BIO-PLASTICS EUROPE

Handbook on the impacts of bio-based and biodegradable plastics on existing waste management frameworks

Project Acronym	BIO-PLASTICS EUROPE
Work Package	WP4
Deliverable	D4.3 Handbook on the impacts of bio-based and biodegradable plastics (and additives) on existing waste management frameworks
Deliverable Lead	KTU
Type	Handbook
Dissemination Level	Confidential, only for members of the consortium (including the commission Services)
Contractual delivery date	2021/10/01
Actual submission date	2021/10/
Author(s)	KTU, TUHH, HengHiap, ECOEMBES, UPM, IVL, AssobioServizi, Taltech, Tuas, TUL, HAW Hamburg, Fraunhofer, T.I.C.A.S.S. ABM

HAW Hamburg

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Table of Contents

Horizon 2020
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

Vocabulary of definitions

Definition	Meaning
Bio-based	Derived from biomass (ISO 16575:2014)
Biodegradation	The microbially mediated process of chemical breakdown of a substance to smaller products caused by micro-organisms or their enzymes (European Environments Agency)
Chemical recycling	Technologies that use physico-chemical processes to transform waste into raw materials for the production of new materials.
Depolymerization	Depolymerization is the process of converting a polymer into a monomer or a mixture of monomers. This process is driven by an increase in entropy.
Gasification	Gasification is a process that converts biomass- or fossil fuel-based carbonaceous materials into carbon monoxide, hydrogen and carbon dioxide. This is achieved by reacting the material at high temperatures, without combustion, with a controlled amount of oxygen and/or steam.
Kerbside collection	Or kerbside collection is a service provided to households, typically in urban and suburban areas, of collecting and disposing of household waste and recyclables. It is usually accomplished by personnel using specially built vehicles to pick up household waste in containers that are acceptable to, or prescribed by, the municipality and are placed on the kerb.
Organic waste management	Management of generation, collection, storage, transport, recycling, recovery and disposal of biological waste, from plants or animals (ISO24161:2022)
Scavengers	A person who salvages reusable or recyclable materials thrown away by others to sell or for personal consumption. There are millions of waste pickers worldwide, predominantly in developing countries
Pyrolysis	Pyrolysis is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition.
Recycling	processing of plastics waste materials for the original purpose or for other purposes, excluding energy recovery (ISO 15270:2008)
Waste Stream	Specific types of waste found in customer's disposal (trash, cardboard, aluminium, metal, etc.) or a broader definition of disposal type. (e.g. MSW, C&D, Hazardous, etc.)
Waste-to-Energy Plant	Facilities consist of large incinerator-type operations where trash is incinerated (burned). The heat from this combustion process is

	converted into high-pressure steam, which can be used to generate electricity for sale to public utility companies under long-term contracts. The residue from the incineration process is disposed of in a Landfill.

List of tables

List of Figures

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Executive summary

Plastic pollution, including through single-use plastics, continues to plague natural environments around the world: the use and consumption of plastic is increasingly high, therefore the goal to find viable options for reuse, recycling and disposal as well as sustainable management of this type of the waste is on the rise. The variety of solutions which were identified to solve the plastic pollution problem cover local, national and regional levels. Some of the proposed interventions focus on post-consumption management, requiring considerable growth in investment and capacity of waste management solutions. Other interventions prioritize reducing plastic through replacement with alternative products, reuse, and the development of new delivery models.

The project BIO-PLASTICS EUROPE addresses the topic "Sustainable solutions for bio-based plastics on land and sea", within the focus area "Connecting economic and environmental gains - the Circular Economy (CE)" and focuses on sustainability strategies and solutions for bio-based products to support the Plastics Strategy. This includes innovative product design and business models facilitating efficient reuse and recycling strategies and solutions, including ensuring the safety of recycled materials when used for toys or packaging food stuffs. In the scope of this project the handbook "On the impacts of bio-based and biodegradable plastics (and additives) on existing waste management frameworks" was developed seeking a goal ensure capacity building to the development of sustainable strategies and solutions for bio-based plastic products, as well as the development of approaches focused on circular innovation for the whole bio-based plastics system.

This handbook brings together a number of key bio-based and biodegradable plastics topics in one place for a broad audience of decision-makers on national and regional level, business representatives, scientists and society. Topics covered include instruction of the concepts of bio-based and biodegradable plastic, Life Cycle Assessment and Circular Economy concepts, analysis of impact of bio-based, biodegradable and compostable plastic on waste management technologies and systems, analysis of the legal and policy framework. Also, the most promising business cases from the project partner countries provided.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

1 Introduction

1.1 Bio-based plastic

All plastic is built up with carbon as a main ingredient. Conventional, fossil-based plastic contains carbon from oil and natural gas while bio-based plastics consist of carbon from renewable sources. There are different types of bio-based plastics:

• Those that are identical with their fossil-based equivalents, for example bio-PE or bio-PET. These are often called drop-ins.

• Those that have a completely different chemical structure compared to conventional fossil-based plastics, such as bio-based polyesters e.g. polylactide (PLA).

Bio-based plastics may partially consist of fossil-based monomers or additives. It is thus important to communicate the bio-content of bio-based plastics to the end users to avoid greenwashing.

Renewable raw materials for bio-based plastics are usually divided into first, second and third generation feedstocks. The first-generation feedstock, the most commonly used feedstock in bio-based plastics today, consists of carbohydrate-rich crops that are suitable for food or animal feed, such as corn or sugar cane. Second-generation feedstock includes crops that are not suitable for food or animal feed, such as non-edible crops or organic waste. Third generation feedstock is under development and can, for example, consist of algae. There seems to be a lot of activity in the PHA sector concerning organic waste (e.g. Mango Materials).

1.2 Biodegradable and compostable plastics

Biodegradable and compostable plastics are promising alternatives to conventional plastics. Biodegradable and compostable materials can degrade in the presence of microorganisms into water, carbon dioxide and microbial biomass. The degradation rate very much depends on the surrounding conditions, including temperature, the presence of microorganisms, nutrients, oxygen and moisture (De Wilde et al., 2013; van den Oever et al., 2017). There are different conditions for biodegradation of bioplastics (EEA, 2020):

- Natural environment – soil, fresh water, marine environment requires certain conditions at different periods of time, biodegradation process is slow.
- Industrial composting – industrial composting plant or organic waste treatment plant. Environmental conditions are stable and monitored.
- Home composting – degradation in less controlled conditions at a smaller scale, with the lower temperature than in industrial composting plant.

Biodegradable or compostable plastics can be produced from either bio-based or fossil raw material (feedstock (EEA, 2020) and degrade in different conditions such as compost (aerobic conditions), soil or anaerobic conditions (Table 1).

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Table 1 *Biodegradable and compostable plastics (Flury &Narayan, 2021; Nova, 2021)*

Name of the polymer	Properties	Biodegradability in environment
Polybutylene succinate (PBS)	Thermoplastic polymer, comparable to polypropylene, consists of polymerized units of butylene succinate.	Proven biodegradability in industrial composting
Polylactic acid (PLA)	Brittle, clear, generally suitable for food contact applications, can also be used as a foam[1]	Proven biodegradability in industrial composting, anaerobic digestion
Polyhydroxyalkanoates (PHA)	Various properties, not used often commercially, normally in blends[1]	Proven biodegradability in home composting, industrial composting, soil, freshwater and marine environment.
Polybutylene adipate terephthalate (PBAT)	Various properties, can replace PP or LDPE, some flexible and very tough, some grades food contact approved, normally found in blends[1]	, Proven biodegradability in industrial composting, certain blends in home composting and in soil.
Starch blends	Wide range of different properties, can be used as a foam [1]	Proven biodegradability in soil, marine and freshwater environment, home and industrial composting
Cellulose acetate	Rigid, some types certified according to EN 13432	proven biodegradability for certain grades for soil, marine and freshwater environments, home and industrial composting
Cellulose (lignin <5%)	Clear, biodegradable in different environments	Proven biodegradability in soil, marine and freshwater environment, home and industrial composting
Notes: [1] Source: Hilton et al., 2020		

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

According to the European Bioplastics factsheet (EEA, 2020), different standards exist to assess the degradability of plastics in industrial conditions and degradation in soil:

1. **Industrial composting and anaerobic digestion**

- EN13432 "Requirements for packaging recoverable through composting and biodegradation". This standard is intended for use for biodegradable packaging for treatment in industrial composting and anaerobic digestion facilities.
- EN 14995 the same requirements as in EN13432, however can be applied for plastics in general.
- ISO 18606 "Packaging and the environment – Organic Recycling"
- ISO 17088 "Specifications for compostable plastics".

2. **Home composting**

- Australian standard AS 5810 "Biodegradable plastics – biodegradable plastics suitable for home composting".
- The OK compost home certification scheme, developed by the Belgian certifier.
- French standard NF T 51-800 "Plastics — Specifications for plastics suitable for home composting".

3. **Biodegradability in soil**

- The certification scheme "Bio products – degradation in soil" developed by Vinçotte, the Belgian certifier.
- EN 17033 "Biodegradable mulch films for use in agriculture and horticulture – Requirements and test methods"
- IN CERTCO awards DIN-Geprüft biodegradable in soil in accordance with CEN/TR 15822.

4. **Biodegradation in other environments**
    - The certification scheme "OK Biodegradable water", developed by TÜV Austria
    - The certification scheme "OK Biodegradable Marine", developed by TÜV Austria

Certification provides a guarantee that certifies product complies with the standard and can degrade under specified conditions. However, according to Hilton et al., 2020 real conditions are different and sometimes can hinder the degradation, especially for home composting and for biodegradability in soil and water. EN13432 standard setup requirements for disintegration, biodegradation and quality of the compost in the controlled environment. For degradation in soil EN17033 was introduced. The standard is developed for the mulch film degradation and includes different eco-toxicity tests and restrictions on hazardous substances. Marine certification requires higher temperature and intended for the lab-test, replicating the marine environment. Certification scheme requires also to carry out tests for environmental toxicity and chemical characteristics including heavy metals. EN14987 set up requirements for biodegradability of plastics in wastewater, used as a proxy for freshwater environment.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Table 2 European Certifications for Biodegradable Plastics (adopted from Hilton et al., 2020)

Labels	Reference standard	Test Conditions	Biodeg Test Threshold	Disintegration
OK compost HOME TÜV AUSTRIA; DIN Geprüft	EN 13432	Ambient temperature (20°C – 30°C)	90% [1] in 12 months	at the end of the test at least 81 % of the test material surface within the slide has disappeared
OK biodegradable SOIL TÜV AUSTRIA; DIN Geprüft	ISO 17033	25^{0} C	90% [1] in 2 years	
OK biodegradable MARINE TÜV AUSTRIA	ASTM D7081 (withdrawn)	30^{0}C ± 2^{0}C	90% in 6 months	10% of material remains after sieving with 2mm after 84 days
OK biodegradable WATER TÜV AUSTRIA	EN 14987	20°C and 25°C	90% [1]in 56 days	10% of material remains after sieving with 2mm after 84 days
OK compost INDUSTRIAL TÜV AUSTRIA; DIN Geprüft	EN 13432	58^{0}C ± 2^{0}C	90% [1]in six months	10% of material fragments larger than 2mm after 12 weeks

[1] 100% biodegradation cannot be found as a part of the carbon is captured in the biomass.

Biodegradable plastics are mostly used in the packaging sector about 59% of the market share followed by other sector, 13% of agriculture and horticulture and 9% of consumer goods (Hilton et al., 2020). Provision of the effective collection system for biodegradable and compostable

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

materials is very essential and can significantly increase effectiveness of bio-waste management infrastructure.

1.3 Biobased plastics application areas

Possible application areas for biodegradable and / or bio-based plastics

- It is important to know that the application area **determines the separation, collection and recycling route**.
- Depending on the polymer, biobased and/or biodegradable plastics could be applied in the following areas (non-exhaustive).

