of contamination in limiting recycling efficiency. Contamination from food residues, additives, and foreign materials significantly reduces the quality and usability of recycled polymers.

Contamination increases processing requirements, reduces yield, and contributes to downcycling. In mechanical recycling systems, even small levels of contamination can lead to defects or instability in the final material, limiting its application in higher value uses and contribute to downcycling (L. Operato et al., 2025).

Importantly, contamination is not solely a technical issue but reflects system-level misalignment between product design, consumer behaviour, and waste management infrastructure. For example:

- Packaging is often designed without considering ease of cleaning or separation
- Consumers may incorrectly sort waste, introducing non-recyclable materials
- Collection systems may lack standardisation across regions

These finding highlights that improving recycling rates requires interventions beyond technology, including behavioural and system-level changes.

4.2.3 Polymer Degradation and Downcycling Dynamics

The analysis also confirms that polymer degradation is an inherent limitation of mechanical recycling. Repeated processing cycles reduce material performance, leading to decreased strength, stability, and barrier properties.

As a result, recycled plastics are frequently diverted into lower-value applications, rather than being reused in their original form. This "downcycling" process challenges the assumption that recycling creates a fully circular material flow.

From a theoretical perspective, this finding suggests that material circularity in plastics may be fundamentally constrained, particularly in high-performance applications such as food packaging. Even with improved collection and sorting, degradation limits the number of effective recycling cycles.

This has important implications for sustainability strategies. Policies and corporate targets that assume closed-loop recycling may overestimate achievable circularity, especially when applied to complex packaging systems.

4.2.4 Food-Contact Safety Constraints

A critical finding relates to the constraints imposed by food safety requirements on recycling systems. Plastics used in food-contact applications must comply with strict regulatory standards to prevent harmful substances from migrating into food.

Food packaging can involve numerous chemical substances, chemical additives, and these contaminants may be introduced via sorting failures or prior use, raising concerns about chemical migration. As a result, recycled materials must undergo rigorous decontamination and regulatory approval processes before being used in food-contact applications Consequently, food-grade recycled plastics require rigorous decontamination and regulatory oversight.

This creates a significant limitation for circularity. While recycling is technically possible in many cases, its application is restricted by safety considerations, particularly for mixed or contaminated waste streams. At the same time, the potential for closed-loop recycling is highly uneven across materials. For example, well-controlled systems such as PET bottle recycling are more viable, while complex flexible packaging faces greater barriers.

4.2.5 Sustainability Trade-Offs and LCA Evidence

The outcome is that environmental performance cannot be evaluated based solely on material properties or recyclability. Instead, sustainability outcomes depend on the interaction between production, use, and end-of-life stages.

LCA evidence demonstrates that plastic packaging is not always environmentally inferior to alternative materials. Outcomes vary depending on factors such as weight, transport requirements, reuse potential, and recycling assumptions. In some cases, heavier materials may result in higher overall environmental impacts due to increased energy use in production and distribution.

A holistic review of LCA studies concludes that environmental outcomes depend on factors such as material weight, reuse patterns and end-of-life assumptions. It also notes that increasing recycled polymer content can improve the eco-performance of plastic packaging (Dolci et al., 2025).

A key insight is that LCA results are highly sensitive to methodological assumptions. Differences in system boundaries, functional units, and treatment of food waste can lead to divergent conclusions.

This reinforces the need for careful interpretation of sustainability claims and supports the argument that packaging decisions should be based on case-specific analysis rather than general assumptions.

4.2.6 Packaging as a Lever for Food Waste Reduction

The conclusions strongly support the role of packaging as a critical factor in reducing food waste, particularly in modern supply chains characterised by long transport distances and extended storage periods.

Packaging contributes to food waste reduction by extending shelf life, protecting products from damage and contamination, enabling portion control and gradual consumption. This protective function is particularly significant for perishable products, where spoilage rates are high.

The analysis also confirms that the effectiveness of packaging depends on a broader frame. Consumer behaviour, including over-purchasing, improper storage, and misinterpretation of expiry dates, can limit the benefits of packaging.

This shows that packaging can help reduce spoilage, but real progress also depends on wider system factors such as business models, infrastructure, and consumer behaviour. Technical solutions alone are insufficient to reduce food waste.

4.2.7 PPWR as a System-Level Driver of Change

PPWR acts as a critical regulatory driver, aiming to address many of the challenges identified above through mandatory requirements for recyclability, recycled content, and waste reduction.

