End-of-life Alternatives of the Compostable Fiber-based Packaging Materials for Foodservice

Heli Viik

Master's thesis
December 2025
Master's Degree Programme in Lifecycle Management

Jyväskylän ammattikorkeakoulu
University of Applied Sciences

Viik, Heli

End-of-life Alternatives of the Compostable Fiber-based Packaging Materials for Foodservice

Jyväskylä: Jamk University of Applied Sciences, December 2025, 64 pages

Degree Programme in Lifecycle Management, Master's thesis.

Permission for open access publication: Yes

Language of publication: English

Abstract

In Europe, regulatory frameworks such as the Single-Use Plastics Directive and Packaging and Packaging Waste Regulation have reshaped the responsibilities of producers through mechanisms like Extended Producer Responsibility. These frameworks have reshaped the packaging and food industries by promoting circular material use and environmental performance. Therefore, there has been a growing demand for sustainable packaging solutions to enhance the transition from conventional plastics to fiber-based materials for foodservice packaging materials.

A comprehensive literature review was carried out. A qualitative scoping review, complemented by a systematic literature review, was used to explore and consolidate existing knowledge.

The objective was to review the insights on end-of-life options for compostable fiber-based foodservice packaging materials. End-of-life pathways for fiber-based foodservice packaging were studied with a particular focus on compostable grades. The review examined how European policies and the regulatory framework reshape producer obligations through Extended Producer Responsibility. Compatibility of compostable fiber-based packaging with industrial composting and anaerobic digestion, especially when mechanical recycling is restricted because of food contamination was reviewed.

Although fiber-based packaging has been often considered preferable to plastics, due to renewable feedstocks and potential compostability, its environmental and economic performance largely depends on end-of-life management and alignment with regulatory frameworks. Findings indicated that effective end-of-life alternatives are critical to delivering environmental benefits through resource recovery (biogas, compost) and to avoid landfills or incineration. The need for early-stage design that anticipates end-of-Life alternatives, harmonized standards, clear consumer guidance, and cross supply chain collaboration is required. Overall, the sustainability performance of fiber-based foodservice packaging is contingent on robust end-of-life infrastructure, regulatory clarity, and materials innovation that maintains food safety while enabling high quality recovery.

Keywords/tags (subjects)

biodegradability, compostability, composting, end-of-life, extended producer responsibility, EPR, fiber-based packaging, foodservice packaging, PPWR, product life cycle, SUPD

Miscellaneous (Confidential information)

-

Contents

Figures

Tables

Statement about using AI

The author of this thesis is responsible for the accuracy of the entire contents of the thesis. The authenticity of this thesis has been checked with the Turnitin similarity checking software. AI was used in this work for language editing (Microsoft Copilot) and generation of Figure 5. Library tool ‘AI Search’ at LUT Primo was used to search for peer reviewed articles.

Abbreviations

AD	Anaerobic Digestion
AI	Artificial Intelligence
AIP	Active and Intelligent Packaging
BioPBS	Biobased polybutylene succinate
bioPE	Biobased polyethylene
bioPET	Biobased polyethylene terephthalate
CO_2	Carbon dioxide
EoL	End-of-life
EPR	Extended Producer Responsibility
PBAT	polybutylene adipate terephthalate
PBS	polybutylene succinate
PE	polyethylene
PFAS	perfluorinated alkyl substances
PHA	polyhydroxyalkanoate
PLA	polylactic acid
PPWR	Packaging and Packaging Waste Regulation
PRO	Producer Responsibility Organization
SUPD	Single-Use Plastics Directive

1 Introduction

The growing demand for sustainable packaging solutions has advanced the transition from conventional plastics to fiber-based materials for foodservice packaging materials. Fiber-based packaging can be seen as an environmentally friendly alternative due to its renewable origin and potential to meet the requirements for compostability. However, the sustainability of these materials depends not only how and of which raw materials those are produced, but also on their end-of-life (EoL) management. Improper disposal or inefficient recovery processes reduce environmental benefits and create extra economic costs for producers and waste management stakeholders. However, this shift toward fiber-based packaging demonstrates to a wider dedication to sustainability and circular economy principles.

In Europe, regulatory frameworks such as the Single-Use Plastics Directive (SUPD) and Packaging and Packaging Waste Regulation (PPWR) are reshaping the responsibilities of producers through mechanisms like Extended Producer Responsibility (EPR). The SUPD restricts certain single-use plastics and introduces EPR obligations, that create incentives to switch to non-plastic or compostable alternatives in cases that those are appropriate. PPWR replaces the old Packaging Directive (94/62/EC), directly applying harmonized rules across the EU. It sets stricter recyclability expectations, tightens hazardous substance thresholds, and includes provisions for compostability in specific applications by 2028 (European Parliament and Council, 2019/904; European Parliament and Council 2025/40). These policies aim to reduce environmental impacts by promoting circularity and ensuring that producers bear the costs of waste management. For compostable fiber-based packaging, the implications of these regulations remain complex, as the material often falls between categories of recyclable and biodegradable waste streams. Therefore, the aspects of single use plastics directive and current view of Packaging and Packaging Waste Regulation will be reviewed in this literature review.

While these fiber-based packaging materials are often perceived as preferable to plastics, their environmental and economic performance is strongly influenced by how they are managed after use. If disposal and recovery processes are inefficient or misaligned with regulatory frameworks, the anticipated sustainability gains may not materialize, highlighting the need for a comprehensive evaluation of end-of-life (EoL) strategies.

2 The purpose and objectives of the literature review

This literature review study focuses on fiber-based packaging used in foodservice. The end-of-life alternatives of the fiber-based packaging materials for foodservice and especially the compostable fiber-based packaging materials are studied. This is because fiber-based packaging materials typically become mechanically non-recyclable when food residues remain on the surface of the package. In such cases, an alternative pathway for these materials lies in their inclusion in biowaste collection and subsequent processing through recycling methods such as anaerobic digestion. The focus is on fiber-based packaging material used in foodservice.

Literature review focuses on questions, such as, how the fiber-based packaging material fits to composting and production of biogas, how the Extended Producer Responsibility fees are considered for compostable fiber-based packaging materials and what are the main challenges and views of the European Union legislation and regulation on the topic. Thesis evaluates the role of fiber-based packaging within the waste collection of bio-fraction, with particular emphasis on its processing in anaerobic digestion plants and its contribution to biogas production. In addition, it is studied how Extended Producer Responsibility (EPR) apply to compostable fiber-based packaging materials.

3 Research questions and theoretical bases

To achieve the objectives of this thesis, a comprehensive literature review is carried out. A qualitative scoping review, complemented by a systematic literature review, is used to explore and consolidate existing knowledge on fiber-based packaging, its end-of-life (EoL) alternatives, and related European Union and Finnish regulations concentrating on compostable packaging. Searches are conducted in academic databases and official European Union and industry sources. Inclusion criteria were the relevance to, for instance, fiber-based packaging, compostability, recycling, or regulation.

Continuous information gathering is necessary throughout the thesis process, enabling the integration of new findings and ensuring the review maintain comprehensive. An abductive approach is applied in literature review, where the enhancement of understanding is refined by moving between theory and data (Dubois & Gadde, 2002, p. 555).

Conducting a literature review requires careful and systematic attention to ensure the inclusion of relevant and high-quality sources. As stated by Ojasalo and all. (2014, p. 31), information retrieval requires criticality and information literacy, and source criticism is always important. A thematic analysis approach was applied to systematically identify and synthesize key themes and concepts relevant to the research topic. Given the qualitative nature of the data, qualitative methods are applied, and the findings are summarized to identify recurring themes and patterns. The aim is to extract key insights and highlight the most significant takeaways.

Toikko and Rantanen (2009) write, that subjective perspectives and differences in interests are raised by qualitative datasets and those can provide a fertile basis for reflective debate (Toikko & Rantanen 2009, p. 117). It is important to keep in mind, as Toikko and Rantanen (2009) also emphasizes, that qualitative datasets are approached from the perspective of the questioning of development activities and thus, it is not appropriate to analyze everything possible information contained in the materials possible information contained in the data. In qualitative development activities often consist of classifying and rough interpretation (Toikko & Rantanen 2009, pp. 140-141).

This thesis can be characterized as research-based, drawing on existing literature to develop a comprehensive understanding of the topic. The literature review establishes the theoretical and regulatory framework and provides a foundation for practical insights into the challenges and opportunities associated with end-of-life management of fiber-based compostable packaging. As a research-based study, thesis is framed by life-cycle thinking and circular economy principles.

The anticipated outcome of this work is to provide insights into life-cycle and especially the end-of-life alternatives for fiber-based packaging materials intended for foodservice. Consequently, the literature review research offers an opportunity to clarify the current level of knowledge and preparedness regarding these issues and, importantly, to discuss how to integrate such considerations into the early research and development stages of new fiber-based products. The literature review addresses the following main research questions shown in Table 1.

Table 1. Research questions

Research question		Clarification
1	How do fiber-based packaging materials fit into the biofraction within waste collection, composting processes and biogas production systems?	This question examines the technical and operational compatibility of compostable fiber-based packaging with organic waste treatment, focusing on anaer-obic digestion and its role in biogas generation.
2	How are Extended Producer Responsibility (EPR) fees be considered for compostable fiber-based packaging materials in foodservice?	This questions explores the economic implications of EPR schemes and their application to compostable packaging within current regulatory frameworks.
3	What are the main challenges and perspectives of EU legislation and regulation regarding composta-ble fiber-based packaging?	By this questions, the target is to evaluate the regulatory landscape, in-cluding the SUPD and PPWR regulations, and to consider how these influence the adoption and EoL management of fiber-based packaging in foodservice.

4 Packaging material for foodservice

4.1 Sustainable packaging material for foodservice

Food waste is a global issue. Due to the depletion of fossil resources, and increased demand to reduce plastic waste, there is a growing need for sustainable packaging solutions. The food and packaging industries are increasingly conscious of the environmental impact, with global policies and initiatives promoting sustainable packaging solutions. Hence, fostering a shift towards increased use of circular packaging and the use of biobased and compostable materials. Sustainable foodservice packaging involves using renewable, recyclable, or recycled materials and at the same time ensuring functionality, quality, and food safety of used packaging materials. (Tiekstra et al. 2021, pp. 1, 2, 8) Along with this, consumer demand plays a crucial role in encouraging companies to adopt sustainable packaging practices.

To maintain consumer preferences, and required barrier properties, are important to achieve consumer acceptance. Food packaging serves the primary role of shielding products from environmental factors, including gases, temperature, and humidity. In addition to the crucial role of food packaging to preserve the qualities and nutrition of food and extend shelf-life, packaging also serves as a means of communication with consumers. Intelligent packaging, focusing on communication and transparency, has good potential, especially with the rise of digitalization and sustainability demands. Active packaging concepts are designed to engage with the product or packaging atmosphere to uphold quality, preserve nutrition, and extend shelf-life, categorized into scavengers/absorbers, emitters, and adaptors. Therefore, innovative packaging concepts, like active and intelligent packaging, can optimize the food supply chain and improve food utilization. (Tiekstra et al. 2021)

Green packaging involves using ecologically friendly materials for packaging while ensuring product safety and effectiveness. There are two main areas in the research on green packaging; 1) consumer-driven and 2) company-driven approaches, that are motivated by increasing level of environmental awareness of the consumers and the government regulations. Consumer demand plays a crucial role in pushing companies to adopt and take in to use sustainable packaging materials and practices. To align with sustainability policies and to meet consumer demands, the businesses are investing in eco-design innovations and more sustainable packaging solutions. (Wandosell et al, 2021)

Furthermore, there is an important role of retailers and packaging manufacturers to educate and provide relevant information for the customers and end-users on proper product and packaging disposal. In addition to new product and process solutions, customers' and end-users' knowledge of disposal alternatives is crucial for protecting the environment and enabling the efficient operation of various end-of-life options for packaging. Consumers value packaging's protective and sustainable aspects, express willingness to purchase Active and Intelligent Packaging (AIP), but require education and clear packaging communication for successful adoption. (Tiekstra et al. 2021)

Eissenberger at al. (2023) emphasizes the significance of using eco-friendly packaging materials to address environmental concerns and use of resources responsibly and the importance of the development of biobased packaging materials and modification techniques, emphasizing potential role of those in creating circular and eco-friendly packaging. The authors highlight the importance of improving sustainability in the packaging industry through use of renewable materials, light-weighting, and enhanced recyclability. Target should be to make packaging that keeps food fresh and can be still recycled after the use. Eissenberger at al. (2023) also highlights the importance of finding the right balance between eco-friendliness and the ability of package to keep the food fresh.

Eissenberger at al. (2023) suggests new ways to make eco-friendly packaging using materials such are PLA, PHA, bioPE, bioPET, paperboard, and molded pulp that can be used for sustainable packaging. These materials can be biobased meaning that those are made from natural sources, derived from biomass or can be biodegradable meaning that the material can be naturally broken down by microorganisms. Nevertheless, it is important to note that biobased material does not always mean that it is in addition biodegradable, and vice versa. Therefore, certifications and labelling standards for biobased and biodegradable materials are required as well as the specification of the environmental conditions for the declaration of biodegradability. (Eissenberger at al., 2023) Paper and cardboard are renewable materials with a long history of use in packaging solutions. Paper and board substrates are generally biodegradable, although some coatings and additives may affect their biodegradability.

Life Cycle Assessment (LCA), based on ISO 14040/44 standards, is widely used to evaluate the environmental impacts of packaging materials from production to disposal. Maga et al. (2019) have studed plastic food packaging and compared nine plastic-based meat tray materials. They found out that material choice and end-of-life treatment significantly influence overall carbon footprint. However, there were limitations to the study, and indirect environmental impacts related to food waste and packaging shelf-life were not considered. (Maga et al., 2019)

By using fiber-based packaging made from responsibly sourced materials can contribute to sustainable practices and reduce environmental impact. Using renewable materials in packaging is in line with circular economy principles, promoting the reuse and recycling of resources.

4.2 Fiber-based packaging materials

A recent approach in packaging design aims to meet multiple end-of-life pathways, where the primary focus is on ensuring both recyclability and suitability for organic waste processing. Paper or paperboard is a common base material due to its affordability, inherent cellulose biodegradability, and well-established recycling infrastructure. (Zimmer, 2025) Paperboard is produced from tree-based wood pulp. Such material forms the basis for a wide variety of packaging solutions, including corrugated boxes, cartons, paper bags, and molded fiber containers, with several applications in the foodservice sector (Kóczán & Pásztory, 2024).

Paper and paperboard are primarily produced from wood pulp. The process begins by mechanically or chemically pulping wood to separate cellulose fibers (Li et al., 2023). These fibers are then screened, refined and bleached. The fiber slurry is spread on a moving screen at paper or board machine. Water is drained, pressed and dried away, leaving a mat of fibers. Board or paper substrate is then subjected to coating and converting operations to provide specific barrier properties, such as resistance to moisture and grease. Fiber-based packaging solutions are widely used across different industries.

From an environmental perspective, fiber-based packaging offers several advantages because of being recyclable and renewable. In Europe, the recycling rate of over 80 % for paper and board is significantly higher when compared to many other materials. (Bugnicourt, 2022, p.28). Fiber-based packaging materials are generally biodegradable, allowing material to break down naturally under appropriate conditions and that way reducing its environmental footprint (Zimmer, 2025). Furthermore, ongoing innovations in barrier coatings and different fiber blends enhance performance of such packaging materials while maintaining their recyclability (Haase, n.d.). Fiber-based packaging represents a responsible choice within a circular economy framework, that is supported by sustainable forestry practices, efficient recycling systems, and continuous improvements in production technologies (Kóczán & Pásztory, 2024).