Table 3 Biobased plastics application areas

Application Areas (Non-Exhaustive)	Description
Rigid packaging	Rigid packaging for food, household products include trays, and tubs.
Soft packaging	Soft packaging is made from thin and flexible foils.
Toys	Children toys and beach items made from plastic material such as pails and shovels.
Single-use plastic items*	Single use household items and take-away packaging such as cutlery and coffee cups and lids.
Agriculture	i.e., Mulch films are plastic films used on agricultural land for certain crops to improve soil conditioning and prevent weed growth.
Aquatic plastic items	Items used in fisheries and on boats such as fish crates and fishing bait.

***The Directive (EU) 2019/904 on single-use plastics in 2019 restricts putting on the market certain single-use plastic items.**

***Figure 1** PLA applications (Source:NaturePlast)*

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 2 *Bio-PET (Source: NaturePlast)*

Similar to their fossil counterparts, bio-based and biodegradable plastics can be used in a variety of applications. Like conventional plastics, the packaging industry also exhibits the highest demand for bio-based and biodegradable plastics, accounting for 47 % of the global biobased and biodegradable plastic production capacity in 2020 (European Bioplastics e.V. n.d.). Soft or flexible packing can be produced from biodegradable starch blends, PBAT, and PLA as well as Bio-PE. Rigid packaging (see Figure 1 and 2) on the other hand, can be produced from biodegradable PLA and PBAT, Bio-PE and Bio-PET. Other application areas are consumer goods, textiles, agriculture, automotive/transport, construction, coatings, and electronics.

Consumer goods can be produced from biodegradable plastics like starch blends and PLA. In the agricultural sector, biodegradable plastics like PBAT and starch blends are used. Apart from the aforementioned application areas, researchers are studying the use of biodegradable plastics in high performance areas such as the drug delivery, composite nanotubes for automotive applications as well as in additive manufacturing (Narancic et al. 2020).

1.4. Recyclable Plastics

Conventional Plastics

- There are certain steps that all plastics undergo when recycled: (i)collection of waste plastic, (ii) sorting of waste plastics according to plastic types, (iii) shredding and resizing to a form that can be recycled (iv) washing to remove impurities, (v) compounding.

The US-based Plastics Industry Association (Plastics), established a classification system in 1988 to allow consumers and recyclers to identify different types of plastic via a code or number that is usually moulded at the bottom of each plastic product.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

There are seven types of plastic, but currently some are recycled more often than others.

Abstract from:(Howard and Lake, 2021).

Figure 3 *Plastics recycling marking (Howard and Lake, 2021)*

Plastic Recycling Number #1: Polyethylene Terephthalate (PET or PETE) (Howard and Lake, 2021)

Figure 4 *Polyethylene Terephthalate (PET or PETE). Photo: The Star/Azman Ghani*

PET is the most common plastic for single-use bottled beverages, because it's inexpensive, lightweight, and easy to recycle. Clear PET plastics are generally considered safe, but can absorb odours and flavours from foods and liquids stored in them. They can also be dangerous if exposed to heat, such as if a water bottle is left in a hot car. Over time, this can cause Antimony to leach out of the plastic and into the liquid.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Found in: Soft drinks, water, ketchup, and beer bottles; mouthwash bottles; peanut butter containers; salad dressing and vegetable oil containers.

Recycling: PET can be picked up through most kerbside recycling programs as long as it's been emptied and rinsed of any food. Their caps and labels usually made of a different type of plastic. There is a need to remove bottle labels and caps during the recycling process.

Recycled into: Polar fleece, fibber, tote bags, furniture, carpet, panelling, straps, bottles and food containers (as long as the plastic being recycled meets purity standards and doesn't have hazardous contaminants).

Plastic Recycling Number #2: High-Density Polyethylene (HDPE) (Howard and Lake, 2021).

Figure 5 *High-Density Polyethylene (HDPE) Photo: The Star/Azman Ghani*

HDPE is a versatile plastic with many uses, especially when it comes to packaging. Because of its internal structure, HDPE is much stronger than PET, and can be reused safely. It can also be used for items that will be stored or used outdoors, because it does well in both high and freezing temperatures. It carries low risk of leaching and is readily recyclable into many types of goods.

Found in: containers for milk and non-carbonated drinks, toys, buckets, motor oil, shampoos and conditioners, soap bottles, detergents, and bleaches; some trash and shopping bags

Recycling: HDPE can often be picked up through most kerbside recycling programs, although some allow only containers with necks. Flimsy plastics (like grocery bags and plastic wrap) usually can't be recycled, but some stores will collect and recycle them.

Recycled into: laundry detergent bottles, oil bottles, pens, recycling containers, floor tile, drainage pipe, lumber, benches, doghouses, picnic tables, fencing, shampoo bottles.

Plastic Recycling Number #3: Polyvinyl Chloride (PVC) (Howard and Lake, 2021).

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 6 Polyvinyl Chloride (PVC) Photo: The Star/Azman Ghani

PVC is tough and weathers well, so it's commonly used for things like piping and siding. PVC is a common plastic that starts out rigid, but becomes flexible when plasticizers are added. Because chlorine is part of PVC, it can result in the release of highly dangerous dioxins during manufacturing. Remember to never burn PVC, because it releases toxins. PVC plastics contain harmful chemicals linked to a variety of ailments, including bone and liver diseases and developmental issues in children and infants. Keep PVC items away from foods and drinks.

Found in: blister packaging, wire jacketing, siding, windows, piping, credit cards and synthetic leather products.

Recycling: PVC can rarely be recycled, but it's accepted by some plastic lumber makers. If you need to dispose of either material, ask your local waste management to see if you should put it in the trash or drop it off at a collection center.

Recycled into: Decks, panelling, mudflaps, roadway gutters, flooring, cables, speed bumps, mats.

Plastic Recycling Number #4: Low-Density Polyethylene (LDPE) (Howard and Lake, 2021).

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 7 *Low-Density Polyethylene Photo: The Star/Azman Ghani*

LDPE is a plastic that tends to be both durable and flexible. LDPE has the simplest structure of all the plastics, making it easy to produce. That's why it's mostly used for many types of bags. More recycling programs are beginning to accept LDPE plastics, but it's still quite difficult to recycle.

Found in: Squeezable bottles; bread, frozen food, dry cleaning, and shopping bags; tote bags; furniture.

Recycling: LDPE is not often recycled through curbside programs, but some communities might accept it.

Recycled into: Trash can liners and cans, compost bins, shipping envelopes, panelling, lumber, landscaping ties, floor tile.

Plastic Recycling Number #5: Polypropylene (PP) (Howard and Lake, 2021).

Figure 8 *Polypropylene (PP) Photo: The Star/Azman Ghani*

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

PP has a high melting point. It is strong and can usually withstand higher temperatures. So, it is often chosen for containers that will hold hot liquid. It's gradually becoming more accepted by recyclers.

Found in: Some yogurt containers, syrup and medicine bottles, caps, straws, food container.

Recycling: PP can be recycled through some curbside programs, just don't forget to make sure there's no food left inside.

Recycled into: Signal lights, battery cables, brooms, brushes, auto battery cases, ice scrapers, landscape borders, bicycle racks, rakes, bins, pallets, trays.

Plastic Recycling Number #6: Polystyrene (PS) (Howard and Lake, 2021)

Figure 9 *Polystyrene (PS) Photo: The Star/Azman Ghani*

PS can be made into rigid or foam products — in the latter case it is popularly known as the trademark Styrofoam. Styrene monomer (a type of molecule) can leach into foods, especially when heated, and is a possible human carcinogen, while styrene oxide is classified as a probable carcinogen. The material was long on environmentalists' hit lists for dispersing widely across the landscape, and for being notoriously difficult to recycle.

Found in: Disposable plates and cups, meat trays, egg cartons, carry-out containers, aspirin bottles, compact disc cases

Recycling: Not many curbside recycling programs accept PS in the form of rigid plastics (and many manufacturers have switched to using PET instead). Since foam products tend to break apart into smaller pieces, you should place them in a bag, squeeze out the air, and tie it up before putting it in the trash to prevent pellets from dispersing.

Recycled into: Insulation, light switch plates, egg cartons, vents, rulers, foam packing, carry-out containers.

Plastic Recycling Number #7: Miscellaneous (Howard and Lake, 2021)

Figure 10 Miscellaneous Photo: The Star/Azman Ghani

This category covers all the other types of plastic not defined by the earlier six codes. Polycarbonate (PC), polylactide (PLA), polyurethane (PU) and acrylonitrile butadiene styrene (ABS), are included in this category. Polycarbonate is hard plastic contains the toxic chemical bisphenol A or BPA that some studies have shown it as a hormone disruptor (Vom Saal FS, 2021). PLA (polylactic acid), which is made from plants and is carbon neutral, also falls into this category.

Found in: Polycarbonate (PC) is used in baby bottles, compact discs, and medical storage containers while polyurethane or PU is commonly used in furniture upholstery. Many types of toys, phone covers and electrical equipment are made from ABS (Acrylonitrile Butadiene Styrene).

Recycling: These materials are seldom recycled and specialized programs for recycling are needed.

Recycled into: Plastic lumber and custom-made products.

1.4 Life Cycle Assessment (LCA)

According to ISO 14040 LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Different impact categories are used, from which the greenhouse gas carbon dioxide equivalent global warming potential, GWP is most familiar to public.

LCA scope can be wide, corporate impacts or narrow, i.e., product modification by replacing part with more sustainable material. According Greenhouse gas protocol standard created by WRI (World Resources Institute) and WBCSD (World Business Council for Sustainable Development) as an international standard for corporate accounting and reporting emissions, GHGs are categorized into three scopes: Scope 1 (emissions influenced from company), Scope 2 (emissions related to the purchase of energy from production) and Scope 3 (emissions from the end use of products sold and the acquisition of goods and services, i.e. all indirect emissions) based on the source.

When investigating product from cradle –to- grave during LCA, all three scopes can be dealt with.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

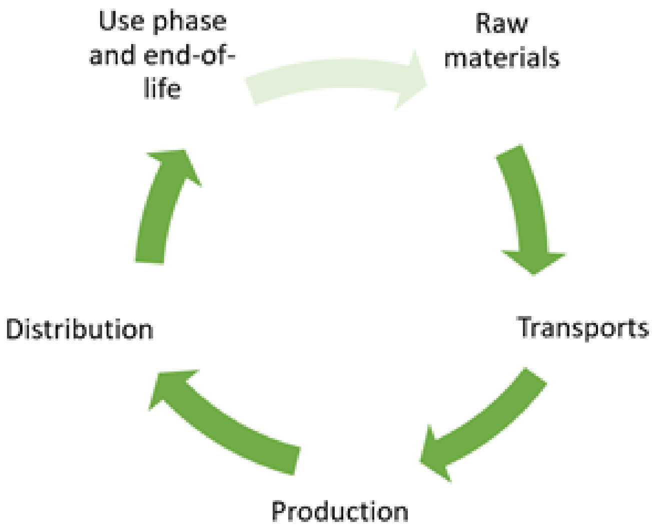

Figure 11 LCA links of the impact

Various impacts can be assessed during different phased of cause-and-effect chain: at midpoint or endpoint. Midpoints are considered to be links in the cause-effect chain (environmental mechanism) of an impact category, prior to the endpoints, at which characterization factors or indicators can be derived to reflect the relative importance of emissions or extractions. Common examples of midpoint characterization factors include ozone depletion potentials, global warming potentials, and photochemical ozone (smog) creation potentials. Recently, however, some methodologies have adopted characterization factors at an endpoint level in the cause-effect chain for all categories of impact (i.e., human health impacts in terms of disability adjusted life years for carcinogenicity, climate change, ozone depletion, photochemical ozone creation; or impacts in terms of changes in biodiversity, etc.) (Bare et al. 2000).