Policy materials emphasise that the PPWR aims to reduce packaging waste, improve recyclability, increase recycled content, enhance labelling and restrict hazardous substances in relevant uses such as food contact (European Commission, n.d.). Sector guidance confirms that PPWR entered into force in February 2025 and becomes broadly applicable from August 2026, with phased requirements including recyclability by 2030 and further targets thereafter.

The analysis reveals that PPWR also amplifies existing tensions within the system. For example:

- Recyclability requirements may conflict with packaging performance
- Recycled content targets may be constrained by material availability and safety requirements
- Implementation may be uneven due to infrastructure differences across Member States

This suggests that PPWR is not simply a solution, but a catalyst for systemic transformation, whose effectiveness will depend on how these tensions are managed.

4.2 Integrated Analysis: Interdependence of Key Themes

A key contribution of this chapter is the identification of interdependencies between the different challenges, which collectively shape sustainability outcomes:

- Packaging design affects recyclability, food waste, and regulatory compliance simultaneously

- Recycling performance depends on both technical and behavioural factors
- Sustainability trade-offs emerge across lifecycle stages
- Policy interventions interact with system constraints and market dynamics

This interconnectedness supports the central argument of the dissertation: sustainability in packaging systems is determined by system optimisation, not by isolated improvements in individual components.

The key obstacles to recycling is material complexity, contamination, quality degradation and food-contact safety constraints, mapping directly onto PPWR compliance challenges. Packaging formats that rely on complex multi-material structures risk failing recyclability requirements, while safety restrictions can constrain the use of recycled content in food-contact applications (UN News, 2026).

4.3 Chapter Summary

This chapter has presented the key findings derived from the analysis, demonstrating that the challenges in plastic recycling are not isolated technical issues, but part of a broader system characterised by interdependencies and trade-offs:

- Recycling performance is limited by material complexity, contamination, and degradation
- Food-contact safety introduces additional constraints on circularity
- Packaging plays a critical but conditional role in reducing food waste
- Sustainability outcomes depend on lifecycle interactions rather than individual factors
- PPWR acts as a regulatory driver, but introduces new tensions within the system

Overall, improving sustainability outcomes requires integrated action: redesigning packaging with recycling compatibility in mind, strengthening collection and sorting systems, and applying life-cycle thinking that recognises packaging's role in food waste prevention (Dolci et al., 2025).

These insights provide the foundation for the next chapter, which interprets the inferences in relation to existing literature and develops strategic implications for sustainability and industry practice.

5. Discussion

5.1 Introduction

The purpose of this chapter is to interpret the above findings of the study in relation to the existing body of bibliography and to develop a coherent, critical argument addressing the research questions. While the previous chapter identified key patterns, the present discussion moves beyond description to examine the underlying mechanisms that shape plastic recycling performance and the role of plastic packaging in food waste reduction.

The analysis reveals that the sustainability of packaging systems cannot be adequately understood through isolated variables such as recyclability or material choice. Instead, it must be examined as a complex, interconnected system, in which design decisions, consumer behaviour, infrastructure capabilities, and regulatory frameworks interact in dynamic and often conflicting ways. Develops the central argument of the dissertation: that sustainability in packaging requires system-level optimisation rather than single dimension improvement.

Pplastic recycling as a system problem rather than only a technology challenge. Food packaging is often materially complex due to performance requirements, and this complexity undermines sorting and mechanical recycling performance. This reinforces the argument that end-of-life outcomes are shaped against design decisions and supply chain choices.

Food-contact applications intensify these constraints. Potential chemical contamination in recycled plastics emphasises the need for controlled recycling processes and regulatory review to prevent harmful migration into food. This finding is consistent with policy direction: PPWR includes substance-related measures and emphasises safe packaging, illustrating that circularity objectives must remain aligned with consumer protection.

5.2 Plastic Recycling as a Systemic Challenge

Plastic recycling is not primarily constrained by technological limitations, but by systemic misalignment across the value chain. Although significant attention has been devoted to improving recycling technologies, such as mechanical and chemical processes, these innovations alone are insufficient to overcome the broader structural challenges.

The persistence of low recycling performance can be traced to a fundamental mismatch between the design of packaging systems and the capabilities of waste management infrastructure. Packaging is typically optimised for functionality, cost-efficiency and product protection, often resulting in complex, multilayer structures that are not compatible with existing recycling processes. At the same time, collection and sorting systems are designed to handle more homogeneous material streams, leading to inefficiencies when confronted with mixed or contaminated waste.