In this thesis, the emphasis is placed mainly on compostable fiber-based packaging, that is designed for foodservice use. Such products often become contaminated with food residues, making recycling impractical and highlighting the need for solutions that support organic waste streams. Typically, the products can be for instance trays, clamshells, and disposable containers in fast-food applications. Figure 1 represents an example of lifecycle of foodservice packaging materials, showing the stages from resource extraction to disposal and reintegration into the ecosystem.

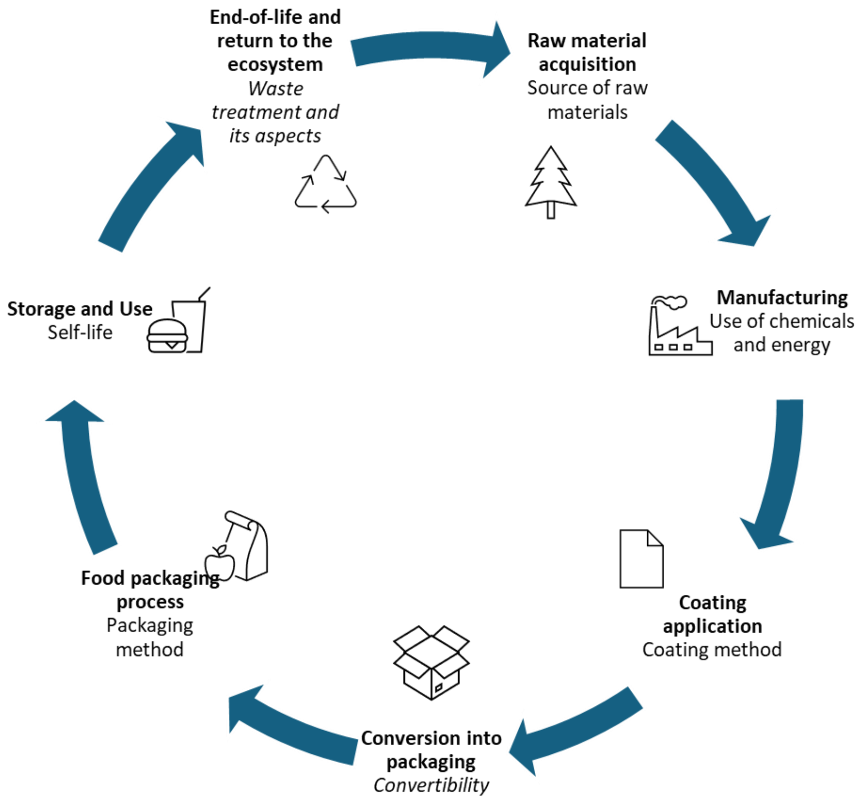

Figure 1. Lifecycle of biobased coatings for fiber-based foodservice packaging (Adapted from Vinitskaia et al., 2025)

Raw material acquisition stage involves sourcing natural resources such as wood, minerals, or other raw materials that are materials used at paper or board production. Paper or board production requires energy and chemicals that influence environmental considerations. For certain applications, board can be coated to provide specific properties like moisture resistance or barrier protection. The choice of coating method can affect the recyclability and environmental impact of the product. In next stage, materials are converted into packaging products, such as boxes or containers. This step considers the convertibility of materials, which also influences efficiency and waste generation. The produced packaging is used to contain and protect food products. The packaging properties and specifications that are chosen also impact food safety, shelf-life, and resource use. In next stage food is stored and consumed in packages. The chosen packaging's design and material properties determine its durability and shelf-life performance. After use, packaging enters waste management systems. This stage includes recycling, composting, or disposal, aiming to minimize environmental harm and return materials to the ecosystem. Sustainability and the environmental impact of each step of lifecycle should be always emphasized.

4.3 Compostable Fiber-based packaging materials for foodservice

Compostability as a product feature is particularly important in foodservice products because packaging often becomes contaminated with food residues and thus makes recycling less feasible. Compostable fiber-based materials can be diverted to organic waste streams and treated through industrial composting or anaerobic digestion, supporting circular economy goals and reducing landfill disposal (Williams, 2025; Zimmer, 2025). Therefore, there is growing interest also in developing packaging materials that are both home and industrially compostable to improve sustainability and end-of-life management for fiber-based foodservice products. This is particularly relevant for items used in quick-service restaurants, on-the-go consumption, and products with a short shelf-life. Such packaging is important for applications where separation from food waste is difficult or where the material is likely to end up mixed with food residues.

Compostable packaging is intended especially for controlled end-of-life scenarios, primarily industrial composting and anaerobic digestion, which enable organic matter recovery and nutrient recycling and reduce reliance on landfill or incineration (Hilton et al., 2020). However, EU regulations set strict conditions for compostable packaging, including contamination levels and compatibility with biowaste streams (European Parliament and Council, 2025). Successful implementation depends on both certification schemes and adequate infrastructure.

Food waste is the most important input for composting processes. Integrating foodservice packaging with food waste in composting process requires that the packaging is certified as compostable. This creates both significant opportunities and but also challenges for innovation. While numerous fiber-based packaging options exist, those may face specific limitations regarding meeting the conditions and standards of compostability. Solutions must satisfy a wide range of criteria, which differ across different regions. (Williams, 2025) Williams’ article (2025) demonstrates that promoting compostability requires substantial, evidence-based, and carefully considered changes in materials, as well as close collaboration throughout the entire supply chain.

Fiber-based materials, paper and board, are adopted due to their biodegradability, cost-effectiveness, and established recycling systems. To meet functional requirements for foodservice packaging, such as barrier properties and heat sealability, paper substrates are often coated with biodegradable polymer coatings that are applied through various technological methods. (Zimmer, 2025)

The biodegradable coatings of the fiber-based packaging materials may be biobased or fossil-based, each suited for specific organic waste treatments (European Bioplastics, n.a.). Current paper-based foodservice packaging uses different barrier technologies to meet functional requirements. These include extruded polymers such as polyethylene (PE) and polylactic acid (PLA), size-press treatments like starches and perfluorinated alkyl substances (PFAS), and coated layers such as wax or water-based formulations. Each coating solution addresses specific performance needs and offers different end-of-life options depending on the degree of food contamination. For instance, size-press treatments and water-based coatings generally support recyclability when contamination is minimal, while for instance PLA coatings are suitable for industrial composting. (Williams, 2025)

Bio-based barrier coatings, that are developed from materials such as polysaccharides, nanocellulose, lignin, and proteins, are increasingly seen as viable alternatives to conventional fossil-based coatings in fiber-based packaging. These materials can significantly improve the environmental profile of packaging by enhancing recyclability and compostability, which supports compliance with sustainability regulations. In addition, certain coatings have demonstrated the ability to prolong the shelf-life by providing improved resistance to moisture and oxygen transfer. (Vinitskaia et al., 2025) Despite these benefits, Vinitskaia et al. (2025) highlights, that there are yet several challenges that remain unresolved and mention one critical issue to be industrial convertibility. Industrial convertibility is the ability of coated board substrates to withstand converting processes like folding, sealing, and forming without losing functionality. Typical problems during converting are for instance surface cracking and poor sealability. To overcome these challenges, a comprehensive and holistic approach that combines material innovation, standardized evaluation methods as well as practical trials under industrial conditions are required. When improving barrier properties, it is also important and essential to note that compostable coatings must not compromise product properties such as food safety or product shelf-life and packaging solutions need to maintain structural integrity and their protective performance throughout the intended use of the product.

There are strong claims regarding the benefits of compostable fiber-based products. Many brand owners aim to develop packaging that is both bio-based and biodegradable under all conditions. The aim is to eliminate fossil-based plastics in their products and to reduce also that way the environmental impact. This ambition aligns with circular economy principles but can yet face significant technical and regulatory challenges, as universal biodegradability is difficult to achieve without compromising performance and safety (de Jong et al., 2025). Further research is needed to understand how these materials behave in real-life environments and applications. However, the market already offers fiber-based foodservice products that are claimed to be compostable (Figure 2).

Figure 2. Example of compostable foodservice product

For instance, Mitsubishi Chemical Corporation offers a compostable fiber-based product for foodservice. They have implemented a circular and compostable foodservice product using its BioPBS™ compostable material. During large events, such as soccer matches, such paper cups are used for beverages. After use, the cups, along with food residues, are collected and those undergo primary fermentation at composting facilities that are located at the stadium. The partially fermented material is then later transported to a composting plant for secondary and tertiary fermentation and ultimately producing compost that is suitable for agricultural use. This initiative demonstrates how also event waste could be transformed into resources as compost. (Mitsubishi Chemical Corporation, n.d.)

A major gap that Vinitskaia et al. (2025) highlights, is the absence of harmonized testing protocols for recyclability and biodegradability under different disposal conditions. These disposal alternatives are for instance composting, soil burial, and marine environments. This lack of standardization makes it difficult to verify environmental claims and ensure compliance across markets. Zimmer (2025) has also stated that packaging design should not aim for degradation in uncontrolled environments, as unintended littering can pose significant ecological risks.

5 Compostability and biodegrability

5.1 Definitions

Compostability and Biodegradability

Misunderstandings often occur regarding the distinction between terms ‘biodegradable’ and ‘compostable’. A material that is biodegradable is not necessarily compostable and thus a product may be biodegradable without qualifying as industrially compostable. Biodegradation is only one of several criteria that must be met for industrial compostability certification. International standards define certification requirements for materials intended for industrial composting, specifying the conditions under which biodegradation occurs. Core requirements include limits on heavy metals and fluorine, biodegradation, disintegration, and eco-toxicity. (Williams, 2025)

Standards define requirements for compostability and biodegradability testing of plastics, packaging, and paper coatings in different regions, ensuring compliance with environmental regulations and facilitating international trade. The most widely recognized international standards for compostability and biodegradability of different materials across regions are shown in table 2(Williams, 2025).

Table 2. International standards for compostability and biodegradability

	Plastic	**Packaging**	Paper coating
Globally	ISO 17088	ISO 18606	Not indicated
Europe	EN 14995	EN 13432	Not indicated
United States	ASTM D6400	No specific standards	ASTM D6868 (coated paper products)
Australia	AS 4736	No specific standards	Not indicated

Material is considered compostable if it undergoes degradation by biological processes during composting, yielding CO_2, water, inorganic compounds, and biomass at a rate aligned with that of standard compostable materials and it leaves no visible, distinguishable, or toxic residue in the final compost (Hilton et al., 2020; Measurlabs, n.d.; Williams, 2025). For a material to be considered compostable, it must not only biodegrade but also produce a homogeneous and stable humus-like substance during the composting process, which is safe for soil enrichment and plant growth (Appropedia, 2024).

According to Standard SFS-EN 13432:2000 there are specific criteria under controlled composting conditions (SFS-EN 13432) shown in table 3.

Table 3. Standard SFS-EN 13432:2000 specific criteria

Biodegradation	At least 90% conversion to CO_2 , water, and biomass within 6 months under controlled conditions (ISO 14855 method).
Disintegration	After 12 weeks, at least 90% of the material (by dry weight) passes through a 2 mm sieve.
Ecotoxicity	The resulting compost must not negatively affect plant growth.
Heavy metals	Must remain below strict limits (e.g., Zn ≤150 mg/kg, Pb ≤50 mg/kg)

Biodegradation and disintegration are distinct tests. Biodegradability is defined as the capability of a material to be broken down by microorganisms (bacteria, fungi) into CO_2, water, methane (in anaerobic conditions), and biomass, without leaving harmful residues. It is measured under controlled conditions (e.g., composting at 58 °C) and requires: ≥90% biodegradation within 6 months compared to reference material. (SFS-EN 14046) Biodegradability is a chemical property independent of whether the material is bio-based or fossil-based (NaturePlast, n.d.). Disintegration refers to the physical breakdown and disappearance of the material, with no more than 10% remaining on a 2.0 mm sieve after 12 weeks of composting. Eco-toxicity ensures that the resulting compost supports plant growth and sets usage limits for additives and coatings.

Thus, biodegradability refers to the ability of a material to break down under specific conditions within a given timeframe. In aerobic conditions, where oxygen is present, microorganisms decompose the material into carbon dioxide (CO_2), water (H_2O), mineral salts, and new biomass. Conversely, in anaerobic conditions, where oxygen is absent, the breakdown results in CO_2, methane (CH_4), mineral salts, and biomass (Bremer, 2022; Sheposh, 2024).

Summary and comparison of compostability and biodegradability are shown in Table 4.

Table 4. Compostability vs. Biodegradability

Aspect	Compostability	Biodegradability
Definition	Ability of a material to break down under composting conditions into CO_2, water, inorganic compounds, and biomass, leaving no harmful residue.	Ability of a material to be broken down by microorganisms into CO_2, water, methane (anaerobic), and biomass.
Environment	Controlled composting (aerobic, ~58 °C)	Various environments (soil, water, compost, anaerobic digesters)
Timeframe	90% biodegradation within 6 months under test conditions	90% biodegradation within 6 months; 90% disintegration within 12 weeks
Additional Criteria	- Disintegration (≤2 mm sieve) - Ecotoxicity test - Heavy metal limits	No ecotoxicity requirement in basic definition
Residue	Must leave no visible or toxic residue	May leave inert residues (definition does not require full disintegration)
End Goal	Safe compost usable for plants	Mineralization into natural substances

Industrial composting environments create highly intensive conditions for biodegradation. These systems carefully regulate moisture, oxygen, and temperature, fostering the growth of micro-organisms such as fungi, bacteria, and actinomycetes that efficiently break down materials. In contrast, landfills provide far less controlled and less aggressive conditions, resulting in significantly slower decomposition. For example, a head of lettuce may decompose within a few weeks in an industrial composting facility, whereas in a landfill, the same item could take up to 25 years to break down. As stated before, a material that is biodegradable is not necessarily compostable as biodegradation can take place in various environments, some highly controlled and intensive, others far less regulated (Figure 3). (Williams, 2025)

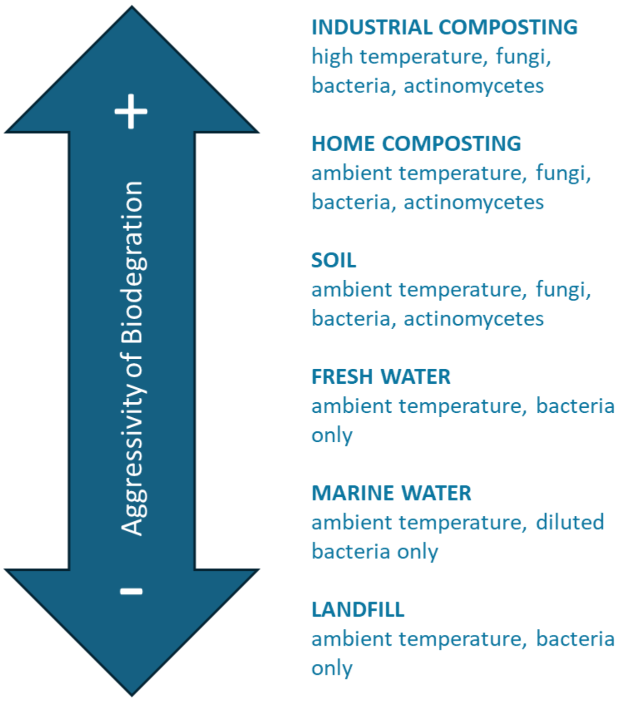

Figure 3. Aggressiveness of Biodegradation in Organic Waste Systems (adapted from Williams, 2025)

Testing standards exist for all biodegradation conditions shown in Figure 3, allowing manufacturers to target specific environments for end-of-life performance in fiber-based foodservice packaging. These standards are issued by organizations such as the International Organization for Standardization (ISO), the American Society for Testing and Materials (ASTM), and the Organization for Economic Cooperation and Development (OECD). Absent from the figure is what might be considered roadside or litter scenarios, as no formal standards exist for typical litter environments, the reason is that such conditions cannot be standardized, degradation rates vary widely depending on local environmental factors. (Williams, 2025)

When selecting a certification scheme, it is crucial to consider the region where the product will be marketed and ultimately disposed of. After selecting a certification, testing must be done by an accredited third-party lab, as required by all certification bodies. These processes are costly and time-consuming, so compostable packaging should be developed strategically. It is also important to note that any formula changes to product after certification may require restarting the certification process again.