"It might be better to present your results at the midpoint level. Midpoint results can look a bit more daunting and require a bit more time to comprehend, but they provided a lot more detailed insight in return. For example, midpoints allow you to identify trade-offs. Consider a situation where one product has a high impact on climate change, while another product has a high impact on ozone layer depletion. Both of these impact categories contribute to the endpoints of human health and ecosystem quality, so in the endpoint results they could cancel each other out. But at the midpoint level, this difference is clearly visible and you can take that trade-off into account. On top of that, midpoint results have a lower statistical uncertainty, so the calculated results are more reliable." (Meijer. E, 2021).

LCA is a methodology that provides data to support decision making for sustainable development. LCA can be complex so the information gained must be used carefully and knowledgeable. Comparison of different individual LCA's should be done by experts as industrial ecosystems studied can be complex.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 12 Applications for LCA, Figure adapted from Saur, K. (2002)

The crucial definitions during life cycle assessment are:

Functional unit: final product evaluated for example i.e., "a cup", the portion of a product system for which data are collected. When comparing materials only they should have same dimension/ weigh or functionality (barrier, load bearing capability etc.).

Product system: collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.

System boundary: defines the unit processes included in the system under investigation.

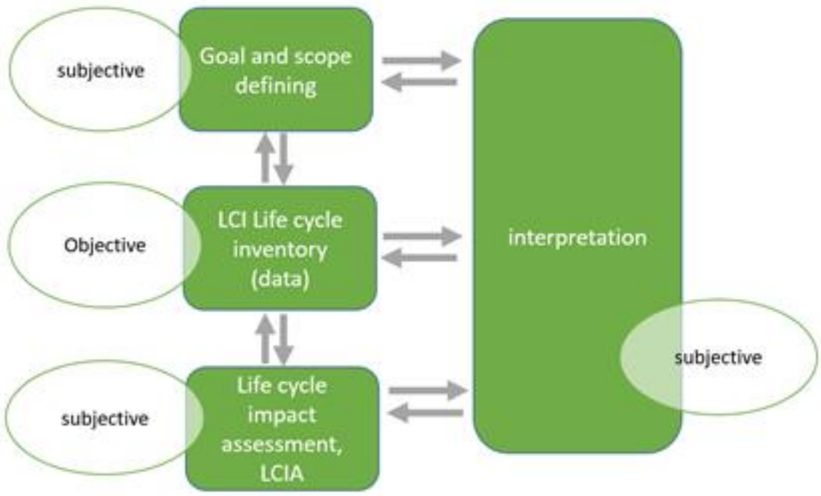

Figure 13 Stages of an LCA according ISO 14040 standard

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Levels of LCA

LCA methodology can be categorized into three levels based on technological details:

Conceptual LCA – First level of LCA based on limited environmental aspects of few life cycle stages where there is still some improvement potential existing for the manufacturer. The results might be useful for qualitative reporting of assessment results, but not suitable for corporate marketing or explicit publication of LCA study.

Simplified LCA – This is the type of comprehensive assessment using generic datasets covering the whole life cycle of a product/system of processes. The time required and expenditures as well reduce significantly here, which is a significant difference from detailed LCA. This consists of a screening of life cycle stages, simplification of LCA results for future recommendation and assuring the reliability of the analysis results. This is often termed as 'Streamlined LCA'.

Detailed LCA – This type of LCA is comprehensive with the full consideration of each life cycle stages with system-specific datasets and analysed in detail for further process improvement (SH Farjana et al. 2021).

When conducting or reading LCAs, consider for whom it's targeted and what's the story told behind if used for environmental claims.

1.5 Circular Economy

The European Union produces more than 2.5 billion tonnes of waste every year. It is currently updating its legislation on waste management to promote a shift to a more sustainable model known as the circular economy. In February 2021, the Parliament adopted a resolution on the new circular economy action plan demanding additional measures to achieve a carbon-neutral, environmentally sustainable, toxic-free and fully circular economy by 2050, including tighter recycling rules and binding targets for materials use and consumption by 2030 (European Parliament, 2021). The circular economy represents a systemic change that builds long-term sustainability, creates new and modifies old business and economic opportunities, and provides environmental as well as social benefits (Ellen MacArthur Foundation 2019).

The purpose of the circular economy is to transform the linear economic model into a circular economy model, in which the aim is to reduce the amount of waste generated and resources circulate. The circular economy is based on three main principles; design out waste and pollution, keep products and materials in use, regenerate natural systems (Ellen MacArthur Foundation 2019).

A circular economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources (E. Macarthur, 2019). Besides, a circular economy can also be defined as an economic system of closed loops in which raw materials, components and products lose their

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

value as little as possible, renewable energy sources are used and systems thinking is at the core (Kennis Kaarten).

The purpose of the circular economy is to keep the value of products, components and materials as high as possible. The Ellen MacArthur foundation has defined the more commonly used the 'Outline of a Circular Economy' definition, which illustrates the continuous circulation of different materials. These cycles can be divided into technical and biological circles (Table 1) (Ellen MacArthur Foundation 2019; Nurmi 2020).

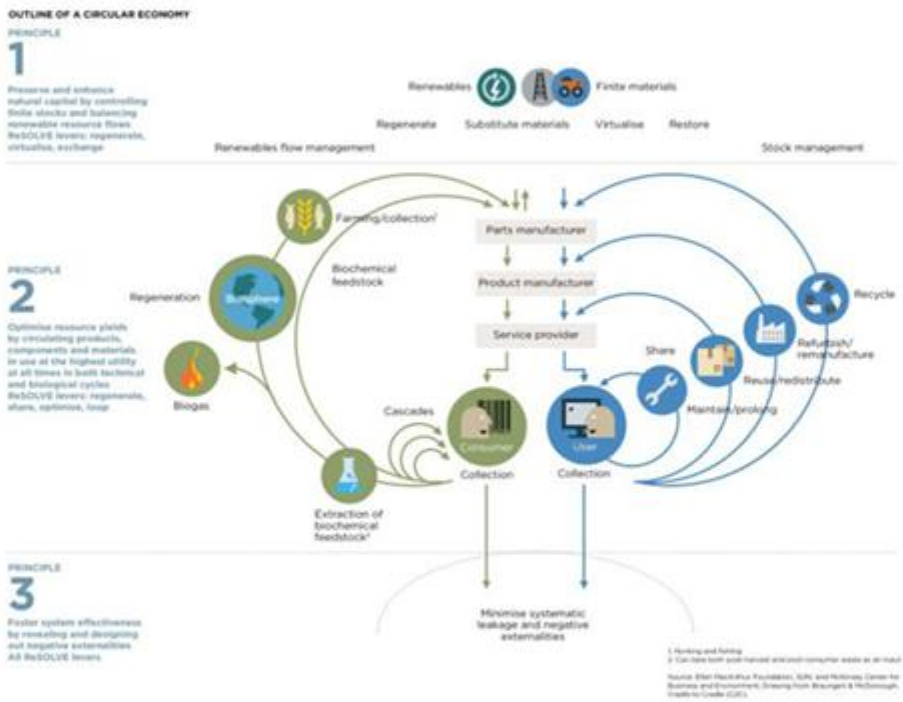

Figure 14 *Outline of a Circular Economy, as defined by Ellen MacArthur Foundation (Ellen MacArthur Foundation 2019)*

Based on the circular economy, the business can be divided into different models to extend the life of the product. For example, sharing, leasing, reusing, repairing, refurbishing and recycling. (Nurmi 2020). In addition to this, the circular economy concept also looks at the economy at all levels from small businesses to large organizations and individuals (Ellen MacArthur Foundation 2019).

In the linear economy, raw natural resources are taken, transformed into products and get disposed of. This take-make-consume-throw away pattern relies on large quantities of cheap, easily accessible materials and energy (Kennis Kaarten, Karttunen 2020). Also, part of this model is planned obsolescence, when a product has been designed to have a limited lifespan to encourage consumers to buy it again. On the opposite, a circular economy model aims to close the gap between the production and the natural ecosystems' cycles – on which humans ultimately depend upon. The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended (Kennis Kaarten). These can be productively used again and again, thereby creating further value.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

In a circular economy economic activity builds and rebuilds overall system health. It is based on three principles (E. Macarthur, 2019):

1. Design out waste and pollution - A circular economy reveals and designs out the negative impacts of economic activity that cause damage to human health and natural systems. This includes the release of greenhouse gases and hazardous substances, the pollution of air, land, and water, as well as structural waste such as traffic congestion.
2. Keep products and materials in use - A circular economy favours activities that preserve value in the form of energy, labour, and materials. This means designing for durability, reuse, remanufacturing, and recycling to keep products, components, and materials circulating in the economy. Circular systems make effective use of bio-based materials by encouraging many different uses for them as they cycle between the economy and natural systems.
3. Regenerate natural systems - A circular economy avoids the use of non-renewable resources and preserves or enhances renewable ones, for instance by returning valuable nutrients to the soil to support regeneration or using renewable energy as opposed to relying on fossil fuels.

1.6 Highlights

Plastics have become one of the most ubiquitous materials used globally and it is recognized that the plastic problem management is a big challenge globally. Therefore, the urgent importance to develop a sustainable plastics economy which will reduce the plastic persistence and accumulation. The European Union produces currently updating its legislation on waste management to promote a shift to a more sustainable model known as the circular economy. In February 2021, the Parliament adopted a resolution on the new circular economy action plan demanding additional measures to achieve a carbon-neutral, environmentally sustainable, toxic-free and fully circular economy by 2050, including tighter recycling rules and binding targets for materials use and consumption by 2030. To reduce plastic pollution, two main approaches can be distinguished: to use recyclable plastic and to increase the use of bio-based and biodegradable plastics.

The recyclable plastic. Five essential steps to recycle plastic materials are: collection of waste plastic, sorting of waste plastics according to plastic types, shredding and resizing to a form that can be recycled, washing to remove impurities, compounding. The US-based Plastics Industry Association (Plastics), established a classification system in 1988 to allow consumers and recyclers to identify different types of plastic via a code or number that is usually moulded at the bottom of each plastic product. Therefore, there is necessary to develop the waste management infrastructure and raise people's awareness.

Bio-based and biodegradable plastics. Bio-based plastics are divided into two categories: bio-based biodegradable and bio-based non-biodegradable. Conventional, fossil-based plastic contains carbon from oil and natural gas while bio-based plastics consist of carbon from renewable sources. Plastic marketed as bio-based is on a rare occasion fully comprised of bio-based feedstock, it is developed from a mix of fossil-based and bio-based feedstock. Biodegradable or compostable plastics can be produced from either bio-based or fossil raw material and degrade in different conditions such as compost (aerobic conditions), soil or anaerobic conditions. Therefore, the biodegradable and compostable plastics are promising alternatives to conventional plastics because can degrade in the presence of microorganisms into water, carbon dioxide and microbial biomass. Depending on the polymer the bio-based and biodegradable plastics can be used in a variety of applications, which a similar to their fossil counterparts. Therefore, the packaging industry exhibits the highest demand for bio-based and biodegradable plastics, accounting for 47 % of the global production capacity in 2020. Other application areas are consumer goods, textiles, agriculture, automotive/transport, building and construction, consumer goods, coatings, and electronics. However, currently (2020), the bioplastics production has a very low share in the total production of plastics, the bioplastics represent only about 1% of the about 368 million tonnes of plastic produced annually.

2 Impact of biobased, biodegradable and compostable plastics on waste management technologies and systems

2.1 Waste management practices

The following section will detail the plastic waste separation, collection and sorting systems currently available. In addition, the potential impacts of biobased and/or biodegradable plastics on the current waste management systems are described.

Elements of a waste management system include source separation, collection and transport, sorting and finally reuse, recycling, energy recovery, treatment and disposal, as shown in Figure 15.