This disconnect highlights the inadequacy of viewing recyclability as an inherent property of packaging. In practice, recyclability is contingent upon a combination of factors, including material composition, user behaviour, and infrastructure performance. As such, a packaging format that is technically recyclable may not be truly recycled. This distinction between theoretical and practical recyclability represents a critical limitation in both policy frameworks and industry practices.

Furthermore, the issue of contamination illustrates how recycling outcomes are shaped by interactions between technology and behaviour. Contamination arising from food residues, incorrect sorting, and inconsistent collection systems reduces the quality of recycled materials and increases processing costs. These challenges cannot be resolved through technological improvements alone, as they are rooted in how packaging is used and disposed of within real-world contexts.

Taken together, these findings suggest that recycling should be understood not as a standalone solution, but as a component within a broader system that requires coordination across multiple actors and stages. Without such coordination, improvements in one area are likely to be offset by constraints in another.

5.3 Rethinking Sustainability Trade-Offs: Packaging and Food Waste

The study’s structure highlights a critical sustainability trade-off: while reducing plastic packaging can lower material waste, packaging can also reduce food losses whose environmental impacts may exceed those of packaging. The relationship between plastic packaging and food waste remains one of the most important pillars of the study. While the environmental impacts of plastic packaging are widely recognised, the analysis demonstrates that its role in reducing food waste is equally important and often underappreciated.

Food production is associated with significant environmental burdens, including greenhouse gas emissions, water use and land exploitation. When food is wasted, these embedded resources are effectively lost, amplifying the environmental impact of the food system. In this context, packaging can play a critical role by extending shelf life and protecting products from spoilage.

The conclusions challenge the assumption that extending shelf life automatically leads to reduced waste. In practice, consumer behaviour significantly mediates this relationship. Over-purchasing, improper storage, and misunderstanding of expiry labels often result in food being discarded despite the presence of protective packaging. This highlights a key limitation of technical solutions: their effectiveness is dependent on behavioural factors that are not directly controlled by the packaging itself.

This interaction leads to an important conceptual shift. Rather than viewing packaging as either beneficial or harmful, it should be understood as a conditional tool, whose impact depends on how it is integrated into the broader food system. Reducing packaging without considering its functional role may lead to unintended consequences, including increased food waste and higher overall environmental impacts.

LCA underscores the need for careful decisions. Conventional plastics are not universally the poorest option and outcomes depend on weight, reuse and end-of-life modelling. Recycled polymers can improve the eco-performance of plastic packaging, which implies that sustainability strategies should not be based solely on material perceptions but on proven assessments that include end-of-life and food waste impacts (Dolci et al., 2025).

From a life-cycle perspective, this reinforces the need to evaluate packaging and food systems together. Strategies that optimise packaging in isolation (whether through material reduction or substitution) may fail to achieve meaningful sustainability improvements if they compromise food protection.

5.4 Challenging Circular Economy Assumptions

The above facts also provide a basis for critically reassessing key assumptions within the circular economy discourse, particularly the emphasis on recycling as the primary pathway to sustainability. While recycling is an essential component of circular systems, its limitations are evident when examined in relation to real-world constraints.

One of the most significant challenges is the degradation of polymer properties during mechanical recycling, which limits the number of times materials can be effectively reused. This leads to downcycling, where materials are diverted into lower-value applications rather than being maintained in closed-loop systems. In addition, contamination and material complexity reduce the quality and applicability of recycled quality, further constraining circularity.

These limitations suggest that circular economy models based on continuous material loops may overstate the feasibility of achieving complete circularity in plastic packaging. Instead, a more realistic perspective recognises that recycling operates within technical and thermodynamic limits, particularly for high-performance applications such as food-contact materials.

The gap between nominal recyclability and actual recycling raises important questions about how circularity is defined and measured. Packaging may satisfy regulatory recyclability criteria but still not be recycled in practice because of infrastructure or market limitations. This underscores the need for more nuanced metrics that reflect real-world system performance rather than theoretical design features.

In review of these challenges, the circular economy should be reframed not as a goal of maximising recycling, but as an approach to optimising resource use across the entire system. This includes reducing unnecessary packaging, improving reuse options, and designing products that are compatible with existing infrastructure, rather than relying solely on recycling to close the loop.