It is also important to emphasize, for instance, that the 1% Rule is critical for determining compostability compliance. Therefore, as mentioned even small formulation changes, such as adjusting preservatives, can affect previously certified materials and require retesting. Therefore, strict control over formulations, procurement, and documentation is essential to maintain compliance. Generally, individual non-biodegradable components under 1% are permitted, but their combined total must not exceed 5%, and they cannot be chemically identical. These requirements are common across international standards and typically apply to the finished product, with one noted exception and thus the lack of a single global packaging standard leads to differences in how rules like the ‘1% Rule’ are interpreted. This leads to challenge that interpretation may make compliance in other countries difficult for certain products, and yet meeting these requirements is essential for obtaining compostability certification. (Williams, 2025)

Home-compostability vs industrial-compostability

Home composting and industrial composting differ primarily in scale, environmental control, and the types of materials they can process. Industrial composting occurs in specialized facilities under controlled conditions of temperature, humidity, and aeration, enabling rapid decomposition of certified compostable materials. In contrast, home composting is performed at ambient temperatures with variable conditions, typically in household gardens, and is suitable for simpler organic waste streams.

Home-compostable and industrial-compostable materials differ primarily in the environmental conditions required for degradation and the timeframe for decomposition. Industrial composting occurs in controlled facilities that maintain high temperatures (typically 50 - 60 °C), regulated humidity, and continuous aeration, enabling rapid breakdown of complex materials such as PLA-based bioplastics within 6 - 12 weeks. These factors accelerate biodegradation, allowing the process to be completed faster. These conditions also ensure pathogen elimination and complete mineralization into CO_2, water, and biomass (Green Symbiosis, 2025; Notpla, 2025). In contrast, home composting relies on ambient and variable temperatures (20 - 40 °C), variable moisture, and natural microbial activity, resulting in slower decomposition, such as 6 - 12 months, and limited capacity to process certain bioplastics or coated fiber products (Bremer, 2022; Jacobus, n.d.). Mislabeling or misunderstanding these distinctions can lead to improper disposal, microplastic residue, and non-compliance with certifications. Home-compostable products must consist entirely of materials that fully biodegrade under ambient conditions and be certified according to recognized standards.

5.2 Compostability of paperboard

Uncoated paperboard is generally considered compostable under controlled industrial conditions due to its lignocellulosic composition, which supports microbial degradation. Cellulose fibers in paperboard break down into carbon dioxide, water, and biomass when exposed to adequate moisture, oxygen, and thermophilic temperatures (Venelampi et al., 2003). However, the rate of biodegradation depends on fiber processing and lignin content. Mechanically pulped boards, which retain higher lignin levels, degrade more slowly compared to chemically bleached boards because lignin interferes with cellulose breakdown and tends to form humus during composting (Ahmed, et al., 2018; Venelampi et al., 2003). Studies show that chemically bleached paper products can achieve over 70% conversion of organic carbon to CO_2 within standard composting tests, meeting EN 13432 criteria for biodegradability (Venelampi et al., 2003).

Despite its compostability, paperboard decomposition is influenced by environmental and structural factors. Optimal degradation occurs at 40 - 50°C with sufficient aeration and microbial activity, conditions typically found in industrial composting facilities but rarely in home composting systems (Ahmed et al., 2018). The presence of fillers, wet-strength additives, or high-density fiber structures can slow disintegration and require extended composting times beyond the 12-week benchmark set by standards (Venelampi et al., 2003). While composting paperboard reduces landfill waste and methane emissions, its contribution to compost quality is limited. However, biological waste treatment processes return nutrients to the soil through compost or digestate (Zimmer, 2025). Therefore, composting is best suited for contaminated paperboard that cannot be recycled. However, this requires that proper collection and processing infrastructure is provided and in place.

5.3 Bioplastics

Fiber-based materials such as paper and board are widely used in foodservice packaging and to achieve essential functional properties these substrates are typically combined with polymer coatings. Increasingly, these coatings include biodegradable plastics applied through aqueous, solventbased, or extrusion processes, which enhance the overall functionality of fiber-based packaging (Zimmer, 2025). Current paper-based foodservice packaging employs various plastic-based barrier technologies, including extruded polymers like polyethylene (PE) and polylactic acid (PLA), as well as coated layers or water-based formulations. These solutions address performance requirements and influence end-of-life options: for example, PLA coatings enable industrial composting, whereas water-based coatings often support recyclability when contamination is low (Williams, 2025).

Bioplastics is a heterogeneous group of materials with varying properties and applications. According to European Bioplastics (n.a.), a plastic qualifies as a bioplastic if it is biobased, biodegradable, or has both characteristics. It is important to note that biodegradability does not necessarily indicate a bio-based origin, as biodegradable materials can also be produced from fossil resources (Figure 4).

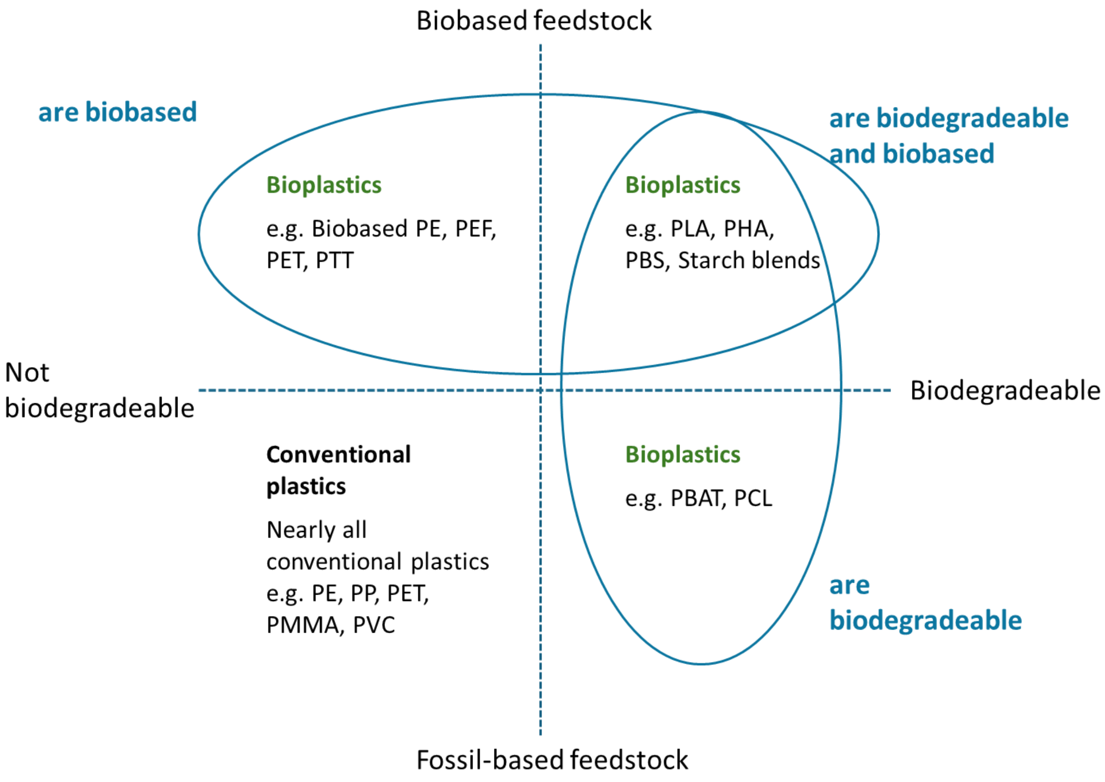

Figure 4. Definition of bioplastics according to European Bioplastics (adapted from European Bioplastics, n.a.)

Compostable coating polymers play a critical role in enhancing the functionality of fiber-based packaging while supporting also circular economy objectives (Jahangiri et al., 2024; Kathuria & Zhang, 2022). These polymers are designed to undergo biodegradation in industrial composting environments, converting polymers into water, carbon dioxide, and biomass without leaving harmful residues. Common examples of such materials include polylactic acid (PLA), polybutylene succinate (PBS), and blends with polybutylene adipate terephthalate (PBAT), which are frequently applied through extrusion or lamination. These polymers are used to provide moisture and grease barriers. (Abdenour et al., 2025; Hamdani et al., 2025) Starch-based coatings, that are often applied as aqueous dispersion or size-press methods, can offer an alternative for lightweight barrier needs (Kathuria & Zhang, 2022). Compliance with standards ensures that these coatings meet the criteria of compostability. However, the performance of such polymers is subject to proper waste management systems. For instance, home composting conditions rarely achieve the required temperature and microbial activity (Jahangiri et al., 2024). Despite their environmental benefits, compostable coatings face challenges related to limited material availability, those tend to have higher production costs, and there are contamination risks that can hinder effective end-of-life processing (Vinitskaia et al., 2025).

It could be concluded also that the cost of polymers can vary considerably depending on whether they are bio-based or biodegradable and largely due to the limited availability. A long-term sustainability objective is and should be to use polymer materials and products that are both fully bio-based and biodegradable.

6 Biowaste collection in Finland

6.1 Biowaste collection

The prohibition of organic waste landfilling in Finland, implemented in 2016, marked a significant shift in national waste management strategies. This regulatory requirement has effectively eliminated the disposal of municipal waste in landfills, redirecting organic waste streams toward alternative treatment methods. Predominantly, organic waste is now directed to incineration with energy recovery, and more environmentally sustainable approaches, such as anaerobic digestion and composting, have also progressively expanded. These developments align with broader objectives of material recovery and the advancement of circular economy principles. (Finnish Environment Institute (SYKE), 2024)

As of 1 January 2024, the separate collection of biowaste became mandatory throughout the EU under Article 22 of the Waste Framework Directive. Member States are required to ensure that biowaste, such as food and garden waste, is either sorted and recycled at source or collected separately, without being mixed with other waste streams. (Directive (EU), 2018/851)

In Finland, municipalities and regional waste management companies have established systems for the separate collection and treatment of biowaste, including food waste. Households use designated containers for biowaste, which typically consists of food residues, leftovers, and other biodegradable materials. Typically, collected biowaste is processed primarily through anaerobic digestion (AD) to produce biogas, which is utilized as a renewable energy source and the digestate is further treated to create nutrient-rich compost for agricultural use or soil improvement. Beyond enhanced collection and processing, Finnish waste management organizations have put strong emphasis on public education and awareness initiatives. The target of public campaigns is to reduce food waste already at its source and at the same time to promote accurate sorting practices. Another important stakeholder initiative it to have good collaboration with restaurants, retailers, and other stakeholders to focus on minimizing overproduction, enhancing inventory control, and encouraging food donation schemes.

The European Compost Network (2022) reports that Europe processes roughly 71 million tons of separately collected biowaste each year. 42 million tons are managed through composting and 29 million tons through anaerobic digestion (European Compost Network, 2022). To achieve the EU’s municipal waste recycling target of 65% by 2035, the recycling of biowaste is essential, because biowaste represents roughly 34% - 46% of municipal solid waste (European Compost Network, 2022; European Environment Agency, 2020). Within this biowaste fraction, food waste constitutes approximately 60% (European Environment Agency, 2020). Estimates suggest that an additional 40 million tons of biowaste must be separately collected and treated via composting and anaerobic digestion to be able to meet the year 2035 target (Zero Waste Europe, 2024). Currently, there are around 3,800 composting facilities and 2,000 anaerobic digestion plants in Europe that are dedicated to biowaste treatment (European Compost Network, 2022). Doubling the amount of biowaste processed over the next decade would require also a significant expansion of treatment capacity. This is particularly needed for anaerobic digestion infrastructure.

From a sustainability standpoint of view, anaerobic digestion (AD) is widely regarded as the most effective method for recycling biowaste and composting as a strong complementary option. Anaerobic digestion offers significant environmental benefits by generating biogas, which can replace fossil fuels. It produces digestate, which is a nutrient-rich material that is suitable for soil improvement. Importantly, the process prevents methane emissions that would occur if biowaste were left to decompose in landfills. Thereby the greenhouse gas impacts are reduced and circular economy objectives enhanced through energy and nutrient recovery (Czekała et al., 2023; Parihar & Choudhary, 2023). In contrast, composting is an aerobic process that enhances soil health and supports carbon sequestration. It is particularly suited for local or small-scale systems, although it does not provide energy recovery like AD (Parihar & Choudhary, 2023). Incineration is considered less sustainable because biowaste's high moisture content limits energy efficiency and destroys valuable nutrients. Landfilling is the least favorable option, as it leads to methane emissions and resource loss; in Finland, landfilling of organic waste has been prohibited since 2016 (Czekała et al., 2023).

In the European Union, the definition of biowaste is established by the Waste Framework Directive (Directive 2018/98/EC). According to Article 3(4) of the directive, '*bio-waste means biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, whole-sale, canteens, caterers and retail premises and comparable waste from food processing plants'* (European Parliament & Council, 2008/98/EC). Furthermore, the Directive allows Member States to include with bio-waste also packaging materials with similar biodegradability and compostability properties, if those comply with relevant European or equivalent national standards for recovery through composting and biodegradation (European Parliament & Council, 2008/98/EC).

While the Directive provides a general definition, it grants Member States flexibility to specify acceptable materials in biowaste streams. Consequently, significant variation may exist across countries regarding what can be collected together with biowaste (European Commission, 2010). In practice, biowaste often exhibits high moisture content, reducing its calorific value and making it less suitable for energy recovery. Thus, fiber-based compostable packaging can be used as a carrier for food waste. Acceptance of such packaging varies: some countries permit home-compostable materials, others allow even industrially compostable packaging, and certain cases involve temporary acceptance for specific events (European Commission, 2022a; VALUEWASTE, 2020).

6.2 Compostable Fiber-based packaging material in waste streams

In the previous section 6.1, EU legislation was examined and the definition of biowaste, particularly the framework provided by the Waste Framework Directive (2008/98/EC) and the flexibility granted to Member States regarding acceptable materials. It was noted that the high moisture content of biowaste limits its suitability for energy recovery and that fiber-based compostable packaging can serve as a carrier for food waste. Furthermore, acceptance of such packaging varies significantly between countries, depending on factors such as home compostability, industrial compostability, or case-specific exemptions. Thus, there is an opportunity that biowaste collection can offer alternative or even better end-of-life solution opportunities for food contaminated fiber-based packaging material such as anaerobic digestion and composting. When product or packaging is biodegradable, it will break down to specific extent in given time and in specific conditions.

The challenge of fiber-based packaging material in waste streams is that due to food contamination, the packaging may become non-recyclable. There may be too much food leftovers and packaging material has become soggy and wet. Thus, the fiber-based packaging material is not anymore allowed to be put in carton bin, but instead a better route would be to disposal of it with mixed waste, where everything goes to incineration. But what if such fiber-based packaging material would instead follow bio waste fraction that would allow an organic recycling scheme? In that case the fiber is maybe not recycled as fiber but at least used as raw material to produce further to biogas and compost.