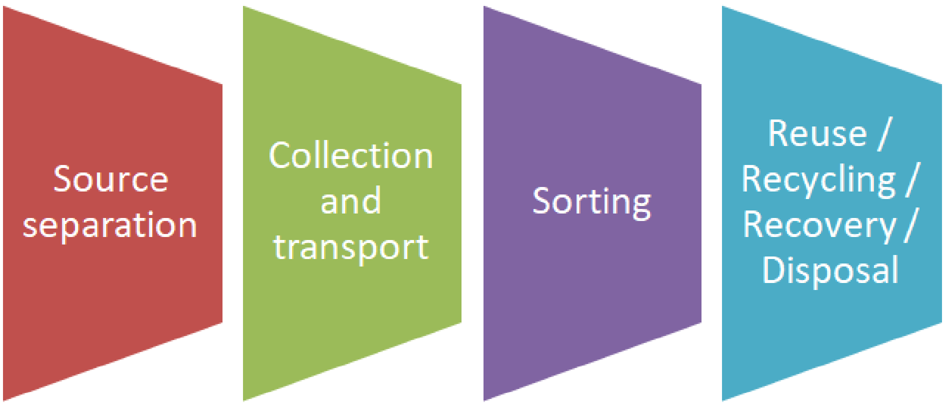

***Figure 15** Elements in a waste management system*

Source separation is commonly done to separate recyclables from non-recyclable waste for recycling. After consumption, the source separated waste will need to be collected and transported

Horizon 2020 This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

to waste management facilities. After collection, sorting might be carried out to separate different materials collected comingled. In the case of plastics, further sorting based on polymer types is needed for recycling. Lastly, waste can either be sent to be reused, recycled, treated energetically or disposal.

2.1.1 Waste separation, collection and storage systems

Household plastic waste collection systems can be generally categorized by the point of collection, which can be door-to-door collection, bring points and civic amenity sites. In addition, they differ by the source separation method, plastic waste can be either collected comingled with other materials or separately (i.e. only plastic). With door-to-door or kerbside collection, the waste is collected by trucks directly from the kerb with a certain frequency, for example weekly or bi-weekly (Weißenbacher et al. 2015). For example, plastic packaging waste can be conducted door-to-door in a comingled stream of plastics and metal packaging, sometimes also mixed with paper and/or glass.

Figure 16 *Bring points (Source: https://commons.wikimedia.org/wiki/File:Recycling_area_-_geograph.org.uk_-_595768.jpg)*

Horizon 2020

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 17 *Kerbside or door-to-door collection (Source: https://www.flickr.com/photos/volvob12b/9735246361)*

Figure 18 *Recycling centre (Source: https://commons.wikimedia.org/wiki/File:Inside_the_Transfer_and_Recycling_Centre_-_geograph.org.uk_-_901253.jpg)*

Bring points or drop-off points are also used for post-consumer plastic packaging waste collection. Bring points are usually located at public places or simply on the streets. Similar to kerbside collection, the plastic packaging waste can be collected in comingled stream or separately. The third collection option is civic amenity sites or manned recycling centres collecting not only plastic waste but also bulky waste, hazardous waste, WEEE, and other recyclables. Usually, a combination of the options is used for plastic waste collection in an area (Weißenbacher et al. 2015).

Due to the extended producer responsibility (EPR) for packaging, which is present in many European countries (Leal Filho et al. 2019; Monier et al. 2014), collection systems that target packaging (including plastic packaging) are commonly in place, while the separate collection of small plastic household items like toys or clothes hangers is uncommon.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

***Figure 19** Reverse vending machines for deposit return systems (Source: https://commons.wikimedia.org/wiki/File:Reverse_vending_machine_for_the_NSW_Container_Deposit_Scheme_located_in_the_Woolworths_Wagga_North_car_park_04.jpg)*

Apart from the above-mentioned collection systems, some European countries collect PET plastic bottles and other recyclable beverage containers within a deposit refund system (DRS). In such a system the costumer is obliged to pay a deposit upon purchasing the beverage product, which can then be redeemed after the costumer returns the empty packaging (Zhou et al. 2020). The collection points of such systems can be located for example in supermarkets.

Table 4 shows a summary of the current collection routes for different plastic product groups. It is important to note that some plastic can be found in residual waste (Edjabou et al. 2015; Di Maria et al. 2013) and not within the dedicated collection routes listed.

***Table 4** Example of collection routes of different plastic product groups*

Product group	Collection route
Plastic packaging	Comingled collection with other packaging items such as composite packaging, either door-to-door collection or through bring points.
	Deposit return system: In the case of PET beverage bottles.
Household small plastic items (not packaging)	Dedicated collection for recycling is not common. Items could end up in the recycling bin or the mixed MSW waste bin.
Bulky waste	Collection varies from region to region and can occur through recycling centres, pick-up services or civic amenity sites.

Impact of biobased, biodegradable and compostable plastics on waste management technologies and systems

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

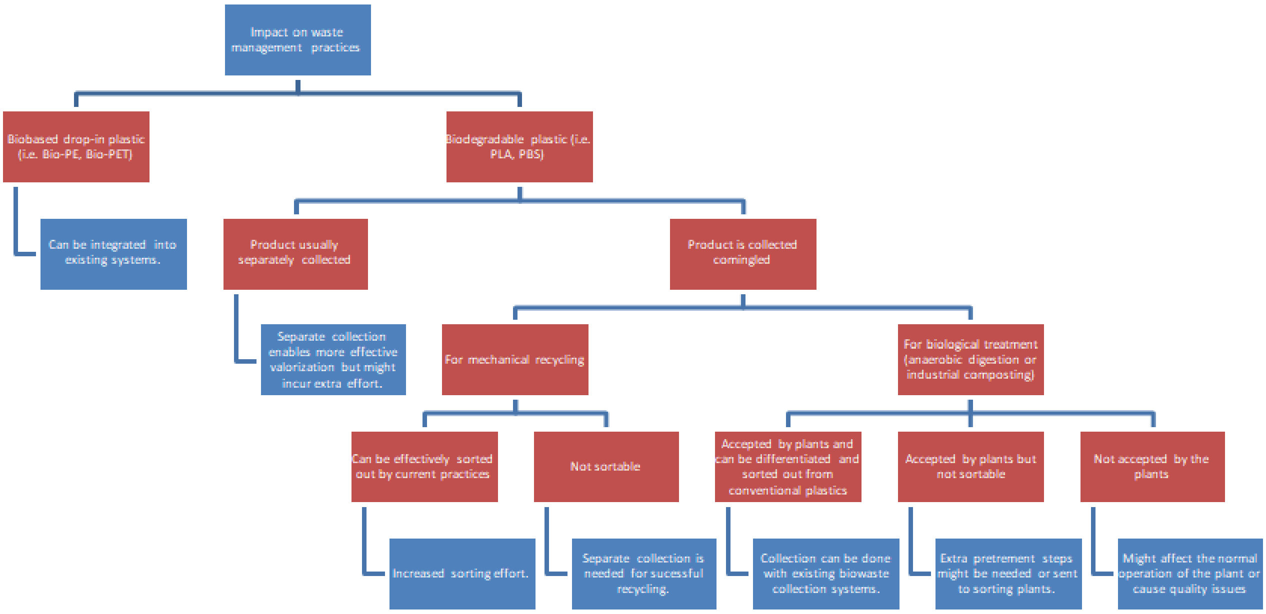

***Figure 20** Decision tree on the impact of biobased and biodegradable plastics on waste collection, separation and sorting*

The potential impact of biobased and biodegradable plastics will depend on:

- The type of plastic or polymer type.
- The targeted recycling route.

Biobased drop-in plastic

Biobased drop-in plastic that are chemically similar to common conventional plastics, such as Bio-PE or Bio-PET derived from biological feedstocks, can be collected, sorted and recycled together with fossil-based PE or PET (Niaounakis 2019; Spierling et al., 2018). Thus, these plastics should not cause significant impact to current waste management practices. This operates under the assumption that consumers will treat Bio-PE and Bio-PET products the same way they do with their fossil-based counterparts.

Bioplastics recycling

Bioplastics can be recycled but the main challenge for recycling is sorting the different types of bio-based plastics in separate streams. If degradable material enters the conventional plastics stream and fully degrades in the recycling process it may change the characteristics and specification of the conventional material it is mixed with. A recent report suggests that 3% of PLA can be added into the PP stream without altering the properties of the recycled PP. Larger proportions of PLA in the waste stream could make a separate PLA stream economically feasible. (Fachpacktgung, 2019) Also, if it does not fully degrade it may continue to do so in the finished recycled product, leading to premature failure (Bioplastics Guide, 2021). As is the case for most conventional plastics, bio-based plastics need to be recycled in separate streams according to material type.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

PET and PE are non-biodegradable and their precursors are fossil fuel derived, they are entirely possible to obtain the monomers from renewable resources and therefore synthesis bio-PET and bio-PE. Bio-based alternative such as Bio-PET and Bio-PE has identical properties as their petroleum derived plastic and can be processed using the same equipment and same polymerisation techniques and conditions. Furthermore, bio-PET and bio-PE can be recycled together with their conventional counterparts, no additional investment into equipment changes or waste sorting is needed to implement bio-PET and bio-PE (Lamberti and et., 2020).

Polylactide (PLA) is a bioplastic that is potentially recyclable but for which no separate recycling stream established yet. Mechanical recycling causes downgrading of the PLA quality. When mechanically recycling PLA, it is possible to add a chain extender which helps partially recover the impaired molar mass and other mechanical properties, making the recycled PLA more comparable with virgin PLA (Andrade and et. 2018). In addition, there is research on solid-state polymerization as an option to regenerate the properties of degraded PLA after recycling (Beltrán, Freddys et al., 2020).

The optimal recycling route for each polymer should first be reuse, after which the polymers should be mechanically recycled for as long as possible until their properties deteriorate and become low grade. The monomers of the low-grade polymers should be recovered via a chemical route (such as alcoholysis, biodegradation, biological recycling, glycolysis and pyrolysis), the monomers can then be repolymerised resulting in a circular production economy (Lamberti and et., 2020).

PLA should be recycled via alcoholysis since it generates a value-added product. Similarly, bio-PET should be recycled via glycolysis since it also generates a value-added product. Bio-PE has strong solvent resistance so it can only be recycled via pyrolysis. Polyglycolide (PGA) has a small amount in circulation and is only used in medical applications where it fully biodegrades. Polyhydroxyalkanoates (PHA) should be biologically recycled as it reduces the need for antibiotics and decreases the cost of animal feed. Undigested PHA in fecal matter is an ideal medium for mixed microbial cultures fermentation to generate new PHA (Lamberti and et., 2020).

The technology and literature for bio-versions of commodity plastics and chemical recycling routes is already well established. All that remains then is for the chemical recycling infrastructure to develop and better plastic waste collection schemes to be put into place.

Biodegradable plastic

Biodegradable plastics such as PLA and PBS, however, might require additional efforts for successful recycling or treatment depending on the targeted treatment process. Here, a differentiation between product types is useful as the collection of different product types differ. For example, conventional household packaging can be collected via comingled kerbside systems while large household plastic items can be collected via recycling centres or civic amenity cites.

High quality mechanical recycling of packaging waste is easier for homogenous polymer streams and thus effective sorting of plastic material is needed in the case of comingled collection (Eriksen et al., 2019; Hahladakis and Lacovidou, 2019). Thus, if chemically distinct biodegradable plastic such

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

as PLA and PBS is to be successfully mechanically recycled, it must be proven that they can be differentiated and sorted out from the mixed plastic stream. For example, PLA as well as a PLA-starch blend are quoted to be a problem for PET recycling in the case of cross contamination (Schyns and Shaver, 2021; Åkesson et al., 2021).

Automated sorting of comingled collected plastic packaging occurs primarily through NIR based sorting systems. Although PLA can be differentiated via NIR spectroscopy (Chen et al., 2021), sorting facilities still need to configure their processes to sort out an extra stream. This change will need to be economically viable based on the expected yield (Briassoulis et al., 2021). When current sorting practices are not able to deal with a certain polymer type, separate collection (i.e., not comingled with other polymer types) might be needed to reduce cross contamination of different polymers, which would incur extra effort. Recent studies suggest that the correct plant configuration has the ability to reduce PLA contamination levels in PET to a level that does not cause significant deterioration to the optical and thermal properties as well as intrinsic viscosity (van Thoden Velzen et al., 2022; Vendrik, 2021).