5.5 PPWR as a Driver of System Transformation

The introduction of the Packaging and Packaging Waste Regulation (PPWR) represents a significant policy intervention aimed at addressing the systemic challenges identified in this study. By establishing binding requirements for recyclability, recycled content, and packaging reduction, PPWR seeks to realign incentives and accelerate the transition toward more sustainable packaging systems.

PPWR is positioned as a structural driver that moves sustainability from voluntary practice toward binding obligations. The European Commission frames PPWR as delivering packaging that is less wasteful, more recyclable and more clearly labelled, with measures that promote recycled content and restrict harmful substances in relevant applications (European Commission, n.d.). Sector guidance clarifies the timeline: PPWR entered into force in February 2025 and becomes applicable from August 2026, with key requirements phased in through 2030 and beyond.

The compliance is likely to be uneven across packaging types. Formats that depend on multilayer performance may face greater redesign pressure, while supply chain players may encounter constraints in sourcing compliant post-consumer ready to be recycle materials for sensitive applications. Industry-oriented analysis suggests a large share of existing packaging portfolios may need redesign to meet PPWR requirements, indicating the scale of transition facing businesses.

The regulation has the potential to act as a catalyst for innovation and structural change. By imposing uniform standards across the European Union, it reduces fragmentation and provides a clear framework for industry action. This can encourage investment in recycling infrastructure, stimulate demand for recycled materials, and promote the adoption of design-for-recycling principles.

PPWR introduces new tensions within the system. The requirement for universal recyclability may conflict with the functional demands of certain packaging applications, particularly those requiring high barrier performance. Similarly, targets for recycled content may be difficult to achieve in the absence of sufficient supplies of high-quality ready to recycle materials, especially in food-contact applications where safety requirements are stringent.

These tensions highlight the risk of policy–practice misalignment. Regulatory objectives that are not fully aligned with technical and market realities may lead to compliance challenges or unintended consequences. At the same time, such tensions can also drive innovation by forcing stakeholders to reconsider established design and production practices.

Ultimately, the effectiveness of PPWR will depend on its ability to balance ambition with feasibility, ensuring that regulatory requirements are supported by adequate infrastructure, market mechanisms, and technological development.

5.6 Strategic Implications for Industry

The new norms, as expected have important implications for industry stakeholders, particularly in the context of increasing regulatory pressure and evolving sustainability expectations. A key conclusion is that packaging decisions should not be made in isolation but considered within the broader system in which they operate.

This requires a shift toward portfolio-level thinking, where companies evaluate the performance of their entire packaging range rather than optimising individual products. Such an approach enables trade-offs to be managed more effectively, ensuring that improvements in one area do not lead to negative outcomes in another.

Three strategic priorities for circularity should be considered: (i) design-for-recycling aligned with real recycling infrastructure; (ii) improved collection and sorting to increase clean feedstock; and (iii) governance and data systems to demonstrate compliance. PPWR's emphasis on harmonised labelling, recycled content and responsibility mechanisms provides incentives for these shifts, but success depends on collaboration across the value chain (European Commission, n.d.).

Recycled content strategies must be designed with safety and performance constraints in mind. For food-contact packaging, the need for strict decontamination and regulatory review may constrain available recycled material volumes (UN News, 2026). This indicates that circular economy targets should be accompanied by investment in approved recycling processes and traceable material flows to avoid unintended safety or quality risks.

Collaboration across the value chain also emerges as a critical factor. Recycling performance depends on coordination between designers, manufacturers, waste management operators, and policymakers. Without such alignment, efforts to improve sustainability are likely to be fragmented and less effective.

In addition, companies should adopt decision-making frameworks, incorporating insights from LCA while recognising its limitations. This involves moving beyond simplistic assumptions and considering the full lifecycle implications of packaging choices, including their impact on food waste.

Finally, innovation should extend beyond materials to include packaging functionality and user interaction. Designing packaging that aligns with real consumer behaviour through improved usability, clearer communication, and better portioning, can enhance its effectiveness in reducing food waste and improving overall sustainability outcomes.

5.7 Integrative Insight

For packaging producers and brand owners, the discussion implies a portfolio-level compliance and innovation programme. Managers should prioritise packaging formats that can achieve recyclability targets without compromising food protection, establish internal governance for packaging data and declarations, and engage early with recyclers and waste management partners to understand infrastructure constraints.

The central insight developed in this chapter is that packaging sustainability is best understood as a problem of system optimisation rather than material substitution. Effective solutions must balance multiple, interdependent objectives, including product protection, environmental impact, recyclability, and regulatory compliance.