Figure 5 illustrates a public waste management challenge at its worst related to discarded fast-food packaging. The waste primarily consists of single-use items such as paper bags, plastic cups, and foodservice containers from fast-food chains. This scenario shows worst case problems in urban waste management of disposable packaging, especially when consumers do not know how to dispose of packaging correctly.

Figure 5. Fast foodservice packaging waste (AI generated by Copilot, 2025)

From a sustainability perspective, the image illustrates the environmental impact of single-use packaging and the challenges of managing it at end-of-life. Many items consist of mixed materials, such as paper with plastic liners, which complicates recycling and composting. This situation reflects the conflict between convenience-driven consumption and circular economy principles and highlights the need for regulatory measures like Extended Producer Responsibility (EPR) and innovations in packaging design to be able to further reduce waste and improve recyclability.

7 End-of-life Alternatives - Recycling, Industrial Composting, Anaerobic Digestion

7.1 End-of-life Alternatives

The designs of fiber-based packaging products for foodservice must consider compatibility with multiple end-of-life pathways, including industrial composting, home composting, and anaerobic digestion and biogas production, while ensuring that mechanical recycling is not hindered (Figure 6). Besides the food residues, mechanical recycling may be hindered also by specific types of barrier layers of the packaging, emphasizing the need for coatings that do not compromise fiber recovery. (Emmert et al., 2021; Kathuria & Zhang, 2022; Mujtaba et al., 2022).

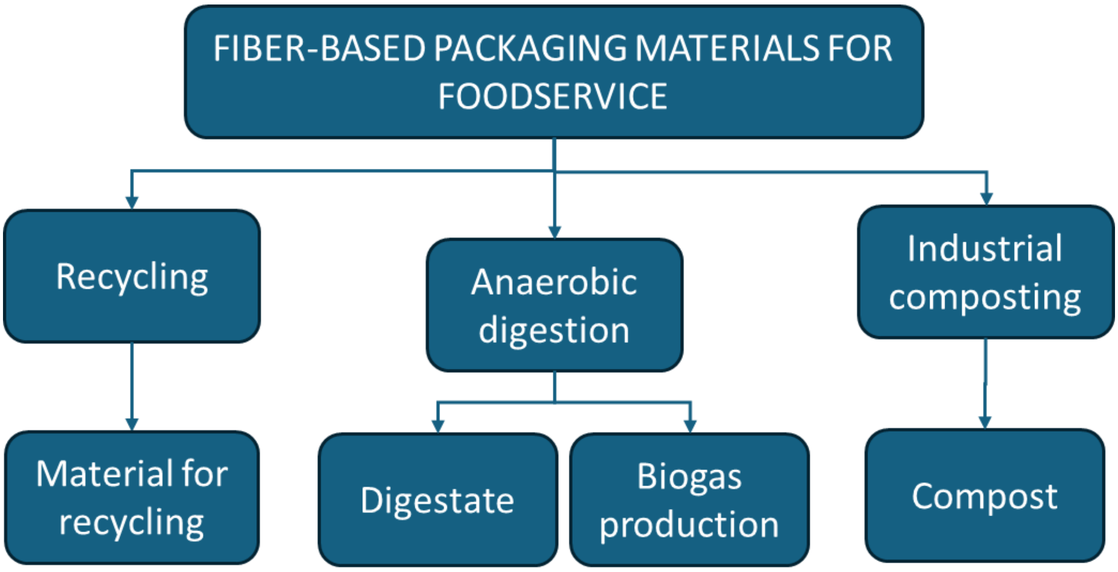

Figure 6. Alternative end-of-life options for fiber-based compostable packaging

Research initiatives are focusing on creating biodegradable and compostable packaging that is suitable for treatment in organic waste facilities. While the preferred approach for foodservice packaging remains reuse or technical recycling, certain designs may include biodegradability under narrowly defined conditions that are established by the European Packaging and Packaging Waste Regulation (European Commission, 2024). These conditions consider factors such as the presence of food contamination at end-of-life, the ability of the packaging to support biowaste separation, and its tendency to appear as a contaminant in organic waste streams. Thus, biological waste management processes, such as composting and anaerobic digestion (AD), offer alternatives to landfill and incineration by enabling nutrient recovery through compost or digestate. (Zimmer, 2025.) Nevertheless, Hilton et al. (2020) noted that biodegradable packaging has little impact on compost quality, which explains the current regulatory criteria limiting its adoption for organic waste treatment.

Zimmer (2025) has emphasized that biodegradation should occur in controlled environments, such as industrial composting facilities or biogas plants that are designed for biowaste processing. The example outlined in figure 7 below, illustrates the intended end-of-life pathways for biodegradable packaging.

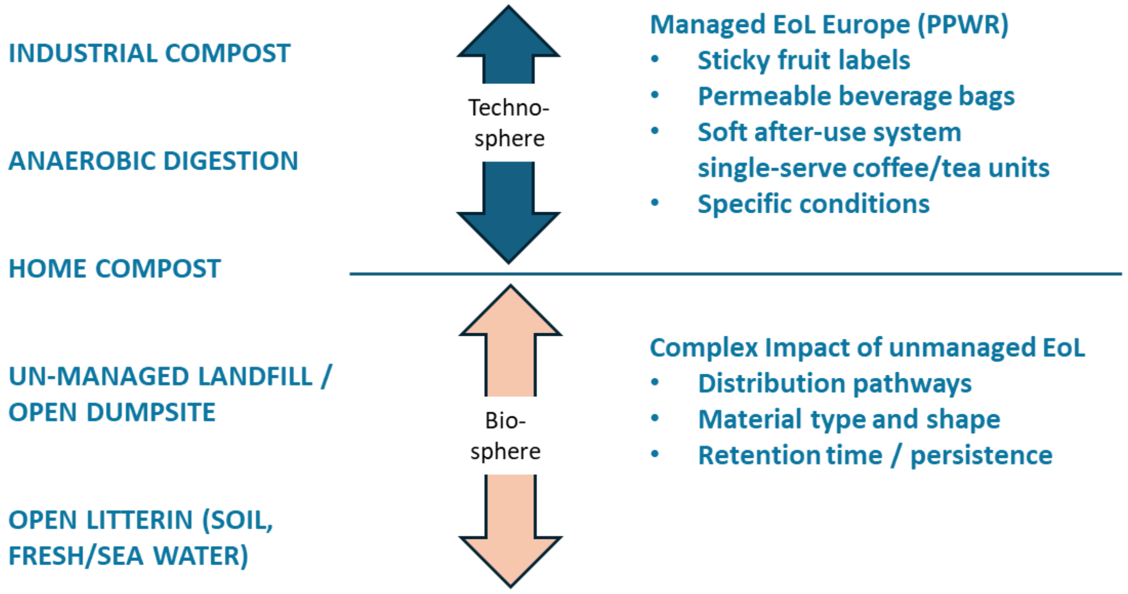

Figure 7. End-of-life pathways for biodegradable packaging (adapted from Zimmer 2025)

Figure 7 illustrates the biodegradability of paper and packaging materials across different end-of-life (EoL) scenarios, distinguishing between managed systems (technosphere) and unmanaged environments (biosphere). Managed end-of-life scenarios, such as industrial composting and anaerobic digestion, operate under controlled conditions and are regulated by standards like EN 13432 and certain certifications that are defined in the EU Packaging and Packaging Waste Regulation (PPWR). These systems can ensure compliance with specific packaging types. In contrast, unmanaged end-of-life scenarios create significant challenges such as open dumpsites and littering in soil or aquatic environments. It is good to note that packaging that has been designed for industrial composting often fails to decompose and break down in home compost or natural environments. (Zimmer, 2025)

Landfill disposal is least ideal for fiber-based packaging, because it does not meet circular economy principles. If paperboard or fiber-based packaging material would end-up in landfills, its organic content can generate methane under anaerobic conditions and methane is a greenhouse gas that has a clearly higher global warming potential compared to carbon dioxide (Ahmed et al., 2018). Additionally, landfilling represents waste management approach, where valuable resources are permanently removed from the material cycle instead of being recovered, recycled or regenerated. This does not only increase the demand for virgin raw materials but also occupies limited landfill space and this contributes to long-term environmental burdens. In contrast, composting or anaerobic digestion allows fiber-based packaging to return to the biological cycle. This supports resource recovery and reduces greenhouse gas emissions. Conversely, discussions often arise regarding scenarios of accidental littering or insufficient recycling infrastructure. Situations that involve unmanaged landfills or environmental littering must not be regarded as chosen end-of-life strategy. (Zimmer, 2025.)

When biodegradable and compostable packaging is developed for controlled end-of-life scenarios, it is essential to consider certification standards and the availability of suitable waste management infrastructures. Zimmer (2025) has stated that various organic waste treatment technologies have emerged and those are primarily driven by the need to process agricultural residues and consumer biowaste. Anaerobic digestion and industrial composting represent the two predominant methods, and those are often implemented sequentially. Consequently, biodegradable and compostable packaging could be designed to ensure compatibility with both processes, anaerobic digestion and industrial composting.

Despite growing interest in anaerobic digestion as a sustainable waste treatment option, the absence of dedicated standards can create uncertainty for compliance and for performance evaluation (Shafana Farveen et al., 2025). The harmonized standard EN 13432 addresses packaging recoverable through composting and biodegradation and includes anaerobic treatability in its scope. It sets requirements for biodegradability, disintegration during biological treatment, and the quality of the resulting compost (European Bioplastics, 2020). However, EN 13432 primarily focuses on industrial composting conditions and does not define performance criteria that are specific to anaerobic digestion or digestate quality (European Bioplastics, 2020). Recent studies highlight this gap, noting that bioplastics and other packaging materials show variable degradation under anaerobic conditions, thus there is a need for standardized methods to assess methane production, disintegration, and biodegradation in anaerobic digestion systems (Gadaleta et al., 2024).

Although the original context of article by Eissenberger et al. (2023) relates to plastics, the principle described in their article is equally applicable here. They emphasize in their article, how important it is to consider end-of-life options for material or product already during the design phase. This is to ensure in design phase that the products are both sustainable and industrially viable. Key strategies in such considerations are include recycling, biodegradation, upcycling, and composting. Among these, improving recyclability is often the most effective way to reduce environmental impact and carbon footprint. Ultimately, the choice of end-of-life pathway should be guided by the material's properties and its intended application.

7.2 Recycling

A circular economy framework aims to preserve highest utility and value of products, components, and materials continuously with a clear separation between technical and biological cycles (Ellen MacArthur Foundation, 2015). For packaging materials, such as plastics and paper, industry advancements include the development of both mechanical and chemical recycling processes that are complemented by regulatory measures that can accelerate the transition towards circularity.

As already discussed, food-contaminated fiber-based packaging is generally unsuitable for recycling due to residual food that reduces the quality of recovered fibers and introduces hygiene concerns Williams, 2025; Zimmer, 2025). Recycling processes require clean, uncontaminated material streams to be able to maintain efficiency and product integrity (Ellen MacArthur Foundation, 2015). Contamination increases operational costs and can lead to the rejection of entire recycled fiber batch. For this reason, foodservice packaging such as trays, clamshells, and disposable containers is rarely recycled after use. Instead, these items are better directed to organic waste treatment systems, such as industrial composting or anaerobic digestion, where both packaging and food residues can be processed together (Williams, 2025; Zimmer, 2025). Consequently, this thesis does not address recycling pathways for food-contaminated fiber-based packaging but focuses on compostable solutions that align with circular economy principles and reduce landfill disposal.

7.3 Composting

There is increasing interest in developing fiber-based packaging materials that are both home and industrially compostable to improve sustainability and end-of-life management for foodservice packaging materials. These solutions are particularly relevant for quick-service restaurants, on-the-go consumption, and products with short shelf-life, where packaging often becomes contaminated with food residues and is difficult to separate from organic waste streams. Compostable materials allow diversion into organic waste treatment systems, reducing landfill disposal and supporting circular economy goals. (Emmert et al., 2021; Kathuria & Zhang, 2022; Mujtaba et al., 2022) However, achieving compostability without compromising functional properties such as moisture and grease resistance remains yet challenging. Critical research and innovation area are to balance these requirements; performance, compostability, and recyclability (Kathuria & Zhang, 2022; Mujtaba et al., 2022; Emmert et al., 2021).

It is important to note that conditions for biodegradation vary significantly. For example, what works in industrial composting may not work in home composting or aquatic environments, mainly because these environments have lower temperatures. In Europe, there is currently no unified standard for this. However, there are methods to test how plastics biodegrade under anaerobic conditions, such as in biogas plants. (Eissenberger et al., 2023) End-of-life alternative alternatives of industrial composting ensure complete biodegradation under controlled conditions. Home composting is less reliable due to lower temperatures and inconsistent environments. (Emmert et al., 2021; Kathuria & Zhang, 2022; Mujtaba et al., 2021).

The minimum requirements for packaging to be recoverable through composting and biodegradation are defined by the European standard EN 13432. It specifies four key criteria 1) *Biodegradability*, conversion of at least 90% of organic carbon into CO_2 within six months, 2) *Disintegration*, less than 10% of the original material remains after 12 weeks in composting conditions, 3) *Effect on the composting process*, material must not hinder biological treatment and 4) *Quality of the resulting compost*, no negative impact on compost quality or soil health (European Bioplastics, 2015). Biodegradability depends on chemical structure rather than material origin, and certified products ensure safe integration into industrial composting systems without contaminating the final compost.

Industrial composting is a controlled biological process that transforms biodegradable waste into stable, sanitized compost suitable for agricultural use and it must operate under optimized conditions. Typically, temperatures vary between 50°C and 60°C, with a hygienization phase that requires at least one week at above 60°C temperature to be able to eliminate pathogens. The process consists of two main stages: active composting, where microorganisms rapidly degrade organic matter, and curing, during which decomposition slows and humic substances form (European Bioplastics, 2009).

Industrial composting contributes to circular economy goals by diverting biowaste from landfills and incineration, reducing methane emissions, and producing valuable compost for soil improvement. It also supports separate biowaste collection and reduces contamination in organic recycling streams. However, successful composting requires strict control of process parameters and input quality. Materials labeled as ‘industrially compostable’ must meet EN 13432 standards to avoid misleading claims and ensure environmental benefits (European Bioplastics, 2015).

Lifecycle assessments indicate that compostable solutions can reduce environmental impact compared to fossil-based plastics, provided they are properly managed at end-of-life to avoid landfill disposal and microplastic formation. (Emmert et al., 2021; Kathuria & Zhang, 2022; Mujtaba et al., 2022) Project Manager Holopainen (Spring 2024) has stated in internal training session of Finnish forest industry company that, beside the market value, when material is directed to compost, it enables carbon sequestration in soil and the compost acts as carbon sink and improves conditions of soil. Compost has also value as fertilizer as compost as product directly from digestate, could replace some fertilizers. The utilization of compost would enable potential to increase the degree of dependency of the imported fertilizers.

7.4 Anaerobic Digestion and Biogas Production

At the end of its lifecycle, fiber-based compostable packaging can also serve as a raw material for anaerobic digestion. Anaerobic digestion offers potential for biogas recovery but requires material compatibility with existing systems (Emmert et al., 2021; Kathuria & Zhang, 2022; Mujtaba et al., 2022). This process enables the production of biogas from food waste with high efficiency, and the biogas can be further upgraded into biofuels. Anaerobic treatment plants utilize anaerobic digestion to break down organic matter in the absence of oxygen and producing biogas as a renewable energy source and a nutrient-rich residue that is known as digestate. This process relies on a microbial ecosystem that converts organic substrates into methane and carbon dioxide and the digestate serves as a valuable fertilizer or soil improver (Alengebawy et al., 2024; Jacob et al., 2025).