Biodegradable plastic destined for biological treatment requires a sorting or pre-treatment system that is able to differentiate them from general impurities, including conventional non-biodegradable plastics. This is because general impurities affect the operation of anaerobic digestion plants (Alessi et al., 2020) and also the output quality of composting plants (Puig-Ventosa et al., 2013). When this is not the case, extra pre-treatment steps might be needed. It is important to note that acceptance of biodegradable plastics in biological treatment plants vary significantly from region to region. If biodegradable plastic is not accepted, it might affect the normal operation of the plant or the quality of the outputs.

Case Study: Collection of Biodegradable Plastics in Germany

In Germany, packaging made from biodegradable plastics need to be registered within the extended producer responsibility system and be collected with other plastic packaging in the recycling bin. The collection of biodegradable plastic packaging with biowaste is not allowed due to concerns that it will not completely biodegrade in time and that composting plants are not able to differentiate between conventional and biodegradable plastics (German Environmental Agency 2020). The only exception is biodegradable bags made predominately from biobased sources for the separate collection of biowaste, which is allowed in the biowaste bin on the condition that the local waste operator, which decides, accepts its use. The biodegradable packaging collected within the recycling bin will be sent to sorting plants. Currently, there is no dedicated sorting stream for biodegradable plastics. Thus, they are predicted to be mostly to be sent to thermal treatment plants with the other sorting residues (Burgstaller et al., 2018).

2.1.2 Sorting systems

The configuration and infrastructure of the different sorting plants in Europe hugely depends on the different schemas of the collection. To better understand the sorting plants, one of the standards for the sorting plans (the one established in Spain for the 96 facilities receiving domestic light

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

packaging financed by Ecoembes) will be explained in detail. In addition, the differences with other standards are also included. The new collection systems including biodegradable packaging with other plastic packaging in the recycling bin, will force the inclusion of a new line for this new fraction at the sorting plant.

Spanish sorting-plants model

Waste treated in light weight packaging sorting plants in Spain is obtained from the selective collection of yellow containers, where citizens deposit domestic light packages. These are plastic, metal and food and drink carton packages and beverage carton. The containers contain impurities or unsolicited material which must be separated from the requested materials during the sorting process.

- **Requested materials**: HDPE (high density polyethylene), PET (polyethylene terephthalate), LDPE (low density polyethylene, generally in film form) and the mixed plastic fraction composed of materials made of PS (polystyrene), PP (polypropylene) and other plastics; also included aluminium and steel packages, as well as beverage cartons (hereinafter BC).
- **Unsolicited materials**: Cardboard, celluloses, P/C, low and high-density film plastics and other impurities such as glass, textile wood, non-packaging plastic, organic matter, other metals, etc.

Figure 21 *Light weight packaging sorting plant. (Source: ECOEMBES, 2021)*

The treatment process in a lightweight packaging sorting plant is divided into four main groups of operations:

- Reception and storage.
- Pre-treatment.
- Sorting of materials.
- Quality controls, adaptation of selected materials and rejected waste management.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

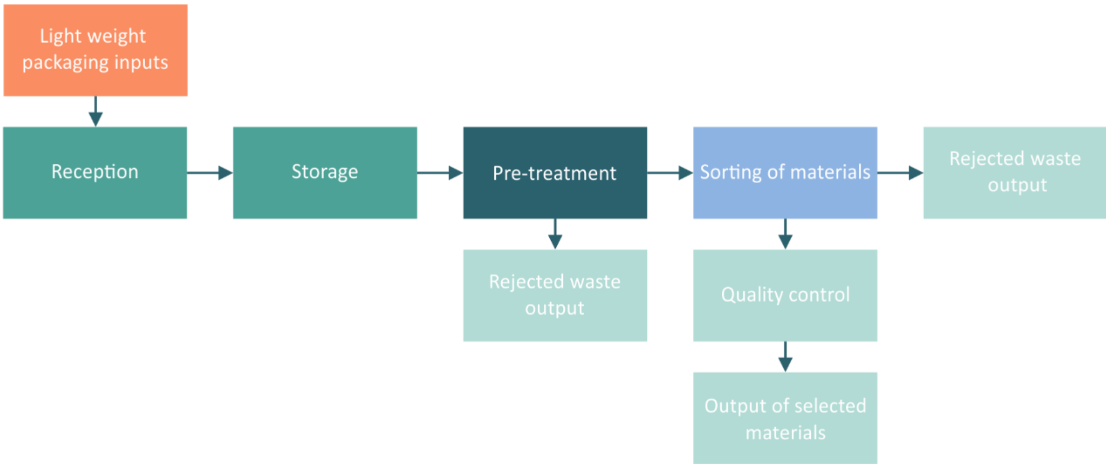

Figure 22 *Outline of sorting process. (Source: Elaborated by ECOEMBES, 2021)*

These operations will vary depending on the automation level of the sorting plants. Facilities are classified as automated or manual depending on how the material sorting operation is performed.

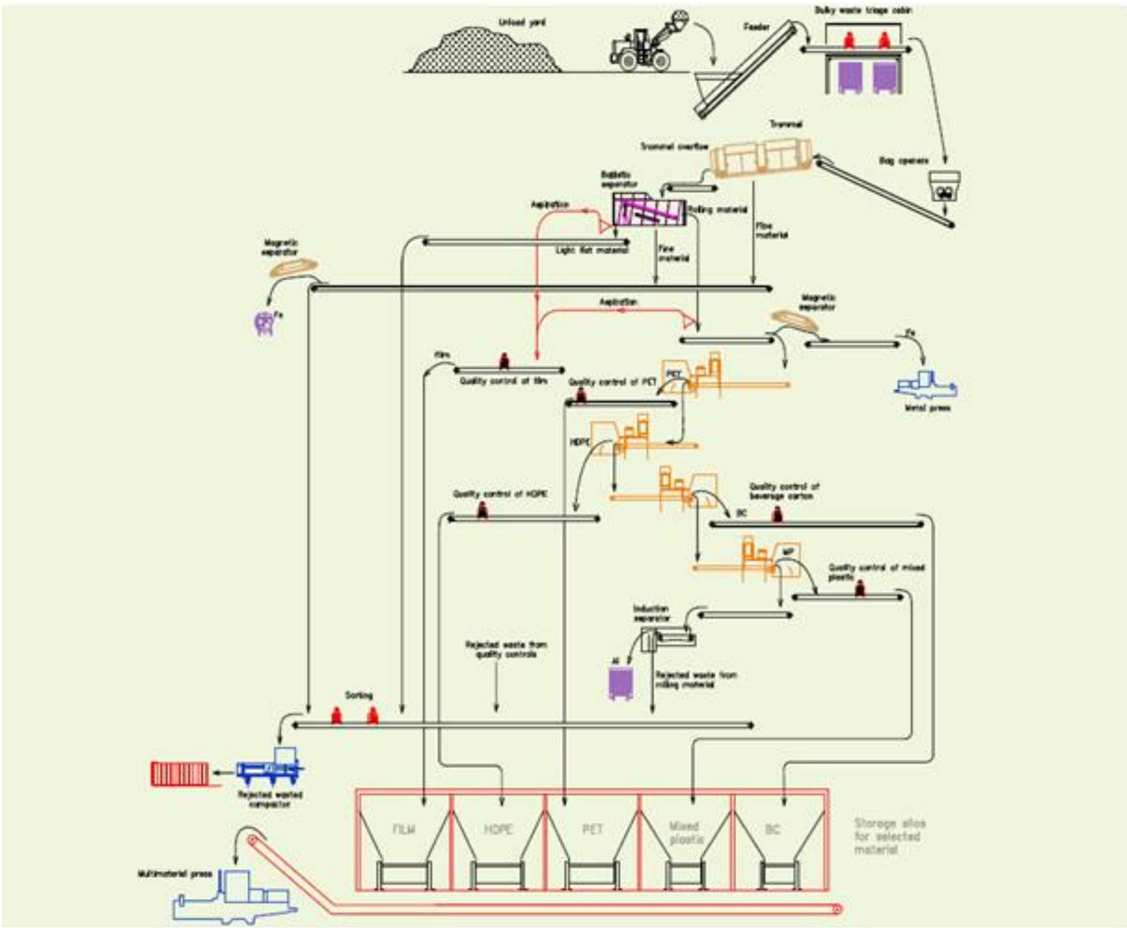

Figure 23 *Diagram of the automated sorting process. (Source: Elaborated by ECOEMBES, 2021)*

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

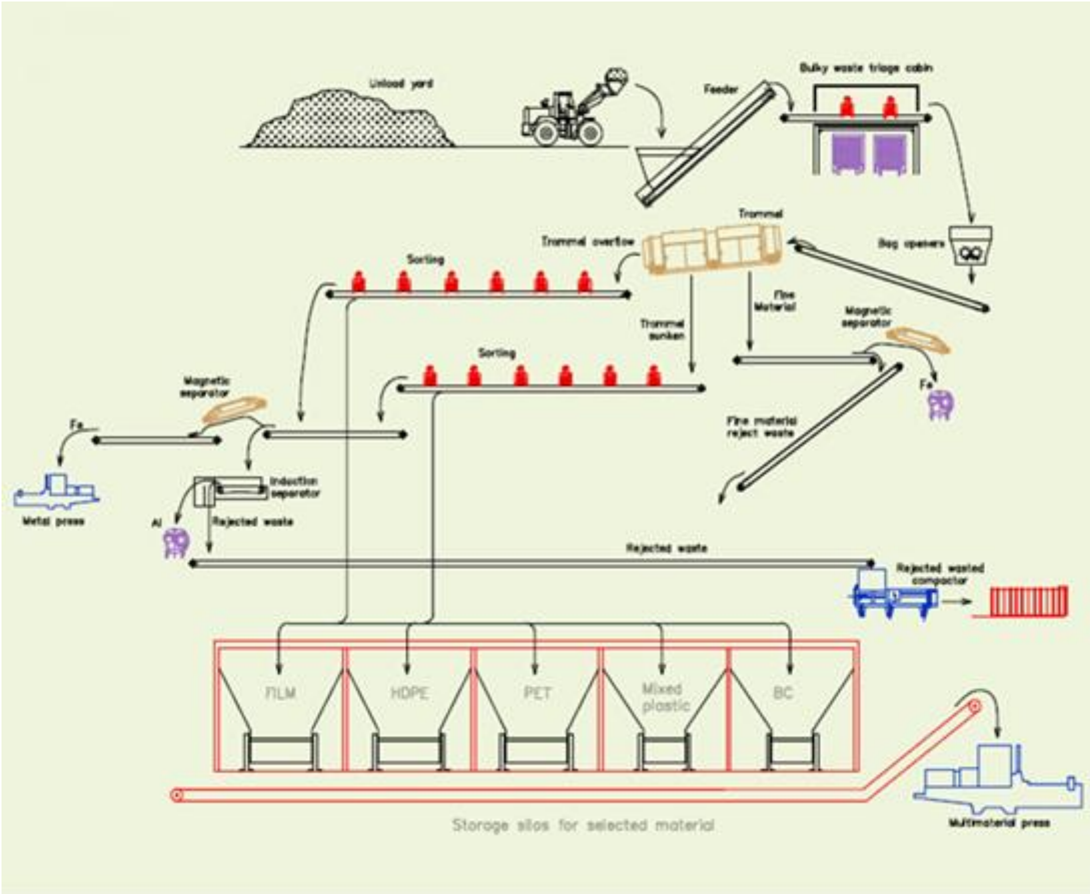

__Figure 24__ Diagram of the manual sorting process. (Source: Elaborated by ECOEMBES, 2021)

Reception and storage operations

The reception and storage operations will be not affected by the inclusion of the bioplastics on the flux of the packaging waste. This stage is composed of three steps:

- **Scales for monitoring and weighing of collection vehicles**: Vehicles with packaging waste collected from streets arrive at the sorting facility passing through access control and weighing (scales). In order to transport the collected material more efficiently, when the street collection vehicles need to travel great distances from the place of collection to the destination plant, it is convenient to unload the material at intermediate locations (transfer stations) for compacting and subsequent transport in larger containers, if possible and those facilities exist. In this case, the material arriving at the plant has a bigger density, which must be considered when sizing the treatment capacity of the facility.
- **Unloading area for transported waste**: After weighing the vehicles and identifying their origin and schedule, they are led to the covered reception area where the transported waste is unloaded in the area or location indicated by the discharge and feeding operator.
- **Positioning and stacking of unloaded waste**: The loading shovel stacks the unloaded waste vertically, optimising the surface available for storage prior to treatment. This process can include several components of bulky waste with sizes or shapes (as in mattresses, large

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

packages, bicycles, etc.) that hinder the work and could affect the sorting equipment to be used. Using the loading shovel the operator must place these in a specific container located on this or another surface.