This perspective leads to the conclusion that optimal packaging solutions cannot be defined universally but must be developed in relation to specific product categories, supply chains, and system conditions. As such, sustainability strategies should focus on improving alignment across the system rather than maximising individual performance indicators.

5.8 Chapter Summary

As PPWR implementation progresses, future research should evaluate real-world impacts by packaging format and by country and assess how design-for-recycling criteria and infrastructure alignment influence actual recycling rates and food waste outcomes.

This chapter demonstrating that the challenges associated with plastic recycling and packaging sustainability are deeply interconnected and cannot be resolved through isolated interventions.

Recycling inefficiencies are rooted in systemic misalignment, that packaging plays a complex and conditional role in reducing food waste, and that circular economy assumptions must be carefully evaluated.

These insights provide the basis for the final chapter, which synthesises the conclusions of the study and outlines strategic recommendations for advancing sustainable packaging systems.

6. Conclusion and Recommendations

6.1 Introduction

This thesis dissertation examines the challenges that constrain plastic recycling and assesses how plastic packaging contributes to food waste reduction and sustainability, with particular focus on PPWR. Recycling is limited by material complexity, contamination and polymer degradation, while food-contact applications introduce additional safety constraints due to potential chemical contaminants and migration risks (L. Operato et al., 2025).

This final chapter merges the data summarises discussions presented and finally draws conclusions in relation to the research objectives and questions. It also outlines key recommendations for both academic research and industry practice, with particular emphasis on the implications for packaging design, recycling systems, and regulatory compliance under the Packaging and Packaging Waste Regulation (PPWR).

The central aim of the dissertation was to analyse the challenges in plastic recycling and to evaluate the role of plastic packaging in reducing food waste and supporting sustainability. Through an integrated analysis combining technical, behavioural, and regulatory perspectives, the study provides a comprehensive understanding of the systemic nature of packaging sustainability.

6.2 Summary of Key Findings

The research demonstrates that the challenges associated with plastic recycling are not isolated technical issues but are embedded within a broader system characterised by interdependencies and trade-offs.

First, recycling performance is significantly constrained by material complexity, contamination, and polymer degradation. The prevalence of multilayer packaging, although functionally necessary for food protection, limits the effectiveness of current recycling systems. At the same time, contamination arising from consumer behaviour and collection inefficiencies reduces the quality of recycled polymers and increases processing requirements.

Second, food-contact applications introduce additional constraints due to strict safety regulations. The presence of chemical additives and potential contaminants requires rigorous decontamination and regulatory approval, limiting the use of recycled materials in sensitive applications. This highlights an inherent tension between circularity objectives and food safety requirements.

Third, the analysis confirms that plastic packaging plays a critical role in reducing food waste, particularly for perishable products. This benefit is conditional and depends heavily on consumer behaviour, storage practices, and the alignment between packaging design and real-world use.

Fourth, life cycle assessment (LCA) structure demonstrates that environmental outcomes cannot be determined solely by material choice or recyclability. Instead, sustainability depends on interactions across the lifecycle, including production, use, and end-of-life stages. In many cases, the environmental impact of food waste exceeds that of packaging, emphasising the importance of integrated evaluation.

Finally, the PPWR represents a significant regulatory driver, aiming to address systemic inefficiencies through harmonised requirements for recyclability, recycled content, and packaging reduction. Its implementation introduces new challenges, particularly in relation to technical feasibility, infrastructure readiness, and market dynamics.

6.3 Conclusions in Relation to Research Objectives

Objective 1 (identify recycling constraints): The study finds that the main constraints are technical (complex formats and contamination), systemic (collection and sorting limitations) and safety-related for food contact and all these challenges are multi-dimensional. They include technical barriers such as material incompatibility and degradation, as well as systemic barriers related to infrastructure, economics, and behaviour. Importantly, these factors interact in ways that limit the effectiveness of recycling systems.

Objective 2 (assess packaging role in food waste reduction): packaging's central role in preserving quality and extending shelf life, implies that packaging reduction strategies should avoid increasing food waste. Packaging provides measurable benefits in extending shelf life and protecting food, its effectiveness is influenced by consumer behaviour and system conditions. Therefore, packaging should be assessed within a broader context rather than as an isolated component.

Objective 3 (evaluate PPWR implications): PPWR introduces binding requirements on recyclability, recycled content, labelling and substance restrictions, accelerating the need for design-for-recycling and stronger recycling systems. The regulation represents a significant step toward system transformation but also introduces conflicts between regulatory requirements and practical feasibility. Its success will depend on the alignment between policy objectives, technological capabilities, and infrastructure development.