Anaerobic digestion helps to make waste management more sustainable when use of landfills is avoided. This can reduce uncontrolled methane emissions and contribute to climate change mitigation and at the same time, biogas production supports renewable energy goals. Digestate recycling promotes nutrient recovery and makes anaerobic treatment plants an essential part of circular economy strategies (González et al., 2022).

Paperboard products can contain coatings or chemical additives, those unwanted components, in respect to anaerobic digestion, hinder anaerobic digestion or lead to harmful byproducts during processing of biogas (Gonzalez-Estrella et al., 2017; Zhang et al., 2015). Additionally, fiber-based waste alone has typically high lignocellulosic content which makes it more resistant to microbial breakdown and potentially prolong the digestion time, which leads to reduced biogas production efficiency (Song et al., 2021). To optimize biogas yield, the overall composition of the feedstock must be carefully balanced. An option for the feedstock optimization is through co-digestion with other organic materials that are more easily degradable. Such material is for example food waste (Dhull et al., 2024). Including fiber-based packaging material together with food waste can be beneficial, as it can help to create balanced feedstock and to support efficient biogas production. This approach can improve process stability and methane output and ensure that anaerobic digestion remains an effective and sustainable waste-to-energy solution.

When feedstock quality is well maintained, more stable and efficient biogas production can be achieved, because substrate characteristics, such as solids content, C/N ratio, particle size also strongly influence hydrolysis rates, microbial community dynamics, and methane yields (Ibrahim et al., 2025; Tomczak et al., 2024). In optimization of biogas production efficiency and to maintain feedstock quality, a proper waste segregation and handling are essential. Equally important is collaboration among waste management authorities, waste producers, and biogas plant operators to secure consistent supply chains and to ensure the successful implementation of a waste-to-energy system while meeting the regulatory and performance targets (Ibrahim et al., 2025; Singh et al., 2022).

Some authors have stated that for instance bioplastics can actually benefit biogas production by improving the carbon-to-nitrogen balance. Ongoing research is exploring different ways, how to make certain polymers degrade more easily and become better suitable for home composting as well. This could enhance both biogas production and anaerobic digestion overall (Eissenberger et al., 2023).

When food contaminated fiber based packaging is used as a raw material for anaerobic digestion, dedicated infrastructure is required, including separate collection and preprocessing (sorting, depackaging, cleaning, and removal of non-biodegradable contaminants), to produce a slurry compatible with digester technology and to mitigate process inhibition associated with lignocellulosic recalcitrance (Environmental Protection Agency, 2021; Gonzalez Estrella et al., 2017; Song et al., 2021). Contamination control is essential. Plastics, metals, and trace chemicals can impair microbial activity, accumulate in digestate, and pose operational risks, underscoring the need for systematic screening and pretreatment prior to digestion (Environmental Protection Agency, 2021). It is essential also to manage the digestate through processes such as separation, hygienization and post-composting in a proper way. Thus, the value of the digestate is preserved and environmental standards met. This emphasizes the need of continuous monitoring and quality control throughout the entire process chain (Ibrahim et al., 2025; Singh et al., 2022).

Anaerobic digestion (AD) is recognized as a form of organic recycling under the EU Packaging and Packaging Waste Regulation (PPWR), there is currently no dedicated European standard that specifies detailed requirements for biodegradation, disintegration, and digestate quality in AD processes. The PPWR acknowledges organic recycling, which includes composting and anaerobic digestion, as recovery options for packaging waste but does not provide technical specifications for AD beyond general sustainability criteria (European Commission, 2024).

8 Regulatory frameworks

8.1 Single-use plastic directive

The EU Single-Use Plastics Directive (SUPD) 2019/904 is primarily aimed at reducing plastic pollution, but it has significant implications also for fiber-based packaging materials. The directive defines ‘plastic’ broadly, including polymer coatings that are applied to paperboard products (European Commission, 2021). The final product falls within the scope of the directive, when product is considered to be such composite product that is made partly of plastic, when a plastic coating or lining is applied to paper or board-based material to provide protection against water or fat. (European Commission, 2021) Consequently, items such as paper cups or foodservice containers with plastic coatings are thus subject to restrictions, labeling requirements, and extended producer responsibility (EPR) fees (European Commission, 2021; European Commission, 2022b).

This regulatory pressure has accelerated innovation towards fully fiber-based solutions and alternative barrier technologies, such as water-based coatings and biodegradable polymers. These products aim yet to maintain functionality while ensuring compliance. However, the sustainability benefits of such packaging materials depend not only on their design but also on the availability of appropriate end-of-life management systems. (Van Eygen et al., 2018) SUPD therefore acts as a 'catalyst' for the development of plastic-free fiber packaging. It reinforces the need for robust end-of-life strategies and the transition to circular and sustainable packaging systems within the EU market (European Commission, 2021; European Commission, 2022b).

8.2 Packaging and Packaging Waste Regulation

The European Union's Packaging and Packaging Waste Regulation (PPWR) introduces comprehensive requirements for packaging sustainability, with significant implications also for fiber-based materials. The regulation entered into force on February 12, 2025, and will apply from August 12, 2026, with sequential requirements applying until 2030 and beyond. Its primary objective is to ensure that all packaging placed on the EU market is recyclable by 2030 and recyclable at scale by 2035, meaning it must be widely collected, sorted, and processed (European Commission, 2025). To achieve this, PPWR establishes recyclability performance grades: Grade A for packaging with at least 95% recyclability, Grade B for 80%, and Grade C for 70%. Packaging that falls below 70% recyclability will be prohibited from 2030 (ERP Recycling, 2025).

Compostable packaging under PPWR is permitted only in specific cases where it provides a clear environmental benefit, such as biowaste collection (European Bioplastics, 2025). By 2028, certain items, including sticky labels on fruits and vegetables, tea and coffee bags, and specific filter materials, must be compostable and comply with the EN 13432 industrial composting standard (European Bioplastics, 2025). The European Commission will request harmonized standards for compostable packaging by February 2026 to ensure technical specifications are consistent across Member States (ERP Recycling, 2025). Compostable packaging is exempt from minimum recycled content requirements for plastics, but Member States may impose additional rules for home composting and joint collection with biowaste (ERP Recycling, 2025). Importantly, compostable materials must not disrupt recycling streams, and mixed systems combining compostable and recyclable components are discouraged (InNaturePack, 2025).

Fiber-based packaging is strongly supported under PPWR due to its high recyclability rate. For food-contaminated fiber packaging, recycling efficiency decreases significantly when contamination is heavy. In such cases, PPWR encourages organic recycling through composting, provided the material meets compostability standards (European Bioplastics, 2025). Additionally, fiber packaging that incorporates plastic coatings must adhere to strict limits. Under the regulation's minimum recycled content requirements for plastic packaging, packaging components comprising a maximum of 5% of the total packaging mass are exempt from the recycled content mandates (ERP Recycling, 2025). Furthermore, the regulation bans the use of PFAS and other restricted chemicals from August 2026 onward.

To ensure compliance, PPWR recommends a structured approach when selecting an end-of-life alternative for fiber-based compostable packaging. First, recyclability should be prioritized whenever possible. When aiming for compostability, certification under EN 13432 is required (European Bioplastics, 2025). Manufacturers must avoid mixing compostable and recyclable fiber streams, eliminate PFAS and other restricted substances, and provide clear labeling to guide consumers on proper disposal (EPR Recycling, 2025).

Table 5 summarizes the conditions representing different states of fiber packaging (clean, food-contaminated, plastic-coated, compostable, or containing restricted chemicals) and the preferred disposal route, indicating whether the packaging should be recycled, composted, or redesigned. It also explains the rationale for each route based on EU PPWR requirements. As shown in table 5, under the PPWR framework, recycling is prioritized as the preferred disposal route for fiber-based packaging whenever feasible, including clean and lightly contaminated items and those with plastic coatings up to 5% by weight. Composting is permitted only for EN 13432-certified packaging in biowaste streams or when heavy food contamination significantly reduces recycling efficiency. Packaging that exceeds the 5% plastic threshold or contains restricted substances such as PFAS is considered non-compliant and must be redesigned. Overall, PPWR emphasizes maximizing recyclability, minimizing contamination, and eliminating harmful chemicals to support circular economy objectives.

Table 5. Decision Matrix for Fiber-Based Packaging Disposal under PPWR (Adapted from PPWR compliance guidelines; ERP Recycling, 2025; European Bioplastics, 2025b)

Condition	Preferred Disposal Route	Reasoning under PPWR
Clean fiber packaging (no food residue)	Recycling	Meets recyclability targets; fiber recycling is widely available.
Light food contamination (e.g., crumbs)	Recycling	Minor contamination is acceptable; prioritize recycling over composting.
Heavy food contamination (e.g., greasy pizza box)	Composting (if EN 13432 certified)	Recycling efficiency drops; composting allowed for biowaste-compatible items.
Fiber packaging with plastic coating <5%	Recycling	Still classified as recyclable under PPWR if plastic ≤5% by weight.
Fiber packaging with plastic coating >5%	Neither (Redesign)	Non-compliant; must be redesigned to meet recyclability thresholds.
Compostable fiber packaging (EN 13432)	Composting (specific streams)	Allowed only for biowaste-related applications; must not disrupt recycling streams.
Contains PFAS or restricted chemicals	Not allowed	PPWR bans PFAS from Aug 2026; must eliminate these substances.

9 Extended Producer Responsibility

9.1 Extended Producer Responsibility (EPR)

Extended Producer Responsibility (EPR) is an environmental policy framework that makes producers financially and, in some cases, operationally responsible for the end-of-life management of products and packaging they place on the market. The goal is to shift waste management costs away from municipalities and consumers and to encourage producers to design packaging that is easier to recycle, reuse, or compost (OECD, 2021a).

EPR schemes involve fees paid by producers to cover collection, sorting, and recycling costs. These fees are often eco-modulated, meaning they vary based on material characteristics such as recyclability and environmental impact. This approach promotes sustainable packaging design, and identifies those materials that hinder circularity (Joltreau, 2022). EPR has become a central component of circular economy policies in the European Union and other regions and is supported by regulations such as the Packaging and Packaging Waste Directive (European Commission, 2025).

Based on national legislation and aligned with the EU Packaging and Packaging Waste Directive, almost all EU Member States have introduced Extended Producer Responsibility (EPR) schemes for packaging material. However, implementation differs significantly across countries. In some Member States, a single Producer Responsibility Organization (PRO) manages compliance, while others have a highly fragmented system with multiple PROs offering EPR services to producers. This diversity reflects the flexibility that is allowed under EU law for national adaptation of EPR requirements. (EUROPEN, 2025)

In most EU Member States, to meet legal obligations under Extended Producer Responsibility (EPR), companies placing packaging on the market must register with an approved Producer Responsibility Organization (PRO) and participation in an EPR scheme is generally mandatory for market access. While the key principles are harmonized under EU law, specific requirements, such as registration procedures, reporting obligations, and fee structures, vary significantly between countries. Therefore, businesses must review and ensure compliance with each national regulations and in each of their target markets. (Deutsche Recycling, 2024)

Current ecomodulation criteria in most EPR systems primarily aim to improve the recyclability of packaging rather than the prevention of waste at its source. Packaging is generally considered a non-durable product that becomes waste after a single use. As a result, criteria related to product’s life time, such as durability, play a minimal role in fee modulation. An exception is when the focus is on reusable packaging products. For effective waste prevention, multiple use cycles and the avoidance of single-use packaging are essential. Thus, reusability is a critical criterion. However, several challenges can hinder the adoption of reusable systems. There are no binding reuse targets, and the current framework emphasizes recycling rates over the reuse and the lack of logistical infrastructure often makes single-use packaging more cost-effective. Implementing reusable systems would require robust return logistics, which are frequently absent. Without such return logistics systems, packaging rarely returns to producers, and heavier reusable packaging can even increase costs for producers (Sachdeva et al., 2021). In some cases, reuse can lead to even greater environmental impacts due to factors such as transportation logistics and the energy and water required for washing.

Figure 8 illustrates how Sachdeva et al. (2021) have stated how EPR fees could better support circular economy goals and the waste hierarchy. Currently, ecomodulation mainly focuses on recycling and recovery, leaving prevention and reuse underemphasized. The desired shift is to align fees with environmental performance. There are lower fees for prevention and reuse, and higher fees for disposal. This approach would incentivize producers to design packaging that avoids waste and supports multiple use cycles, rather than relying solely on end-of-life recycling.

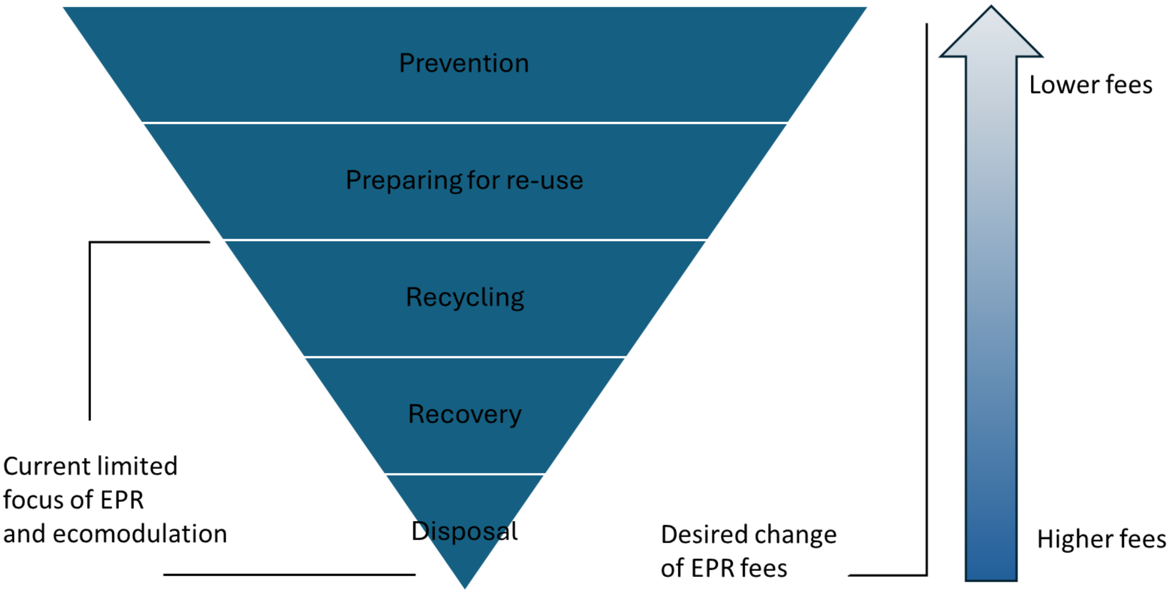

Figure 8. Waste hierarchy and ecomodulation of EPR fees (Adapted from Sachdeva et al. 2021)

The criteria for EPR fees should also be easily understandable, auditable, and enforceable (OECD, 2021b). Existing EPR frameworks emphasize end-of-life handling rather than promoting design strategies for waste reduction and reuse. In most EU countries, Extended Producer Responsibility (EPR) fees primarily cover downstream waste management costs, such as collection, transport, sorting, and recycling/treatment. These fees rarely address upstream measures like eco-design, reparability, or reusability. (Sachdeva et al., 2021)

9.2 Extended Producer Responsibility for packaging material

Recent developments include compostable fiber-based alternatives, which promise enhanced sustainability but may introduce new challenges in infrastructure and compliance. Extended Producer Responsibility (EPR) places both financial and operational obligations on producers for managing packaging materials at the end of their lifecycle. (European Commission, 2025; OECD, 2021b) EPR schemes aim to incentivize sustainable packaging design and reduce waste generation by imposing fees that are based on material type, recyclability, and environmental impact (OECD, 2021b). In foodservice packaging, where both fiber-based and plastic-based materials dominate, EPR fees can significantly influence the material selection and innovation (European Commission, 2025; OECD, 2021b). As mentioned, EPR fees are typically eco-modulated, meaning they vary according to recyclability, material complexity, toxicity, and environmental performance (European Commission, 2025; OECD, 2021b). Materials that are easily recyclable have generally lower fees, whereas multilayer plastics and composite structures have higher charges due to limited recycling options and possible challenges in sorting (OECD, 2021b).