Pre-treatment operations

In this stage, the bioplastics starts to be separated in different streams depending of the type of the packaging (bottles, trays, bags...). This stage is composed of different steps inside the sorting plant:

Primary feeding-dosing: The waste deposited in the reception area is collected with the loading shovel (unload yard) or grapple hook (pit), transferred and unloaded in the dosing feeder with variable speed and flow limiter, used to control the treatment flow rate.

Bulky waste sorting: Waste regularly supplied by the feeder is unloaded in a bulky waste sorting conveyor belt, where sorting operators select the materials which due to their size or shape are detrimental to subsequent treatments, such as film sheets, cardboard, EED waste, etc. The selected bulky materials (recoverable and non-recoverable) are stored in containers located under the sorting cabin for delivery to the recycler or the treatment rejects section.

Bag opener: Non-sorted waste is downloaded by the same sorting belt in a bag opening unit designed to extract the materials from the bags when they are ready for the remaining sorting operations.

Classification in trommel: In many cases, the components of the bags are subjected to a sieving process using a trommel or revolving sieve, which classifies the materials into three sizes:

• Fine components with a high content in organic and inert material.

• Intermediate components with a high content in recyclable packages.

• Large components or sieving rejects.

Figure 25 *Classification in trommel by size to separate light weight packaging (underflow) from organic matter (fine waste underflow) and bulky waste (overflow). (Source: ECOEMBES, 2021)*

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Classification in ballistic separator: The stream of intermediate size materials of the trommel, if that exist, or from the bag opener directly, if that doesn't exist, is subsequently subjected to ballistic classification according to size, shape and density, and again separated into three new material streams:

• Stream of heavy-rolling material formed by the majority of the heavy and/or rolling material, mainly packaging for liquids, metal packaging and beverage carton. This falls down the inclined slope of the ballistic separator.

• Stream of light flat materials, mainly formed by cardboard, paper and other film plastics with a flat or flattened shape that rise up the inclined plane of the separator.

• Stream of fine materials made up of fine material that could not be sieved in the trommel because it was attached to or blocked by other material, which falls through the mesh of the separator.

The amount of material reaching each of the three fractions will depend on the quality of the material introduced in the equipment. For examples, in facilities with 75-85% of requested material at the inlet, the classification performed by a ballistic separator is about 80% rolling material, 15% light flat material, and 5% fine material.

At facilities where the sorting operations are performed manually, the ballistic separator is not used. The material arriving from the trommel, if exists, is taken directly to the sorting cabin, where the operators sort the requested materials

Figure 26 *Classification using the ballistic separator based on density in segregating light-flat material (film and P/C) from heavy rolling material (packages). (Source: ECOEMBES, 2021)*

Sorting of materials operations

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Primary feeding-dosing: The waste deposited in the reception area is collected with the loading shovel (unload yard) or grapple hook (pit), transferred and unloaded in the dosing feeder with variable speed and flow limiter, used to control the treatment flow rate.

Pneumatic separation: The main objective of pneumatic separation is to clean film and paper from the rolling and light flat material streams, since these hinder the segregation of the remaining materials. The selected material is subjected to a manual quality control to separate impurities. It is subsequently stored to prepare it for dispatch (compaction).

Magnetic separation: The rolling material stream obtained from ballistic segregation is subjected to segregation of magnetic materials (steel) using over-band separators. Similarly, the fine material fraction from the trommel, if the plant is equipped with this equipment, and ballistic separator are subjected to magnetic material sorting before being sent to the rejected waste fraction.

Optical separation: The rolling material stream that has not been selected by pneumatic aspiration on this line nor by the magnetic separator is subjected to optical segregation by infra-red or colorimetry detectors to segregate the following requested materials:

• PET packaging.

• HDPE packaging.

• Beverage carton packaging.

• Mixed plastic packaging.

To improve the performance and quality in the sorting of these materials, the magnetic and pneumatic sorting must take place prior to the optical separation.

In case of bioplastics flux, a new NIR optical detector should be added to produce a new stream.

Figure 27 *Optical separators. (Source: ECOEMBES, 2021)*

Induction separation: The stream of materials not sorted by the optical separation is subjected to a sorting of non-magnetic metals (aluminium) by an eddy current separator.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 28 Induction separators remove aluminium material using eddy currents. (Source: ECOEMBES, 2021)

Manual separation: Materials not selected in the rolling and light flat material streams converge on a belt in which they are subjected to manual sorting. The remaining unselected material is sent to the rejected waste fraction.

Quality control, material adaptation and rejected waste management operations

Quality control: Due to errors occurring in the different types of equipment, the selected packaging material contain impurities that reduce the purity of the final product. These impurities are removed through manual sorting. This operation is usually performed after the sorting of each of the recovered materials (PET, HDPE, beverage cartons and mixed plastics) before storing in silos for compaction. In other facilities, the quality control is performed before compaction, so that a single operator can perform the operation. The sorted impurities are sent to the rejected waste stream at the facility or, if they are requested materials, recirculated to previous points of the process for sorting.

Figure 29 Quality control of selected materials. (Source: ECOEMBES, 2021)

Temporary storage of selected materials: The selected materials are deposited in specific confined spaces for each one (intermediate storage silos) awaiting compaction operations. Storage silos are compartments sized according to the following parameters:

- Apparent density of each material
- Production of each selected material per shift
- Hourly capacity of the compacting press.

The extraction of the materials stored in the silos is performed using moving bases, conveyor belts or directly with a loading shovel, which evacuate them to the feeder of the baling press placed downstream. If the selected amount of any material is small (e.g. aluminium) the production is stored in auxiliary containers for subsequent compaction.

Figure 30 *Temporary storage of selected materials. (Source: ECOEMBES, 2021)*

Compaction of selected materials: Materials stored temporarily in the containers are subsequently subjected to density increasing operations using baling presses, which produce bales with a density suitable for final storage and subsequent transport. A single properly sized press can bale the output of all selected materials (PET, HDPE, FILM, beverage cartons and mixed plastics; and, if required, PLA or other bioplastics) except metals, and particularly steel, which require different bale sizes and features as well as specific presses.

Rejected waste management at the facility: all sorting facility rejects are typically concentrated on a single output conveyor belt that discharges them at the evacuation point. Occasionally the fine materials current is discharged at different points from other rejected waste. Due to the low density of the rejected waste material, its volume needs to be adapted for an efficient disposal to the landfill. This can involve several alternative systems:

- Self-compacters.
- Static compacters.
- Rejected waste press.
- Containers (for low-volume facilities).

Transport of containers with rejects is performed using container vehicles to take them to processing sites (landfill or energy recovery).

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 31 The rejected waste material at the facility is compacted or stored in containers for delivery to the landfill. (Source: ECOEMBES, 2021)

Differences among plants

The model presented is a standard designed in Spain to define the sorting plants for light packaging. Not all these plants follow the standard literally; there are differences among them. The operations in a sorting plant will vary depending on the automation level of the sorting plant. Find here some differences:

- There are facilities with discharge pit and facilities with unloading yard as a reception area.
- Treatment lines with discharge pit are feeded by grapple hooks.
- Treatment lines with unloading yard are feeded by loading shovel.
- There are some sorting plants with trommel.
- Size mesh of the ballistic separator used to vary between 50 and 70 mm.
- Some plants have incorporated optical separation for film.
- We can find a lot of different configurations of optical separator chains.
- Induction separation with a different intensity is used for the sorting of beverage carton packaging in some plants.
- The selected materials quality control is performance by an operator, mostly. However, we can find optical separator quality control.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Figure 32 Classification Trommel: Divides the material stream into two or more categories according to grain size using specific size sieves. (Source: ECOEMBES, 2021)

Other European sorting-plants models

According to the Circular Economy Action Plan (EC, 2020), the Commission will propose to harmonise separate waste collection systems in all Europe. At the future, all the requested materials will be harmonised, so a European sorting-plan model should be established.

The typical sorting-plant model in Europe involves several similar sorting steps, as presented in the above Spanish example. These include manual dismantling and sorting by automated processes, separation according to density and size, and optical or magnetic separation. However, the exact process can vary according to consumer behaviour and collection systems. For example, in the Nordic countries, consumer behaviour and market availability mean that less beverage carton packaging (TetraPack) is used than in Spain, meaning there is no separate stream for this kind of packaging.

The collection system used in different countries has also had a large influence on the historical development of MRFs. When recyclable materials are collected in separate streams, this can reduce the number of sorting steps needed, or free up capacity to sort a greater number of types or grades. On the other hand, mixed collection of recyclables saves resources at the front end but require a higher degree of technical complexity in MFRs (Cipram et al, 2015).

In general, there are four main collection models applicable in Europe:

1. Single-stream collection: all dry recyclables (plastic, metal, paper, cardboard, and sometimes glass) are collected together. For instance, this is the main collection model in Greece, Ireland, Malta and Romania.
2. Dual-stream collection: 'fibres' (paper and cardboard) and 'non-fibre' (i.e. plastic, metal and glass) are collected separately. This is the main collection system in the Finland and the UK.

Horizon 2020 This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

3. Mono-stream collection: each material is collected separately (i.e. paper and cardboard, glass, and lightweight packaging), and treated in a MRF. The Spanish model described above fits in this category. This collection system is the most prevalent in Europe, being applied in Belgium, Bulgaria, Croatia, Cyprus, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, Poland, Portugal, Slovenia. In addition, some countries further separate the lightweight packaging stream into its constituent parts, including Austria, Denmark and the Netherlands.
4. Mixed Municipal Solid Waste (MSW) collection scheme: no separate collection of recyclables. This leads to high contamination rates and need for intensive treatment. While the Waste Framework Directive (2008/98/EC) required separate collection of paper, metal, plastic and glass from household waste by 2015, and 50% preparation for re-use and recycling by 2020, 14 Member States were identified as being at risk of missing this target. Ineffective separation of recyclables was cited as a contributing factor in 11 countries (Bulgaria, Croatia, Cyprus, Estonia, Greece, Latvia, Malta, Poland, Portugal, Romania, and Slovakia) (European Commission, 2019).

In practice, however, the collection and sorting model may vary widely within countries, as decision-making powers on the selection and operation of waste collection systems usually sits with local authorities.

2.2 Waste processing technologies

2.2.1 Method for Circular Economy

Innovative recycling and recovery technologies have enormous economic value in transforming post-use and difficult-to-recycle plastic into their original building blocks that can be continually reintegrated to supply chains as feedstocks for new plastics and chemicals, other raw materials for manufacturing, and lower-environmental-footprint transportation fuels without the need for virgin materials (Solender, 2021).