Objective 4 (strategic recommendations): Achieving sustainability gains, requires integrated action across design, infrastructure and governance supported by life-cycle thinking. In that direction, the need for integrated approaches that balance performance, circularity, and system compatibility are required.

6.4 Strategic Recommendations for Industry

The ones that have direct affect but at the same time been part of the solution-improvement, are stakeholders of the industry and more particularly packaging manufacturers, food producers, and retailers.

Embed new ready to recycle attitude in packaging developments is the fundamental remedy. Organisations should prioritise new packaging architectures that are compatible with existing sorting and recycling streams, reducing avoidable complexity while maintaining food protection. This aligns with PPWR's objectives of making packaging more recyclable and less wasteful (European Commission, n.d.).

The adoption of an innovative approach to packaging design, with new solutions R&D oriented, not solely focusing on individual attributes such as recyclability or material reduction. Companies should evaluate packaging solutions in terms of their overall contribution to performance. This includes considering product protection, food waste prevention, recycling feasibility, total footprint and regulatory compliance simultaneously.

In this direction, ready to recycle designs should be implemented in a way that is aligned with actual infrastructure capabilities. Packaging that is theoretically recyclable but not compatible with existing collection and sorting systems is unlikely to deliver meaningful environmental benefits. Therefore, collaboration with waste management operators and recyclers is essential to ensure practical feasibility.

Strengthening packaging data, follow documentation and respect compliance governance (see PPWR). These norms form a strict frame, increasing emphasis on demonstrating compliance through technical documentation, labelling and responsibility mechanisms. Companies should establish internal ownership of packaging data, including material composition, recyclability figures and declarations of conformity where required.

An additional recommendation concerns the use of life cycle assessment as a decision tool. Companies should adopt LCA-based frameworks to evaluate trade-offs between different packaging options, particularly in relation to food waste impacts.

Companies should collaborate across the value chain to improve collection and sorting. Recycling performance depends on feedstock quality; therefore, packaging producers and brand owners should partner with waste management and recyclers to support improved collection, sorting and contamination reduction strategies (L. Operato et al., 2025).

There is an absolute need to enhance consumer-centred design and communication. Packaging should be designed not only for technical performance but also for usability and behavioural alignment. Clear labelling, intuitive packaging features, and improved guidance on storage and disposal can help reduce both food waste and contamination in recycling systems.

Applying LCA attitude, that includes food waste impacts is mandatory. Material substitution can yield mixed sustainability outcomes, and that recycled content can improve performance. Decisions should therefore be guided by LCA and scenario analysis that account for material weight, end-of-life routes and food waste prevention benefits (Dolci et al., 2025)

Prioritise safe circularity in food-contact applications. Given the risks identified for recycled plastics in food-contact uses, organisations should focus on approved recycling solutions and traceability to protect consumer safety while progressing circularity (UN News, 2026).

Finally, innovation should extend beyond materials to include new business models and system solutions, such as reusable packaging, improved logistics, and digital tools for consumer engagement. These approaches can complement recycling efforts and contribute to more sustainable outcomes.

6.5 Academic Contributions

This dissertation contributes to the academic literature by addressing the identified key gaps. One of the primary contributions is the integration of plastic recycling, food waste reduction, and regulatory analysis into a single framework. Existing research often treats these areas separately, resulting in fragmented understanding. By combining these perspectives, the study provides a more holistic analysis of packaging sustainability.

In addition, the research offers a critical perspective on circular economy assumptions, highlighting the limitations of recycling as a standalone solution and emphasising the importance of system-level optimisation. This contributes to ongoing debates regarding the feasibility and implementation of circular economy principles.

The study also reinforces the importance of incorporating behavioural and contextual factors into sustainability analysis, particularly in relation to food waste. This supports a shift toward more interdisciplinary approaches in packaging research.

6.6 Limitations of the Study

While this study provides valuable insights, it is important to acknowledge its limitations. The research is based entirely on secondary data, which limits the ability to capture real-time developments and context-specific variations. In particular, the implementation of PPWR is still evolving, and reported data on its full impact remains limited.

In addition, the study does not include primary data collection, such as interviews or case studies, which could provide deeper insights into industry practices and decision-making processes.

Finally, the complexity of the topic makes it difficult to quantify certain trade-offs, particularly those between packaging reduction and food waste. While LCA provides a useful framework, its application is subject to methodological variability.