Eco-modulation within EPR schemes promotes sustainable design choices by rewarding recyclability and penalizing those materials that hinder resource recovery (European Commission, 2025; OECD, 2021b). Compostable materials can receive preferential treatment under some EPR programs. However, it is required that they meet recognized standards such as EN 13432 for industrial compostability. Modulation remains complex because compostable packaging requires specialized facilities, and its environmental benefits depend on proper collection and processing systems. (European Commission, 2025) The presence of hazardous substances, such as PFAS, can further increase fees because these substances should be avoided (European Commission, 2025; OECD, 2021b) and their presence can contaminate recycling streams (European Commission, 2025). Additionally, packaging that incorporates recycled content often qualifies for fee reductions because it aligns with circular economy objectives (European Commission, 2025; OECD, 2021b).

As already mentioned, the level of EPR fees can vary significantly depending on whether the fiber-based packaging is recyclable or compostable. Recyclable fiber packaging can integrate well into existing collection and recycling systems, which generally results in lower fees and compostable fiber packaging can receive discounts if it meets certain criteria (OECD, 2021b). However, the lack of industrial composting infrastructure in many regions may limit their practical advantage (Dolci et al., 2025). For example, the conditions required for the biodegradation of polylactic acid (PLA) are not met in several composting plants (Dolci et al., 2025, p. 52). In practice, the lack of infrastructure in many regions may limit the realization of these discounts (Dolci et al., 2025), which can lead to fees remaining at the same level or even increasing compared to recyclable alternatives. Eco-modulation within EPR systems rewards actual recyclability or compostability in practice, not merely technical properties, which highlights the importance of compatibility between packaging design and waste management systems (Joltreau, 2022; OECD, 2021b).

Comparative studies indicate that plastics outperform fiber-based materials in terms of durability and shelf-life, whereas fiber-based options excel in biodegradability and offer benefits in carbon footprint reduction (Dolci et al., 2025, p. 3). Plastic packaging, particularly multi-layer films and rigid containers, have significantly higher EPR fees due to their low recyclability (Joltreau, 2022). While plastics offer superior durability and barrier properties, their environmental footprint and end-of-life challenges can result in higher costs under EPR schemes (Dolci et al., 2025, p. 1). By contrast, compostable fiber-based alternatives align better with circular economy principles, but may require systemic changes in waste management infrastructure (Dolci et al., 2025, p. 2, 52).

Regulatory trends impact design choices seem to be pushing manufacturers towards biodegradable coatings materials and compostable solutions. However, functional requirements for foodservice packaging often require barrier coatings or laminates, which can hinder recyclability and compostability. Fiber-based packaging is increasingly favored under EPR frameworks due to its high recyclability and renewable origin. These materials often fall into the lowest fee levels because they seem to integrate well with existing recycling systems, even if those may require systemic changes in waste management infrastructure. (Kathuria & Zhang, 2022).

10 Stakeholders

Stakeholders in different stages of lifecycle of product’s value chain should be considered to ensure a comprehensive understanding of the end-of-life alternatives for fiber-based packaging for foodservice. Figure 9 illustrates the stakeholder interactions throughout the lifecycle of fiber-based packaging under PPWR. Figure highlights the roles of packaging manufacturers, foodservice operators, and representatives of waste management and biogas plants, while showing oversight by regulatory authorities and producer responsibility organizations (PROs). Figure 9 emphasizes collaboration across the whole value chain to ensure compliance with technical, economic, and regulatory requirements.

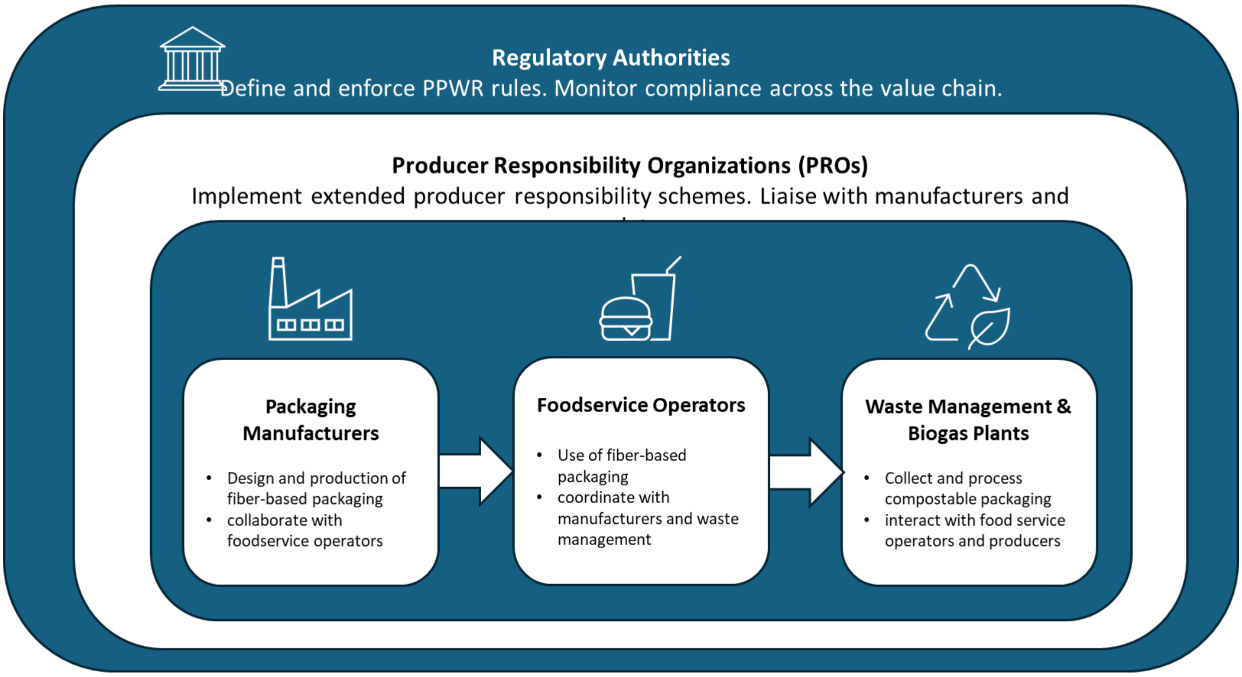

Figure 9. Stakeholders Throughout the Life Cycle of Fiber-Based Packaging

Different stakeholder groups play specific roles in the fiber-based packaging value chain and pursue objectives that are aligned with their responsibilities. Packaging manufacturers focus on product development and compliance with compostability and EPR requirements. Foodservice operators aim to address practical sorting challenges and procurement decisions. Waste management and biogas plants evaluate the suitability of packaging for composting and anaerobic digestion. Whereas authorities concentrate on regulatory impacts and end-of-life solutions. Producer Responsibility Organizations manage EPR fees and clarify their implications for compostable packaging. A complete lifecycle assessment of fiber-based packaging depends on considering the views of all stakeholders, from material producers to end-of-life operators, to provide a truly holistic understanding of viable end-of-life alternatives. Table 6 presents the stakeholder groups and their roles in the value chain.

Table 6. Stakeholders and their Objectives in value chain

Stakeholder Group	**Role in Value Chain**	**Objective**
Packaging Manufacturers	Product development and manufacturing	Understand the importance of compostability, the impact of EPR fees, and development challenges.
Foodservice Operators	Use and sorting of packaging	Identify practical challenges in sorting and the influence of compostability on procurement decisions.
Waste Management & Biogas Plants	Biowaste processing and biogas production	Assess the suitability of fiber-based packaging for composting and anaerobic digestion.
Authorities	Regulation and guidance	Understand the impact of legislation and identify development needs for EoL solutions.
Producer Responsibility Organizations	Management of EPR fees	Clarify how EPR fees are determined and their implications for compostable packaging.

11 Findings and discussion

In Europe, regulatory frameworks such as the Single-Use Plastics Directive (SUPD) and Packaging and Packaging Waste Regulation (PPWR) are reshaping the responsibilities of producers through mechanisms like Extended Producer Responsibility (EPR). These frameworks are reshaping the packaging and food industries by promoting circular material use and promoting environmental performance standards. Therefore, there is a growing demand also for sustainable packaging solutions to enhance the transition from conventional plastics to fiber-based materials for foodservice packaging materials. Although fiber-based packaging is often considered preferable to plastics, its environmental and economic performance largely depends on end-of-life management.

The purpose of this thesis was to collect and summarize insights on end-of-life options for compostable fiber-based foodservice packaging materials, as well as the factors influencing these alternatives.

Regulatory challenges

Current EU legislation (SUPD, PPWR) does not necessarily fully address the unique position of compostable fiber-based packaging, which often falls between recyclable and biodegradable categories. The prioritization of PPWR is to enhance recyclability as the default requirement, and compostable packaging must not disrupt recycling systems. Another aspect to consider in respect to compostable fiber-based packaging materials is, that SUPD (Single-Use Plastics Directive) and PPWR are complementary. However, SUPD mainly targets plastic items, while PPWR covers all packaging types. Thus, compostable fiber-based packaging may fall into a gray area because it is neither fully recyclable nor fully exempt under SUPD.

Economic implications

The costs associated with different end-of-life alternatives for foodservice packaging vary significantly depending on factors such as used raw material types, local waste management infrastructure, and implementation scale. Each disposal method presents specific economic, environmental, and logistical challenges.

Recycling is often cost-effective for materials like paper and cardboard. However, due to food contamination, foodservice packaging is no longer suitable for recycling or would increase processing expenses due to additional cleaning and sorting requirements. Composting biodegradable packaging could be with lower costs when supported by established infrastructure. Although, the costs can rise if special conditions are needed for decomposition or if industrial facilities impose fees. Incineration generally incurs high costs because of specialized facilities, yet energy recovery can partially offset these expenses.

Traditionally, consumers have had financial and logistical responsibilities associated with the recycling and disposal of packaging materials. Extended Producer Responsibility (EPR) legislation reallocates this to manufacturers by imposing fees that contribute to the costs of waste management processes. Extended Producer Responsibility framework has differentiated fee structures and there are higher charges for materials such as plastics, which have more challenges in recycling and in contrast, the fees are lower for more easily recyclable materials, such as paper, glass, or metal. Use of such materials that are easier to recycle can create economic motivators for producers to adopt more sustainable packaging alternatives.

Unfortunately, regulatory uncertainty can create challenges for producers and waste managers as Extended Producer Responsibility (EPR) fees for compostable fiber-based packaging are yet unclear. Currently, compostable packaging does not automatically qualify for reduced EPR fees and in fact, those may even face higher fees unless future exemptions or differentiated fee structures are introduced. For compostable fiber-based packaging, the implications of these regulations can be complex, as the material often falls between categories of recyclable and biodegradable waste streams. There is a need to align packaging design with real waste management capabilities. Recyclable options fit existing recycling systems and usually have lower fees, and compostable packaging may qualify for discounts under EN 13432 but this can be limited due to possible lack of existing industrial composting infrastructure. In practice, fees of the compostable packaging can remain high or even exceed those for recyclable alternatives unless exemptions or differentiated fee structures are introduced.

Composting offers clear benefits and potential value for communities and downstream actors in the value chain. However, adopting such a compostable product concept is likely to increase production costs of fiber-based packaging materials. It is therefore essential to consider where the added value for board producers and their customers originates. Particularly in justifying a possible increase in product prices. A critical question is whether customers could compensate these costs? One of the ultimate targets also should be that, when packaging is minimized or designed to be more recyclable with appropriate end-of-life alternative, financial benefits should not gain financial benefit only to producers but also to consumers who choose products with lower environmental impacts compared to similar alternatives.

Due to regulatory uncertainty and expected higher production cost, it could be speculated that the economic viability of compostable fiber-based packaging also depends on balancing between increased production costs with potential savings from reduced EPR fees, but this would require differentiated fee structures as reduced EPR fees for compostable alternatives. For these efforts to succeed, policymakers must ensure that fee structures remain transparent and that infrastructure for composting and recycling is expanded. Without such systemic support, the potential benefits of compostable packaging will remain limited.

Technical properties and research of compostable fiber-based materials

A key difficulty in sustainable packaging design is in the trade-offs between functional requirements. To overcome such technical properties or specification limitations, manufacturers frequently use multi-layered or composite structures. While effective for performance, these designs significantly hinder waste stream separation.

Compostable fiber-based materials may lack moisture and oxygen resistance and provide weaker barrier properties compared to plastics, leading at the end to the need for coatings that can compromise compostability. When packaging is designed to biodegrade in controlled industrial composting facilities often biodegradable polymer coatings are also used to enhance the barrier properties. However, packaging should never be intended to degrade in uncontrolled environments. Additionally, the cost considerations can be significant, as compostable fiber-based packaging materials generally entails higher raw material costs. As mentioned, these costs could be partially offset by Extended Producer Responsibility (EPR) fee reductions and growing consumer demand for sustainable solutions. These gaps highlight that there is a need to assess lifecycle cost considerations already early in product research and development when making material choices.

It is important to note as well that not all fiber-based packaging is suitable for composting or recycling with food waste. Some fiber-based packaging may have coating materials, used ink types, or other additives that could hinder biodegradation or contaminate the compost. To ensure that fiber-based packaging is compatible with food waste composting, it is essential to use packaging that is specifically designed to be compostable and also certified as compostable according to relevant standards. Proper labeling and certification information on the packaging can help consumers and waste management facilities identify compostable materials correctly.

More and more companies use the term ‘compostable’ to position their products as eco-friendly, reflecting the growing priority of sustainability and environmental concerns. For a product to be truly compostable, it must be made from materials that fully decompose without leaving toxic residues and meet the standards defined by relevant regulations. However, not all products claiming to be compostable are accepted by local councils. It is also important to note that packaging designed for industrial composting may not be suitable for home composting, and some industrially compostable materials do not fit into general waste management systems. Therefore, always the proper disposal by end-users is essential.

Although fiber-based packaging is often considered preferable when compared to plastics, its environmental and economic performance largely depends on end-of-life management. Inefficient disposal or recovery processes, or misalignment with regulatory frameworks, can decrease expected sustainability benefits. Therefore, these factors must be addressed already during the product development stage through a comprehensive evaluation of end-of-life (EoL) strategies.

The growing gap in EPR fees between fiber-based and plastic packaging is accelerating material substitution and innovation. There is interest in mono-material fiber solutions and exploring compostable technologies to reduce compliance costs and meet sustainability targets. As stated before, also the Extended Producer Responsibility fee is intended to encourage producers to consider environmental factors already during the design and manufacturing stages of product development. The goal is to reduce the overall environmental impact of products throughout their entire lifecycle, from production to end-of-life.