To efficiently recycle large amounts of plastic packaging wastes, a circular economy requires suitable technologies, such as chemical recycling (Meys et al., 2020). Chemical recycling turns plastic packaging waste into chemical products, avoiding their production from fossil feedstock in the first place. Therefore, chemical recycling is expected to decrease the demand for the planets' finite fossil resources as well as the emissions of greenhouse gases (World Economic Forum, 2017). At the same time, chemical recycling provides chemical products that are chemically identical to the replaced products. Thereby, chemical recycling avoids performance losses currently observed for mechanical recycling of plastic packaging, so-called "downcycling" (Hong & Chen, 2017). Due to downcycling, products ultimately have to be incinerated or end up in landfills after shorter use cycles.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

However, there is a mismatch between expected environmental benefits and results from prospective environmental evaluations for chemical recycling. At the same time, chemical recycling is still in early development and has not been fully assessed environmentally. It is therefore timely to assess if and to which extent chemical recycling of plastic packaging waste can achieve environmental benefits before research funds and time are invested (Meys et al., 2020).

Technology has incalculable potential to enable humanity to be the best stewards of the biosphere, and usher into existence a truly inclusive, circular economy faster, more effectively, and more efficiently to create positive economic, environmental, and societal impact. The four strategic system enablers where technology can accelerate solutions to the waste crisis and serve as a model for broader circular economy initiatives (Sullivan & Hussain, 2020):

- Responsible Sourcing and Marketplace: Expanding the trade of secondary and alternative materials by incorporating existing marketplaces in specific geographic regions helps drive responsible sourcing and multi-supply strategies. The business problem here is that brands need new sources of steady and assured supply to replace materials such as virgin plastic with recycled or alternatives and suppliers need visibility into demand. Technology can help aggregate these local marketplaces and formalize informal sector waste pickers while ensuring they are not exploited and are paid fair wages. It also assures corporates and consumers that all sourcing is done ethically. By streamlining the processes, buyers and sellers have full transparency into the lifecycle of materials.
- Responsible Production: Recycling and reuse is a massive and growing issue. For example, the EU has set targets of 50 percent recycled consumer waste by 2020. In addition, hundreds of consumer packaged goods (CPG) companies have made public statements about their goals of 100 percent recyclable or reusable materials by 2025, however one of the challenges faced by companies is that their data exists in silos, making it hard to generate a comprehensive map of what they make, where they sell it, and whether component materials get recycled post-consumer. Technology — such as intelligent product design — enables close cooperation between chemical, packaging, and consumer product companies while blockchain provides a means of traceability of both upstream suppliers and the product once it leaves the factory. Some real-time tracking technologies make it possible to see precisely where a product ends up and how it will be reused or recycled. Technology also helps track, calculate, and optimize for material bans — such as plastic bags or straws — and tax liabilities from increasing costs of Extended Producer Responsibility schemes worldwide.
- Responsible Consumption: Business-to-business customers and consumers are critical partners in the effort to close the economy’s material loop. They have the ability to buy ‘more sustainable’ products and a responsibility to understand how disposable materials and packaging can be best avoided — for instance, through product reuse models — or recycled back into productive use. Technology can help enable this through traceability apps and by providing deep insights into citizen sentiment or ‘product experience’ to help brands better engage with their customers and provide insights based on product needs and shared values back into product design.

Horizon 2020

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

- Resource Recovery and Reuse: Many companies and their stakeholders not only want to know whether products are designed for recyclability, but also whether they are actually being recycled across regions and waste schemes. For their part, recyclers want granular, high-quality data on sources of these recyclable materials in order to support investment decisions around new collection and processing capacity. Geospatial technology, data science, and real-time analytics — as in the Topolytics example — enable investors, waste managers, consumer industries, and startups to invest in and build physical infrastructure where it is most needed to increase cycling of material flows at their highest value.

2.2.2 Mechanical Recycling

2.2.2.1 Introduction

Some of the problems derived from the incorrect management of plastic waste, such as environmental pollution and the generation of micro and nanoplastics that can be found in water, soil and air, and from there enter us, have been revealed recently. In addition, it should not be forgotten that incorrect plastic waste management involves a loss of valuable materials, that is, an unacceptable loss of resources and raw materials. Mechanical recycling, which basically consists of the collection of plastic waste and its reprocessing to obtain recycled plastic with which to manufacture new products, makes it possible to address both problems, the loss of valuable resources and the uncontrolled dumping of waste.

Mechanical recycling is a well-known alternative for conventional, petroleum-based plastics such as PET or HDPE. Different collection and recycling systems are implemented in different countries. However, mechanical recycling of biobased and biodegradable plastics is much less well known and practiced, for reasons that will be discussed later.

This chapter discusses the mechanical recycling of biodegradable plastics obtained from renewable sources that have an important implantation in the market, such as PLA, PHAs or TPS. Non-biodegradable biobased plastics known as drop-in bioplastics, such as bioPE or bioPET, which are identical and recycled like PE and PET from petroleum, are not included. The recycling of plastics obtained directly from lignocellulosic materials is not considered either.

2.2.2.2 Definition and advantages of mechanical recycling

As shown in fig. 1, the mechanical recycling of plastics basically consists of the collection of waste, its sorting, separation and purification (which can include washing steps), its crushing and its reprocessing, usually by melt-compounding (Figure 1) (Niaounakis et al., 2013). The result is recycled plastic with which new products can be made.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

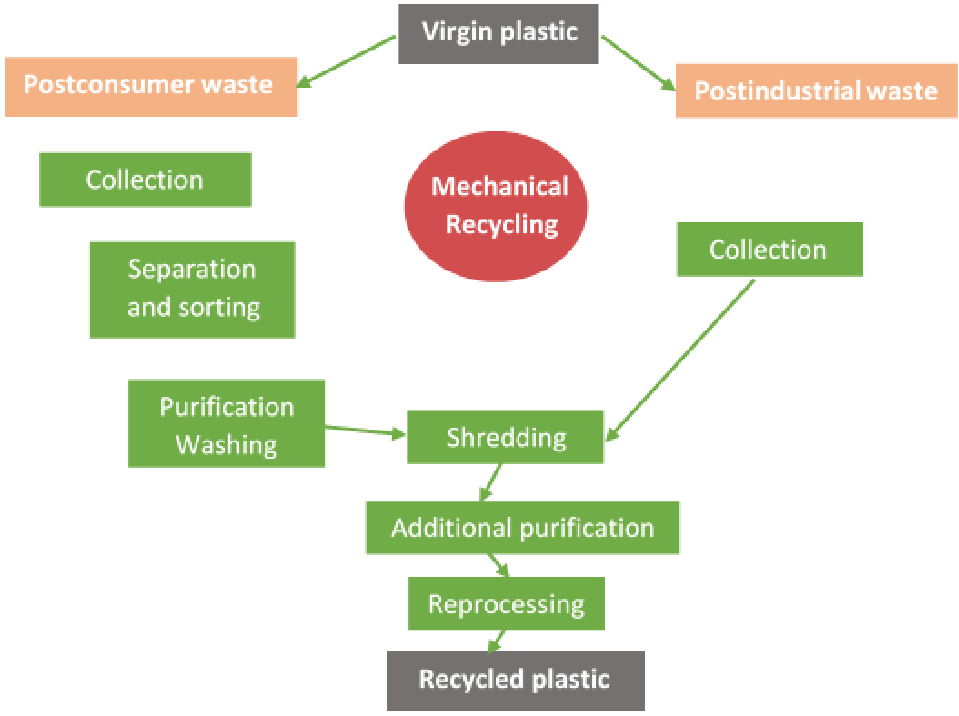

Figure 33 *Stages of the mechanical recycling process.*

During the shredding stage, the plastic waste is transformed into small pieces, such as flakes. Special attention should be paid to the high temperatures and shear stresses since some biobased and biodegradable plastics, such as PLA and PCL, present low melting and glass transition temperatures, making them especially susceptible for thermomechanical degradation (Niaounakis et al., 2013; Al-Salem et al., 2009). Sorting is also a very important step in the mechanical recycling process, since contamination of separated plastic waste streams with other plastic can lead to recyclates with poorer properties. In this regard, several technologies including manual sorting, float-and-sink methods, FT-NIR and fluorescence spectroscopy, are already used in conventional plastics recycling facilities. However, the introduction of biobased and biodegradable plastics into the equation represents a new challenge. For instance, PLA and PET cannot be easily separated by manual or density-based methods, yet it has been reported that FT-NIR led to 98% efficiency in the sorting process (Firas et al., 2004).

The washing stage plays a key role in removal of contaminants that might negatively affect the properties of the recycled material. In some materials, such as PET, a demanding washing step including NaOH, surfactants and even some solvents such as tetrachloroethylene have been reported [4]. In the case of biobased and biodegradable plastics, since most of them are polyesters (such as PLA and PHAs), they are very susceptible to suffer hydrolytic degradation which could lead to the reduction of their performance (Badia et al., 2017).

Furthermore, special attention should be paid if the recycled plastics are meant to be used in food contact applications, in which stricter regulations are established. In this regard, the 'Panel on Food Contact Materials, Enzymes and Processing Aids' of the EFSA has proposed a process for

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

decontamination of recycled PET used in food packaging applications. The process consists in washing PET waste flakes coming from food contact applications with a 2% caustic soda solution, preheating those washed flakes and introducing them into a continuous solid-state polymerization (SSP) reactor at high temperature, obtaining higher molecular weights and limited migration of contaminants (Silano et al., 2018). This process might be technically feasible with some biobased and biodegradable plastics, since some studies with thoroughly washed PLA wastes pointed out that SSP led to the increase of the intrinsic viscosity of PLA (Beltrán et al., 2019).

Lastly, the reprocessing of the plastic waste is carried out. Melt extrusion is the most used technique to produce regranulated material from plastic wastes, due to it being large-scale, available for many polymers, solvent-free and cheap (Schyns & Shaver, 2021).

Overall, mechanical recycling is a very interesting method for the treatment of plastic waste because it allows eliminating waste and possible contamination, while valuable materials are recovered. Compared to manufacturing virgin plastic, mechanical recycling can enable substantial savings in raw materials and energy (Zhao et al., 2018), also in the case of biobased plastics (Scaffaro et al., 2019).

It is important to distinguish between post-industrial waste and post-consumer waste. In the first case, waste generated in the plastic manufacturing processes, which has not been used, is collected and reprocessed. In post-consumer recycling, it is waste that is collected after the product is consumed (Niaounakis, 2013; Meys et al., 2020).

Post-consumer recycling is much more complex and expensive because the waste is more dispersed, tends to be more degraded, and often contains pollutants such as soil substances, food waste, different plastics, and others. The presence of pollutants is undesirable, even that of other plastics, because they are immiscible with the plastic to be recycled and greatly reduce the performance and, therefore, the quality of the recycled material (Niaounakis, 2019; Samper et al., 2014). Therefore, the collection, sorting and purification stages are much more important and expensive in this case. Of course, the problem is reduced if the waste comes from a separate collection route of only one type of plastic.

A key issue in this type of recycling is the degradation that occurs in the polymeric matrix. It must be considered that reprocessing usually takes place in the melt state and that high temperatures cause breaks in the polymer chains and the subsequent decrease in the molecular weight which lead to a reduction in the overall performance of the plastic. This degradation depends on the recycling conditions and on the nature and previous degradation of the polymer. In general, biobased and biodegradable polymers are especially susceptible to chain-breaking processes (Briassoulis et al., 2020).

For this reason, the use of stabilizing additives during reprocessing to minimize degradation is common. Sometimes treatments are performed to reverse the degradation of the polymer. For example, in the above mentioned SSP stage, frequently used in the mechanical recycling of PET, the

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

plastic is heated for several hours at the appropriate temperature to promote polymerization reactions that counteract degradation (Firas et al., 2004; Cruz & Zanin, 2006).

2.2.2.3 Current situation in the mechanical recycling of biobased and biodegradable plastics.

Although various studies have shown that mechanical recycling is the best alternative for biobased plastic waste such as PLA (Fredi & Dorigato, 2021), at present this type of recycling is rarely used for post-consumer waste of biobased plastics.

However, the recycling of post-industrial waste is commonly used in the plastics industry (ERESMA, 2021). In fact, nowadays PLA post-industrial waste is one of the cases of mechanical recycling of biobased and biodegradable plastics applied at industrial level (Maga et al., 2019).