The study is based on secondary data and does not measure outcomes directly in a specific market or product portfolio. In addition, PPWR implementation is ongoing, and evidence on its full operational effects is still emerging.

6.7 Future Research Directions

Future research should examine PPWR implementation impacts by packaging type (especially flexible formats), quantify trade-offs between recyclability and food waste prevention using integrated LCAs, and evaluate the scaling potential of approved recycling technologies for food-contact materials (Dolci et al., 2025; UN News, 2026).

Future research should focus on generating data to support and validate the findings of this study, and is mandatory to examine:

- Case studies examining PPWR implementation across different industries
- Integrated LCA models that explicitly account for food waste impacts
- Experimental research on consumer behaviour and packaging use
- Analysis of recycling system performance for specific packaging formats

In addition, further research should explore the scalability of emerging recycling technologies and their potential role in addressing the limitations identified in this study.

6.8 Direct Answers to the Research Questions

The four research questions are answered directly below, drawing together the main findings from the literature review, findings, discussion and recommendations chapters.

Research Question 1: What are the dominant technical, economic and regulatory challenges limiting plastic recycling? The dominant challenges are material complexity, contamination, polymer degradation, insufficient collection and sorting infrastructure, weak market incentives and strict food-contact safety requirements. Multilayer and multi-material packaging improves food protection but is difficult to separate and recycle. Contamination from food residues, additives, inks and mixed waste streams reduces recycled material quality and increases processing costs. Repeated mechanical recycling can degrade polymer properties, leading to downcycling rather than true closed-loop circularity. Economically, recycled plastics often compete with cheaper virgin polymers, while regulatory requirements, especially for food-contact applications, restrict the use of recycled content unless safety and traceability can be demonstrated.

Research Question 2: How does plastic packaging contribute to food waste reduction across the supply chain? Plastic packaging contributes to food waste reduction by protecting products from oxygen, moisture, light, physical damage and microbial contamination. These functions extend shelf life, support transport and storage, maintain product quality in retail environments and enable portion control or gradual consumption at household level. The contribution is especially important for perishable products such as meat, dairy and fresh produce. However, the effect is conditional: packaging can reduce food waste only when its protective functions are matched by appropriate consumer behaviour, correct storage, clear labelling and supply-chain practices. Therefore, packaging should be assessed not only as waste material, but also as a functional tool that can prevent the larger environmental burden associated with wasted food.

Research Question 3: How does the PPWR influence packaging design and circular economy strategies? PPWR influences packaging design by moving sustainability from voluntary commitments toward binding regulatory obligations. It requires packaging to become more recyclable, increases the importance of recycled content, strengthens labelling and consumer information, and restricts substances of concern in relevant applications. As a result, companies must redesign packaging portfolios, shift toward design-for-recycling principles, reduce unnecessary material use and improve documentation and compliance systems. PPWR also encourages circular economy strategies by creating demand for high-quality recycled materials and by aligning design, waste management and producer responsibility. At the same time, its implementation creates tensions, where recyclability requirements conflict with food protection, material availability or food-contact safety constraints.

Research Question 4: What strategic actions can support the transition toward sustainable packaging systems while maintaining food safety and performance? The transition requires integrated action across packaging design, infrastructure, governance and consumer use. Industry should prioritise recyclable and, where feasible, mono-material designs while preserving essential barrier properties and food safety. Companies should apply life cycle assessment and scenario analysis that include food waste impacts, rather than focusing only on packaging weight or recyclability. Collaboration with recyclers, waste-management operators, suppliers and regulators is necessary to improve collection, sorting, feedstock quality and the supply of food-grade recycled materials. Stronger packaging data systems, traceability, compliance documentation and clear consumer communication are also essential. The overall strategy should be system optimisation: packaging should be designed to be recyclable, safe, functional and effective in preventing food waste.

6.9 Final Conclusion

In conclusion, the dissertation demonstrates that sustainability in plastic packaging cannot be achieved through isolated measures such as increasing recycling rates or reducing material use. Instead, it requires a comprehensive approach that considers the entire system in which packaging operates.

Plastic packaging, while contributing to environmental challenges, also plays a critical role in preventing food waste and supporting modern supply chains. The relationship between these functions involves complex trade-offs that must be carefully managed.

Recycling remains an important component of circular economy strategies, but its effectiveness is limited by technical, behavioural, and economic constraints. At the same time, regulatory frameworks such as PPWR are driving necessary changes, although their success depends on alignment with real-world conditions.