Compostable fiber-based materials in waste streams

Compostable fiber-based packaging offers a viable alternative to conventional plastics, particularly for single-use foodservice. Fast-food package waste is for instance the waste generated from the containers, wrappers, cups, and utensils that are used as packages and to serve fast-food items in restaurants, cafes, etc. This type of waste can make significant environmental challenges due to its volume, single-use nature, and potential for littering. As already discussed, the challenge of fiber-based packaging material in waste streams is that due to food contamination, foodservice packaging often becomes non-recyclable. There may be too much food leftovers and packaging material has become soggy and wet. Thus, the fiber-based packaging material is not anymore allowed to be put in carton bin together with cartonboard, but instead a better route would be to dispose it with mixed waste, where everything goes to incineration. But as discussed earlier, what if such fiber-based packaging material would instead follow other biowaste fractions that would allow an organic recycling scheme? In that case the fiber is maybe not recycled as fiber but at least used as raw material to produce compost or biogas and digestate to be further treated to create nutrient-rich compost for agricultural use or soil improvement. Fiber-based packaging can be produced to be biodegradable, meaning it can naturally break down into organic materials over time. When it is together with food waste, both the packaging and the food waste could be composted together, that can promote a more sustainable waste management approach.

There are already fiber-based packaging materials that are certified as compostable. This means that they meet specific standards for biodegradation in a composting environment. When composting food waste and fiber-based packaging together it can help create nutrient-rich compost that can be used as a natural fertilizer for plants and soil. The increased use of compostable fiber-based packaging for foodservice can help to reduce contamination in organic waste streams, when having compostable packaging instead of non-compostable packaging which may hinder composting process and result in lower-quality compost if non-compostable packaging is mixed with food waste.

Fiber-based waste can be utilized for biogas production. When combined with other organic materials, fiber-based waste may become a valuable feedstock for biogas generation.

Compostability of high yield pulps

It is also important to note that the rate of biodegradation during composting depends on the type of fiber used in the board and the lignin content of the fiber type. High yield mechanical and chemimechanical pulps decompose slower as those retain higher levels of lignin compared to chemical pulps. This is because lignin interferes with cellulose breakdown, slows down the fiber decomposition and tends to form humus rather than degrading fully during composting. This restricts the proportion of mechanical and chemimechanical pulps that can be used in board production when compliance with compostability standards is required.

That said, research shows that adding structural materials such as fibers during composting can significantly improve the process and the quality of the final product. Fiber addition is an effective strategy for producing high-quality organic soil amendments as fibrous additives in compost enhance aeration and reduce compaction. Fibrous material also helps to maintain optimal moisture levels of the compost, which further accelerates microbial activity and decomposition. Fibrous material also contributes to a balanced carbon-to-nitrogen ratio and improves nutrient retention in the compost. (Barthod et al., 2018)

For this reason, it would be essential to adopt also a holistic perspective and consider the entire lifecycle of composting when defining compostability criteria. The question arises whether all fiber materials should fully biodegrade, if fibers are yet to be added to the compost at a later stage of the process? Addressing this requires evaluating not only the initial composting phase but also later steps to ensure that the material does not compromise the quality or safety of the final compost product.

Recommendations and directions for future research

A holistic approach that accounts for both material compatibility and regulatory requirements is necessary to ensure that the final product achieves product’s intended environmental and functional objectives. When considering compostability and technical properties of packaging material, it is essential that not only the individual materials are evaluated separately, but to evaluate also what is the performance of the combination of those materials? For instance, what is the interaction between the paperboard substrate and applied barrier coatings layer? Do those interactions have an influence or impact on disintegration, biodegradation rates, and compliance with established standards. These factors will also determine whether the product will meet compostability standards criteria under industrial or home composting conditions. Furthermore, it needs to be evaluated does the material integration affects critical aspects such as food safety, barrier functionality, and sustainability performance.

Vinitskaia et al. (2025) highlight significant research gaps that are also relevant to this thesis. These include the absence of systematic environmental performance assessments, such as life cycle analysis (LCA), the frequent use of terms like ‘sustainable’ and ‘biodegradable’ without standardized metrics, limited research on material convertibility and film formability after industrial processing, and a lack of studies evaluating real food preservation and shelf-life when using bio-based coatings. When searching for literature this thesis, these research gaps can be agreed as a need for further study. Vinitskaia et al (2025) have also highlighted, that there is yet absence of harmonized testing protocols for recyclability and biodegradability under different disposal conditions. This lack of standardization makes it difficult to verify environmental claims and ensure compliance across markets.

Consumer demand for compostable products is strong and often based on the misunderstanding that such items will biodegrade anywhere. Improving consumer awareness and education is critical to the success of compostable packaging systems. Clear labeling and identification of compostable products and packaging is essential also for effective waste management. Informed consumers are more likely to dispose compostable products correctly and thus contamination in waste streams can be reduced and ensured that these compostable materials reach appropriate processing facilities and end-of-life alternatives. Labels should provide required information to consumers and waste operators. Information in label should indicate that the material meets compostability standards and whether the material is suitable for industrial or home composting. By consistent labeling it is possible to prevent contamination of compost streams, support correct disposal behavior, and ensure that compostable items are processed in appropriate facilities. If there is no clear identification, compostable packaging may end up in recycling or landfills.

Ensuring transparency and verification of compostability through standardized certification as well as proper labeling are essential to maintain system reliability. Fiber-based compostable packaging offers sustainability potential, but it needs to align with recycling compatibility, biowaste treatment processes, and regulatory frameworks. Misleading claims about compostability and greenwashing practices are a significant risk. Example of misleading claim is labeling products as biodegradable without meeting recognized standards that can lead to failing to appreciate consumer trust. Misleading claims can also lead to more technical problems like contamination of compost streams and disturbances in the effectiveness of organics recycling programs.

Collaboration between waste management authorities, waste producers, and biogas plant operators is essential for the successful implementation of such a waste-to-energy system. Fiber-based packaging materials can technically fit into industrial composting and anaerobic digestion systems. While compostable fiber-based packaging can contribute to biogas generation, as discussed earlier its efficiency can be lower compared to pure organic waste streams. This suggests that integration into biowaste treatment requires clear guidelines and infrastructure adjustments. Thus, further discussion is still necessary among the stakeholders to understand how food-contaminated fiber-based packaging materials can be utilized as raw materials for biogas production and is there any specific infrastructure required to support the processing, while identifying the most critical uncertainty in this approach. It is important to note that using food-contaminated fiber-based packaging as raw material for biogas production can be more challenging than using clean organic waste due to potential contamination issues.

To gather more insights into the effectiveness of circular economy initiatives and identifying possible barriers to large-scale adoption, future research could be done in form of semi-structured interview approach. It is essential to capture a broad perspective on fiber-based compostable packaging by involving all stakeholders, including policymakers, waste management operators, and consumers. A comparative study across different regions or regulatory environments could reveal how infrastructure, legislation, and cultural practices influence end-of-life management of compostable fiber-based packaging waste fraction. Another perspective could be to compare compostable fiber-based and plastic-based materials in industrial composting. Additionally, integrating qualitative interviews and quantitative methods, such as surveys or lifecycle assessments, more data would be provided for evaluating environmental impacts and economic feasibility. As the operating environment is undergoing change, studies could also track changes in stakeholder attitudes and industry practices over time.

It is crucial to address the potential challenges related to infrastructure that enables proper collection of food-contaminated (compostable) fiber-based packaging. Equally important is to determine which entity should have the responsibility for developing and maintaining this infrastructure to ensure system functionality and compliance. If packaging material is compostable and can be collected together with biowaste without requiring separate infrastructure, then the question arises, should compostable items follow the same route as food waste, especially since separate food waste collection has already become mandatory? Infrastructure availability can still remain a major barrier to the practical adoption of compostable packaging. This scarcity may leave single facilities serving large regions, resulting in high collection fees.

12 Conclusion

Consumer demands for compostable foodservice packaging are driving brands to revise their selection to meet evolving legislation at local, state, and national levels. Developing products that support the circular economy is no longer optional, it has become a requirement. Modern circular economy principles require foodservice packaging to balance functionality with sustainability. Due to regional differences in waste management practices there is a need for harmonized standards and clear consumer guidance. Packaging must not only provide protection and mechanical strength but it must also integrate with existing recycling or end-of-life solutions. Developing fiber-based solutions for compostable foodservice packaging involves navigating a complex set of requirements that is shaped by regional regulations, certification standards, and limitations within existing waste management infrastructure.

End-of-life alternatives, such as recycling, industrial composting, and anaerobic digestion, are critical for ensuring that fiber-based packaging contributes to circularity rather than becoming residual waste. Regardless of the chosen end-of-life pathway, it is important to prioritize the use of safer materials and chemicals to prevent contamination of recycling and composting systems, thereby ensuring the integrity and sustainability of waste management processes. Fiber-based packaging contaminated with food residues may end up in landfills or incineration if effective systems for collection and processing are missing. Research shows that treatment options like anaerobic digestion and industrial composting enable resource recovery through biogas and nutrient-rich compost. These alternatives enable to reduce greenhouse gas emissions compared to landfilling. Pathways for compostable fiber-based packaging material for foodservice depends on their inclusion in biowaste collection and thus further to industrial composting or anaerobic digestion and biogas production.

Innovations in coatings and barrier layers can improve compostability without compromising food safety or functionality. Early-stage product design should consider end-of-life pathways, ensuring compatibility with composting and anaerobic digestion processes. Effective development of compostable packaging requires collaboration across the entire supply chain. Proper end-of-life management is required to achieve sustainability benefits offered by compostable fiber-based packaging materials.

References

Abdenour, C., Eesaee, M., Chabot, B., Barnabé, S., Bley, J., Tolnai, B., Njamen, G., & Nguyen-Tri, P. (2025). *Improved water resistance and air barrier performances of paper coated with polylactic acid/organoclay nanocomposites*. Polymer Engineering and Science, 65(4), 2068–2079. https://doi.org/10.1002/pen.27134

Ahmed, S., Hall, A. M., & Ahmed, S. F. (2018). *Comparative biodegradability assessment of different types of paper*. Journal of Natural Sciences Research, 8(14), 1–8. Accessed on 13 November 2025. Retrieved from https://www.iiste.org/Journals/index.php/JNSR/article/viewFile/44098/45478

Alengebawy, A., Ran, Y., Osman, A. I., Jin, K., Samer, M., & Ai, P. (2024). *Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: a review*. Environmental Chemistry Letters, 22(6), 2641–2668. https://doi.org/10.1007/s10311-024-01789-1

Appropedia. (2024). *Humus*. Accessed on 20 November 2025. Retrieved from https://www.appropedia.org/Humus

Barthod, J., Rumpel, C., & Dignac, M.-F. (2018). *Composting with additives to improve organic amendments. A review.* Agronomy for Sustainable Development, 38(2), Article 17. https://doi.org/10.1007/s13593-018-0491-9

BiopolyLab. (2025). *Home vs industrial composting: What it means for your food packaging*. Accessed on 20 November 2025. Retrieved from https://biopolylab.com/blog/home-vs-industrial-composting-what-it-means-for-your-food-packaging/

Bremer, J. (2022). *Aerobic and anaerobic biodegradation*. Journal of Ecosystem & Ecography, 12(4). Retrieved from https://www.omicsonline.org/open-access-pdfs/aerobic-and-anaerobic-biodegradation.pdf

Bugnicourt, E. (2022). *Going full circle with fibre. Food Science and Technology*, 36(1), 28–32. https://doi.org/10.1002/fsat.3601_8.x

Czekała, W., Nowak, M., & Bojarski, W. (2023). *Anaerobic digestion and composting as methods of bio-waste management*. Agricultural Engineering, 27(1), 173–186. https://doi.org/10.2478/agriceng-2023-0013

Dhull, P., Kumar, S., Yadav, N., & Lohchab, R. K. (2025*). A comprehensive review on anaerobic digestion with focus on potential feedstocks, limitations associated and recent advances for biogas production*. Environmental Science and Pollution Research International, 32(32), 19129–19164. https://doi.org/10.1007/s11356-024-33736-6

de Jong, E., Goumans, I., Visser, R. H. A., Puente, Á., & Gruter, G.-J. (2025). *The opportunities and challenges of biobased packaging solutions*. Polymers, 17(16), 2217. https://doi.org/10.3390/polym17162217

Deutsche Recycling. (2024). *EPR regulations across the EU – comparison & overview*. Accessed on 29 November 2025. Retrieved from https://deutsche-recycling.com/blog/comparing-epr-regulations-europe/

Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. (2018). Official Journal of the European Union, L 150, 109–140. https://eur-lex.europa.eu/eli/dir/2018/851/oj/eng

Dolci, G., Puricelli, S., Cecere, G., Tua, C., Fava, F., Rigamonti, L., & Grosso, M. (2025). *How does plastic compare with alternative materials in the packaging sector? A systematic review of LCA studies*. Waste Management & Research, 43(3), 339–357. https://doi.org/10.1177/0734242X241241606

Dubois, A., & Gadde, L.-E. (2002). *Systematic combining: An abductive approach to case research.* Journal of Business Research, 55(7), 553–560. https://doi.org/10.1016/S0148-2963(00)00195-8

Eissenberger, K., Ballesteros, A., De Bisschop, R., Bugnicourt, E., Cinelli, P., Defoin, M., Demeyer, E., Fürtauer, S., Gioia, C., Gómez, L., Hornberger, R., Ißbrücker, C., Mennella, M., von Pogrell, H., Rodriguez-Turienzo, L., Romano, A., Rosato, A., Saile, N., Schulz, C., … Schmid, M. (2023). *Approaches in Sustainable, Biobased Multilayer Packaging Solutions*. Polymers, 15(5), 1184. https://doi.org/10.3390/polym15051184

Ellen MacArthur Foundation. (2015). *Towards the circular economy: Business rationale for an accelerated transition.* Ellen MacArthur Foundation. Accessed on 29 November 2025. Retrieved from https://www.ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition

Emmert, K., Amberg-Schwab, S., Braca, F., Bazzichi, A., Cecchi, A., & Somorowsky, F. (2021). bioORMOCER®—*Compostable functional barrier coatings for food packaging*. Polymers, 13(8), 1257. https://doi.org/10.3390/polym13081257

Environmental Protection Agency. (2021). *Emerging issues in food waste management: Commercial pre processing technologies* (EPA 600 R 21 114). U.S. EPA Office of Research and Development. Accessed on 13 November 2025. Retrieved from https://www.epa.gov/system/files/documents/2021-09/commercial-pre-processing-technologies_508-tagged_0.pdf

ERP Recycling. (2025). *Packaging and Packaging Waste Regulation guide. What to expect from the EU Packaging Regulation*. Accessed on 19 November 2025. Retrieved from https://erp-recycling.org/wp-content/uploads/2025/05/PPWR-Packaging-and-Packaging-Waste-Regulation-EN-final.pdf

European Bioplastics. (2009). *Industrial composting fact sheet*. Accessed on 27 November 2025. Retrieved from https://docs.european-bioplastics.org/2016/publications/fs/EUBP_fs_industrial_composting.pdf

European Bioplastics. (2015). *Performance in industrial composting – EN 13432.* Accessed on 27 November 2025. Retrieved from https://www.docs.european-bioplastics.org/publications/bp/EUBP_BP_En_13432.pdf

European Bioplastics. (2020). EN 13432: *Certified bioplastics, performance in industrial composting*. Accessed on 27 November 2025. Retrieved from https://www.docs.european-bioplastics.org/publications/bp/EUBP_BP_En_13432.pdf

European Bioplastics. (2025). *Article 9 PPWR: Why certain packaging formats should be compostable*. Accessed on 20 November 2025. Retrieved from https://docs.european-bioplas-tics.org/publications/2025/EUBP_Briefing_Article9_PPWR_Compostability_for_packaging_applications.pdf

European Bioplastics. (n.d.). *What are bioplastics?* Accessed on 20 November 2025. Retrieved from https://www.european-bioplastics.org/bioplastics/