Ultimately, the study highlights the need for a shift from material-centric thinking to system-centric optimisation, where sustainability outcomes are determined by the interaction of multiple factors rather than by individual attributes. By adopting such an approach, both industry and policymakers can develop more effective strategies for achieving long-term environmental and economic sustainability.

7. References

Alhazmi, H., Almansour, F.H. & Aldhafeeri, Z. (2021) Plastic waste management: a review of existing life cycle assessment studies. *Sustainability*, 13(10), p.5340. Available at: https://scienceforgeorgia.org/wp-content/uploads/2021/07/PlasticWasteMgmt-Lifecycle-Review-Alhazmi-et-al.pdf

Amienyo, D. & Azapagic, A. (2016) Environmental impacts of ready-made meals and implications for plastic packaging. *Journal of Cleaner Production*, 112, pp.4510–4522.

Cabrera, G., Li, J., Maazouz, A. & Lamnawar, K. (2022) A journey from processing to recycling of multilayer waste films: a review of main challenges and prospects. *Polymers*, 14(12), 2319. Available at: https://hal.science/hal-04143320v1/file/polymers-14-02319-v2.pdf

Dolci, G. et al. (2024) How does plastic compare with alternative materials in the packaging sector? A systematic review of LCA studies. Politecnico di Milano Research Repository. Available at: https://re.public.polimi.it/retrieve/57a70f7e-e8a9-4b92-86e0-ec4231a5c8a6/dolci-et-al-2024-how-does-plastic-compare-with-alternative-materials-in-the-packaging-sector-a-systematic-review-of-lca.pdf

European Environment Agency (2023) *Plastics, the environment and human health*. Luxembourg: Publications Office of the EU.

Ciawi, Y., Tonyes, S.G. and Dwipayanti, N.M.U. (2025) Multilayer packaging recycling: challenges, current practices and prospects. Academia Environmental Sciences and Sustainability, 2.

FAO (2019) *The State of Food and Agriculture: Moving Forward on Food Loss and Waste Reduction*. Rome: Food and Agriculture Organization.

Operato L., Panzeri A., Masoero G., Gallo A., Gomez L., Hamd W., (2025) *Frontiers in Food and Science and Technology: Food Packaging used and post-consumer plastic waste management: a comprehensive review.*

Kaiser, K., Schmid, M. & Schlummer, M. (2018) Recycling of polymer-based multilayer packaging: a review. *Recycling*, 3(1), p.1. Available at: https://www.mdpi.com/2313-4321/3/1/1

Molina-Besch, K., Wikström, F. & Williams, H. (2019) *The environmental impact of food packaging: a review. Food Packaging and Shelf Life*, 20, 100314.

OECD (2023) *Workshop on Flexible Food-Grade Plastic Packaging*. Paris: OECD, p11. Available at: https://one.oecd.org/document/ENV/CBC/MONO(2023)1/en/pdf

Saunders, M.N.K. (2012) *The layers of research design (research onion)*. Available at: https://www.academia.edu/4107831/The_Layers_of_Research_Design

Camila Tavora de M.S., S. Karlsson, Monica Ek, E. Ostmark, M. Gallstedt (2020) *Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios.* Available at: Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios - ScienceDirect

United Nations News (2026) *Recycled plastics for food use require stronger safeguards, warn UN food security experts, UN News*
Available at: Recycled plastics for food use require stronger safeguards, warn UN food security experts | UN News

European Commission (n.d.) *Packaging and packaging waste regulation*. Available at: https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste/packaging-packaging-waste-regulation_en

European Commission (2022) *Proposal for a Regulation on Packaging and Packaging Waste (PPWR).* COM (2022) 677 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A677%3AFIN

ISPT (2025) *Full Utilization of Hard-to-Recycle Mixed Plastic Waste by Conversion toward Pyrolysis Oil and BTX Aromatics on a Pilot Scale***.** Available at: https://ispt.eu/projects/inrep/

8. Appendices

PPWR Legislation,
Available at: L_202500040EN.000101.fmx.xml

Author's Statement:

I hereby declare that, in accordance with article 8 of Law 1599/1986 and article 2.4.6 par. 3 of Law 1256/1982, this thesis/dissertation is solely a product of personal work and does not infringe any intellectual property rights of third parties and is not the product of a partial or total plagiarism, and the sources used are strictly limited to the bibliographic references.