European Commission. (2010). *Communication from the Commission to the Council and the European Parliament on future steps in bio-waste management in the European Union* {SEC(2010) 577}. Accessed on 26 November 2025. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52010DC0235

European Commission. (2021). *Guidelines on the interpretation of the Single-Use Plastics Directive (EU) 2019/904*. Accessed on 18 November 2025. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021XC0607(03)

European Commission. (2022a). *EU Policy Framework on Biobased, Biodegradable and Compostable Plastics (COM/2022/682).* Accessed on 26 November 2025. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0682

European Commission. (2022b). *Assessment of the implementation of Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment*. Accessed on 26 November 2025. Retrieved from https://ec.europa.eu/environment/topics/plastics/single-use-plastics

European Commission. (2024). *EU rules on packaging and packaging waste, including design and waste management*. Accessed on 18 November 2025. Retrieved from https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en

European Commission. (2025*). Regulation (EU) 2025/40 of the European Parliament and of the Council on packaging and packaging waste*. Official Journal of the European Union, L 40. Accessed on 18 November 2025. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202500040

European Compost Network. (2022). *Compost and digestate for a circular bioeconomy: ECN data report 2022. Accessed on 20 November 2025.* Retrieved from https://www.compostnetwork.info/wordpress/wp-content/uploads/ECN-rapport-2022.pdf

European Environment Agency. (2020*). Bio-waste in Europe — turning challenges into opportunities (EEA Report No 04/2020).* Publications Office of the European Union. Accessed on 26 November 2025. Retrieved from https://www.eea.europa.eu/publications/bio-waste-in-europe

European Parliament & Council. (2008). *Directive 2008/98/EC on waste and repealing certain Directives (Waste Framework Directive).* Official Journal of the European Union. Accessed on 27 November 2025. Retrieved from https://eur-lex.europa.eu/eli/dir/2008/98/oj/eng

European Parliament and Council. (2019*). Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment (Text with EEA relevance).* Official Journal of the European Union, L 155, 12 June 2019, pp. 1–19. Accessed on 26 November 2025. Retrieved from https://eur-lex.europa.eu/eli/dir/2019/904/oj/eng

European Parliament and Council. (2025*). Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC (Text with EEA relevance).* Official Journal of the European Union, L 2025/40, 22 January 2025. Accessed on 18 November 2025. Retrieved from https://eur-lex.europa.eu/eli/reg/2025/40/oj/eng

EUROPEN. (2025). *EUROPEN's recommendations for a cohesive EU Extended Producer Responsibility environment. EUROPEN – European Organisation for Packaging and the Environment*. Accessed on 19 November 2025. Retrieved from https://www.europen-packaging.eu/wp-content/uploads/2025/02/EUROPEN-EPR-Recommendations-January-2025.pdf

Finnish Environment Institute (SYKE). (2024). *Waste and recycling.* Accessed on 26 November 2025. Retrieved from https://www.ymparisto.fi/en/state-environment/circular-economy/waste-and-recycling

Gadaleta, G., De Gisi, S., Picuno, C., Heerenklage, J., Kuchta, K., Sorrentino, A., Notarnicola, M., & Oliviero, M. (2024). *Assessment of methane production, disintegration, and biodegradation potential of bioplastic waste in anaerobic digestion systems.* Journal of Environmental Chemical Engineering, 12(1), Article 111658. https://doi.org/10.1016/j.jece.2023.111658

González, R., Pena, D. C., Gomez, X. (2022). *Anaerobic Co-Digestion of Wastes: Reviewing Current Status and Approaches for Enhancing Biogas Production*. Applied Sciences, 12, 8884. https://doi.org/10.3390/app12178884

Gonzalez-Estrella, J., Asato, C. M., Stone, J. J., & Gilcrease, P. C. (2017). *A review of anaerobic digestion of paper and paper board waste*. Reviews in Environmental Science and Biotechnology, 16(3), 569–590. https://doi.org/10.1007/s11157-017-9436-z

Green Symbiosis. (2025). *Home vs industrial compostable bags: What's the real difference and disposal path?.* Accessed on 20 November 2025. Retrieved from https://green-symbiosis.com/home-vs-industrial-compostable-bags-whats-the-real-difference-and-disposal-path/

Haase, S. (n.d.). *A new horizon for fibre-based packaging recyclability. Paper Technology International*. Accessed on 18 November 2025. Retrieved from https://papertechnologyinternational.com/wp-content/uploads/2025/09/A-New-Horizon-for-Fibre-Based-Packaging-Recyclability-4-Evergreen.pdf

Hamdani, S. S., Elkholy, H. M., et al. (2025). *Recyclable and biodegradable paper coating with functionalized PLA and PBAT.* ACS Omega, 10, 11483–11497. https://doi.org/10.1021/acsomega.4c11134

Hilton, M., Geest Jakobsen, L., Hann, S. et al., (2020). *Relevance of biodegradable and compostable consumer plastic products and packaging in a circular economy.* European Commission: Directorate-General for Environment, Eunomia, Publications Office, Accessed on 20 November 2025. Retrieved from https://data.europa.eu/doi/10.2779/497376

Ibrahim, N. A., Majeed, H. H., Jwaid, T. A., & Silas, K. (2025). *Advancements in anaerobic digestion of organic waste for sustainable biogas production*. Environmental Science and Pollution Research International, 32(30), 17916–17930. https://doi.org/10.1007/s11356-025-36783-9

InNaturePack. (2025). *How the EU's PPWR is reshaping compostable and recyclable packaging*. Accessed on 27 November 2025. Retrieved from https://www.innaturepack.com/how-the-eus-ppwr-is-reshaping-compostable-and-recyclable-packaging/

Jacob, S., Kundu, D., Chintagunta, A. D., Kumar S, S., Samanta, P., Mahata, C., Dey, S., Shibirathna, R. G., Barathi, A., Kumar, S., Wang, Z., & Goel, G. (2025). *Anaerobic digestion-derived digestate valorization: green chemistry innovations for resource recovery and reutilization*. Green Chemistry: An International Journal and Green Chemistry Resource : GC, 27(25), 7472–7755. https://doi.org/10.1039/d5gc01053e

Jacobus, K. (n.d.). *Home compostable vs industrial compostable: What's the difference?. Good Start Packaging*. Accessed on 20 November 2025. Retrieved from https://www.goodstartpackaging.com/home-compostable-vs-industrial-compostable-whats-the-difference/

Jahangiri, F., Mohanty, A. K., & Misra, M. (2024). *Sustainable biodegradable coatings for food packaging: challenges and opportunities*. Green Chemistry : An International Journal and Green Chemistry Resource : GC, 26(9), 4934–4974. https://doi.org/10.1039/d3gc02647g

Joltreau, E. (2022). *Extended Producer Responsibility, Packaging Waste Reduction and Eco-design.* Environmental & Resource Economics, 83(3), 527–578. https://doi.org/10.1007/s10640-022-00696-9

Kathuria, A., & Zhang, S. (2022). *Sustainable and repulpable barrier coatings for fiber-based materials for food packaging: A review*. Frontiers in Materials, 9, 929501. https://doi.org/10.3389/fmats.2022.929501

Kóczán, Z., & Pásztory, Z. (2024). *Overview of natural fiber-based packaging materials*. Journal of Natural Fibers, 21(1), 2301364. https://doi.org/10.1080/15440478.2023.2301364

Li, P., Xu, Y., Yin, L., et al. (2023). *Development of raw materials and technology for pulping—A brief review.* Polymers, 15(22), 4465. https://doi.org/10.3390/polym15224465

Maga, D., Hiebel, M., & Aryan, V. (2019*). A Comparative Life Cycle Assessment of Meat Trays Made of Various Packaging Materials*. Sustainability (Basel, Switzerland), 11(19), 5324. https://doi.org/10.3390/su11195324

Measurlabs. (n.d.). *Industrial compostability testing.* Accessed on 26 November 2025. Retrieved from https://measurlabs.com/products/compostability-in-an-industrial-compost/

Mitsubishi Chemical Corporation. (n.d.). *Paper cups to compost: BioPBS™.* Accessed on 26 November 2025. Retrieved from https://us.mitsubishi-chemical.com/paper-cups-to-compost-biopbs/

Mujtaba, M., Lipponen, J., Ojanen, M., Puttonen, S., & Vaittinen, H. (2022). *Trends and challenges in the development of bio-based barrier coating materials for paper/cardboard food packaging: A review.* Science of the Total Environment, 851, 158328. https://doi.org/10.1016/j.scitotenv.2022.158328

NaturePlast. (n.d.). *Bioplastics and biodegradability*. Accessed on 26 November 2025. Retrieved from https://natureplast.eu/en/

Notpla. (2025). *Home compostable vs industrial compostable packaging: What's the difference?*. Accessed on 20 November 2025. Retrieved from https://www.notpla.com/magazine-posts/home-compostable-vs-industrial-compostable-packaging-whats-the-difference

OECD. (2021a*). Extended Producer Responsibility: Updated guidance for efficient waste management.* Accessed on 18 November 2025. Retrieved from Retrieved from https://www.oecd.org/content/dam/oecd/en/publications/reports/2016/09/extended-producer-responsibility_g1g6742c/9789264256385-en.pdf

OECD. (2021b). *Modulated fees for extended producer responsibility schemes (EPR). OECD Environment Working Papers, No. 184.* Accessed on 18 November 2025. Retrieved from Retrieved from https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/11/modulated-fees-for-extended-producer-responsibility-schemes-epr_bbf84337/2a42f54b-en.pdf

Ojasalo, K., Moilanen, T. & Ritalahti, J. (2014). *Kehittämistyön menetelmät. Luku 2.2 ”Tutkimuksellisen kehittämistyön prosessi” [Methods of Development Work. Chapter 2.2 'The Process of Research-Based Development Work]*. Helsinki: Sanoma Pro Oy.

Parihar, P., & Choudhary, R. (2023*). Composting and anaerobic digestion: Review on sustainable methods for management of food waste. Journal of Waste Management & Recycling Technology.* Accessed on 20 November 2025. Retrieved from Retrieved from https://www.onlinescientificresearch.com/journals/jwmrt/articles/composting-and-anaerobic-digestion-review-on-sustainablenbspmethods-for-management-of-food-waste.html

Sachdeva, A., Araujo, A., & Hirschnitz-Garbers, M. (2021). *Extended Producer Responsibility and ecomodulation of fees: Opportunity—Ecomodulation of fees as a way forward for waste prevention.* Ecologic Institute. Accessed on 19 November 2025. Retrieved from https://www.ecologic.eu/sites/default/files/publication/2021/50052-Extended-Producer-Responsibility-and-eco-modulation-of-fees-web.pdf

Shafana Farveen, M., Muñoz, R., Narayanan, R., & García-Depraect, O. (2025). *Enhancing Bioplastic Degradation in Anaerobic Digestion: A Review of Pretreatment and Co-Digestion Strategies.* Polymers, 17(13), 1756. https://doi.org/10.3390/polym17131756

Sheposh, R. (2024). *Biodegradation.* EBSCO Research Starters. Accessed on 20 November 2025. Retrieved from Retrieved from https://www.ebsco.com/research-starters/chemistry/biodegradation

Singh, P. K., Mohanty, P., Mishra, S., & Adhya, T. K. (2022). *Food waste valorisation for biogas based bioenergy production in circular bioeconomy: Opportunities, challenges, and future developments.* Frontiers in Energy Research, 10, 903775. https://doi.org/10.3389/fenrg.2022.903775

Song, C., Li, W., Cai, F., Liu, G., & Chen, C. (2021). *Anaerobic and microaerobic pretreatment for improving methane production from paper waste in anaerobic digestion*. Frontiers in Microbiology, 12, 688290. https://doi.org/10.3389/fmicb.2021.688290

Suomen Standardisoimisliitto. (2002). SFS-EN 13432: *Pakkaukset. Vaatimukset pakkauksille, jotka ovat hyödynnettävissä kompostoinnin ja biohajoamisen avulla. Testausmenettely ja arviointiperusteet pakkauksen hyväksynnälle*. Helsinki: Suomen Standardisoimisliitto.

Suomen Standardisoimisliitto. (2003). SFS-EN 14046:en *Packaging. Evaluation of the ultimate aerobic biodegradability of packaging materials under controlled composting conditions. Method by analysis of released carbon dioxide.* Helsinki: Suomen Standardisoimisliitto.

Tiekstra, S., Dopico-Parada, A., Koivula, H., Lahti, J., & Buntinx, M. (2021). *Holistic Approach to a Successful Market Implementation of Active and Intelligent Food Packaging.* Foods, 10(2), 465. https://doi.org/10.3390/foods10020465

Toikko, T. & Rantanen, T. 2009. *Tutkimuksellinen kehittämistoiminta [Research-oriented development work]*. Tampereen yliopistopaino Oy.

Tomczak, W., Daniluk, M., & Kujawska, A. (2024). *Food waste as feedstock for anaerobic mono digestion process: A review*. Applied Sciences, 14(22), 10593. https://doi.org/10.3390/app142210593

VALUEWASTE Project. (2020). *EU Policy on Biowaste Management: a review*. Accessed on 21 November 2025. Retrieved from https://valuewaste.eu/wp-content/uploads/2020/02/D-9.2.EU-Policy-on-biowaste_VALUEWASTE.pdf

Van Eygen, E., Laner, D., & Fellner, J. (2018). *Circular economy of plastic packaging: Current practice and perspectives in Austria.* Waste Management (Elmsford), 72, 55–64. https://doi.org/10.1016/j.wasman.2017.11.040

Venelampi, O., Weber, A., Rönkkö, T., & Itävaara, M. (2003). *The biodegradation and disintegration of paper products in the composting environment.* Compost Science & Utilization, 11(3), 200–209. https://doi.org/10.1080/1065657X.2003.10702128

Vinitskaia, N., Lindstad, A. J., Lev, R., Leminen, V., Li, K. D., Pettersen, M. K., Kvikant, M., Xu, C., & Grönman, K. (2025). *Environmental sustainability, food quality and convertibility of bio-based barrier coatings for fibre-based food packaging: A semisystematic review.* Packaging Technology and Science, 38(3), 255–280. https://doi.org/10.1002/pts.2868

Wandosell, G., Parra-Meroño, M. C., Alcayde, A., & Baños, R. (2021). *Green Packaging from Consumer and Business Perspectives.* Sustainability (Basel, Switzerland), 13(3), 1356. https://doi.org/10.3390/su13031356

Williams, E. (2025). *Developing verified solutions for compostable, paper-based foodservice packaging. Converting Quarterly.* Accessed on 14 November 2025. Retrieved from https://convertingquarterly.com/developing-verified-solutions-for-compostable-paper-based-foodservice-packaging/

Zero Waste Europe & Bio-based Industries Consortium. (2024). *Bio-waste generation in the EU: Current capture levels and future potential (2nd ed.).* Brussels: BIC/ZWE. Accessed on 26 November 2025. Retrieved from https://zerowasteeurope.eu/library/bio-waste-generation-in-the-eu-current-capture-levels-and-future-potential-second-edition/

Zhang, A., Shen, J., & Ni, Y. (2015). *Anaerobic digestion for use in the pulp and paper industry and other sectors: An introductory mini-review*. BioResources, 10(4), 8750–8776. Accessed on 18 November 2025. Retrieved from https://bioresources.cnr.ncsu.edu/resources/anaerobic-digestion-for-use-in-the-pulp-and-paper-industry-and-other-sectors-an-introductory-mini-review/

Zimmer, J. (2025). *Compostability and biodegradability of fiber-based packaging and bioplastics.* IPPTA Journal, 37(E2), 75–77. Accessed on 17 November 2025. Retrieved from https://ippta.co/wp-content/uploads/2025/06/75-77.pdf