As it was previously stated, biobased and biodegradable plastics are especially susceptible to degradation during reprocessing at high temperatures. Several studies have reported considerable decreases on the molecular weight of PLA after several reprocessing cycles, as a result of the different degradation processes that take place during melt processing (Badia & Ribes-Greus, 2018). This decrease of the molecular weight comes along with a change on the properties of PLA. For instance, melt-flow index, a parameter crucial for the plastic processing industry, increased after each reprocessing cycle (Żenkiewicz et al., 2003; Carrasco et al., 2010), which is problematic for the design of processes at industrial level. The thermal properties of PLA were also affected by reprocessing, which led to an increase on the crystallization ability and a slight decrease on the thermal stability of the materials (Brüster et al., 2018; Agüero et al., 2019). Lastly, it is worth to note that reprocessed showed poorer mechanical properties, such as lower tensile strength and stress at break (Żenkiewicz et al., 2009; Pillin et al., 2008).

This data reflects that recycled post-industrial PLA waste can lead to materials with poorer properties than the PLA-based product from which it comes. Nevertheless, they can still be suitable for many industrial applications; therefore, special attention should be paid to the final application of the recycled materials. In addition, it must be taken into account that the decrease in properties is moderate, so it is very common to consider that a certain percentage of recycled post-industrial plastic can be assumed, for example 20% in the case of many high-consumption grades of PLA, in blends with virgin plastic, without significantly impairing the properties of the final product.

Regarding the mechanical recycling of post-consumer waste from biobased and biodegradable plastics, this is rarely done today, for different reasons (Niaounakis , 2013; Niaounakis, 2019):

+ The consumption of this type of plastics is still low, compared to the consumption of plastics derived from petroleum. This makes it economically unfeasible to implement collection, sorting and purification systems at the regional or national level for this type of plastics yet.

+ There is a special alternative for the treatment of this waste, which does not exist for plastics derived from petroleum. Many of this type of plastics are compostable under the right conditions, for example under industrial conditions. Composting, which is analysed in another chapter of this

Horizon 2020 **This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407**

document, makes it possible to eliminate the problem of waste, although the possibility of reusing materials is also lost.

+ Many people consider that biodegradable plastics decompose and disappear quickly in the environment. So, they believe that the abandonment of their waste is not a major environmental problem. However, this is not true because the rate of degradation depends not only on the polymer, but also on environmental conditions. For example, PLA degrades within a few weeks under industrial conditions, at around 60 ° C, at the right pH, in the presence of the right amounts of oxygen and moisture, but it degrades very slowly under other conditions, such as those found in landfills or in the seas. Under these conditions, the degradation of these plastics can release potentially toxic additives and generate microplastics in a similar way that conventional plastics do.

+ Some biobased and biodegradable plastics are especially sensitive to degradation during service as well as during the recycling process. In these cases, the performance of recycled plastic can be clearly lower than that of virgin plastic.

Despite these barriers, mechanical recycling of post-consumer waste from biobased and biodegradable plastics could still be feasible, although, a different approach might be needed. Distributed recycling, an approach in which each consumer (or group of consumers) recycles their own plastic wastes, is gaining a lot of interest with the growth of additive manufacturing technologies (e.g.: 3D printing). This approach could allow to recycle plastics with currently small markets such as PLA or PHAs (Peeters et al., 2019). Furthermore, it could reduce the costs and the environmental impact of the recycling process, since transport of wastes is reduced.

The most common example of the distributed recycling approach can be found on mechanical recycling of 3D printing wastes inside a university campus. Some studies have pointed out that it is possible to obtain recycled materials with acceptable properties, although, special care have to be paid to the homogeneity of the wastes, since wastes with a heterogeneous origin can lead to increased degradation (Beltrán et al., 2021).

2.2.2.4 Some technical issues in the mechanical recycling of PLA

As it was pointed out in previous sections, biobased and biodegradable plastics are susceptible to a wide variety of degradation agents, which can act during both their service and mechanical recycling. However, the lack of a separate stream for biobased and biodegradable plastics, such as PLA, have made difficult to evaluate the degradation in use and after recycling of real post-consumer samples. Nevertheless, some researchers have simulated, at laboratory scale level, the degradation during service and during recycling of PLA. For instance, accelerated ageing during seven weeks, at 50 °C and 90 % RH led to a severe increase of MFI of PLA in PLA/PC blends (Yarahmadi et al., 2016). Furthermore, it has been reported that the introduction of a demanding washing step (15 min at 85 °C, using NaOH and a surfactant) prior to reprocessing caused a 20 % decrease of the intrinsic viscosity in PLA samples, with the subsequent decrease in some important properties such as thermal stability (Beltrán et al., 2018a).

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

The degradation of biobased and biodegradable plastics during service and mechanical recycling, with the consequent decrease of the performance that comes with it, could threaten the feasibility of mechanical recycling fort these materials. Therefore, in recent years several cheap and environmentally sound methods to upgrade the performance of recycled biobased and biodegradable plastics, have been published. For instance, the use of different additives such as stabilizers, chain extenders or crosslinking agents during the extrusion is one the most interesting alternatives. Promising results have been reported by using epoxy-based chain extenders, diisocyanates and organic peroxides, which result in increased molecular weight, lower MFI and overall improved thermal and mechanical properties of mechanically recycled PLA (Beltrán et al., 2019a; Cosate de Andrade et al., 2018; Tuna & Ozkoc, 2017). Another approach consists in the improvement of the properties of recycled biobased and biodegradable plastics by using fillers such as cellulose (Laadila et al., 2017, Laadila et al., 2020), silk fibroin nanoparticles (Beltrán et al., 2020a), lignocellulosic nanoparticles (Beltrán et al., 2020b) or clays (Beltrán et al., 2018b). Lastly, the utilization of solid-state polymerization (SSP) in adequately chosen conditions led to an increase of the molecular weight of recycled PLA samples (Beltrán et al., 2019b). SSP is an especially interesting upgrading method, since it is simple and accessible to most plastic processing industries, and does not imply the use of solvents or catalysts that could threaten the low environmental impact of the use of PLA.

2.2.2.5 Mechanical recycling of PHAs

In the previous paragraphs, the mechanical recycling of PLA, a bioplastic with good properties and widely used today, has been specially considered. Many of the issues that have been discussed are common to all biodegradable and biobased plastics.

The mechanical recycling of other plastics of this type, such as PHAs, has been less studied. However, the importance of its mechanical recycling will increase in the coming years, since the production and consumption of these plastics is growing significantly.

The main drawback of PHAs is that are characterized by their low thermal stability. They present the melting temperature close to the degradation temperature (Arrieta et al., 2017). Thus, they can undergo thermal degradation at processing temperatures (Vu et al., 2019). Considering mechanical recycling, PHAs undergo significant thermal degradation in the reprocessing stage of mechanical recycling process due to their low thermal stability. For example, reprocessing of PHB leads to a significant decrease in the mechanical properties of plastic; tensile strength drops by half after just two processing cycles. A great increase in the degree of crystallinity, due to the presence of shorter macromolecules produced by the degradation (chain scission), was also observed (Rivas et al., 2017). The mechanical recyclability of PHB blended with PLA has been also studied. PLA-PHB-based blends showed better resistance against thermal degradation at multiple reprocessing stages than neat PLA and neat PHB (Plavec, 2020).

PHBV, one of the most promising PHAs nowadays, shows much better performance during reprocessing than PHB. The decrease in tensile strength was only 7% after 5 reprocessing cycles

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

(Zaverl et al., 2012). Zembouai et al. (2014) reported that a blend of PHBV and PLA showed even greater resistance to thermomechanical degradation during reprocessing, since the mechanical properties remained almost constant after 6 reprocessing cycles (Zembouai et al., 2014).

These results are very interesting because they open the possibility of mechanical recycling of PHAs and their blends and mixtures with other biobased and biodegradable plastics.

2.2.2.6 Concluding remarks

Mechanical recycling of plastics is a well-known valorisation technique, vastly used in commodities such as PET and PE. It allows to reduce the amount of wastes, and also to reduce the consumption of raw materials and emissions. It is worth to note that mechanical recycling does not come without drawbacks, such as structural and thermal degradation with the consequent decrease of the overall performance of final recycled plastic products, to which some biobased and biodegradable plastics (e.g.: PLA and PHAs) are especially susceptible. Nevertheless, it is possible to mitigate these problems using different methods, which allow obtaining recycled materials with acceptable properties.

However, currently the most important barrier for the recycling of post-consumer waste coming from biobased and biodegradable plastics is their still small market. This makes unfeasible to implement conventional and centralized recycling schemes, although, distributed recycling could provide currently an alternative suitable for this kind of materials.

2.2.3 Chemical

The chemical recycling can be grouped in two technology categories: chemical depolymerisation and solvent-assisted separation.

Chemical depolymerisation

Chemical depolymerisation consists on breaking down polymer chains through the use of chemicals. It can be also referred in literature as chemolysis and solvolysis.

The plastic waste is first pre-treated to remove solid contaminants before initiating the process. Chemicals are used to break down the polymer chains into either shorter chain oligomers (partial depolymerisation) or the monomers (full depolymerisation).

Once the depolymerisation is completed, monomers are recovered and purified.

The chemical depolymerisation process is only applicable to certain types of plastics. The most significant ones are condensation polymers. Their name comes from the way in which they are formed (polymerysation by condensation).

Polyethylene Terephthalate (PET) and other polyesters, Polyurethane (PU=, Polyamides (PA) and Polylactic Acid (PLA) are the most relevant polymers that can be subjected to chemical depolymerisation.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

The way in which the depolymerisation process works is essentially the same for each polymer. The bonds uniting monomers are broken apart. However, the reaction pathway by which the chemical bonds are broken depends on the molecule used for depolymerisation.

There are five main chemical inputs, each with a distinct reaction pathway and, therefore, a different monomer output. The table below shows the different outputs that can be obtained for PET.

Table 5 *Chemical inputs and outputs of the reaction*

Chemical input	Reaction pathway	Monomer output	Other product(s)
Glycol	Glycolisis	bis(2-Hydroxyethil)terephthalate (BHET)	Ethylene Glycol
Water	Hydrolysis	Terephthalic acid (TPA)	Ethylene Glycol
Methanol	Methanolysis	Dimethyl Terephthalate (DTM)	Ethylene Glycol
Amines	Aminolysis	Bis(2-hydroxyethylene) terephthalamide (BHETA)	---
Ammonia	Ammonolysis	Terephthalamide	Ethylene Glycol

These pathways are not right now commercially exploited. Glycolysis, hydrolysis, and methanolysis have demonstrated success at pilot plant level or larger, glycolysis being the most advanced in terms of demonstrating commercial viability on a larger scale. For aminolysis and ammonolysis there is no evidence to date that these have progressed beyond laboratory trials.

A common factor in any chemical depolymerisation process is the utilisation of **catalysts**, which are chemical compounds that aid the reaction process by helping to increase the rate of the reaction.

The use of these substance, however, can be an issue in the process, not only because the cost associated with their production is high, but also because they need to be separated from the monomer products once the reaction is completed.

Several attempts have been carried out to assess the **environmental performance** of chemical depolymerisation processes. In general, chemical depolymerisation is still too demanding in terms of energy requirements and mechanical recycling is still considered the most favourable technology overall.

However, chemical depolymerisation allows addressing the issues with unavoidable contaminants in mechanically recycled PET, especially after a number of recycling cycles. So, this aspect should not be obviated.

According to the report on Chemical Recycling by Hann and Connock (2020) here you are a summary of the advantages and disadvantages of chemical depolymerisation.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Advantages:

- Monomer outputs can be utilised to produce plastic products of equal quality to virgin equivalents, potentially suitable for food contact applications.
- Demonstrated examples of systems that allow the recovery and reuse of chemical reagents such as catalysts and solvents.
- High yields demonstrated for a number of technologies.
- Demonstration of commercial viability for bottle and fibre inputs.

Disadvantages:

- Can currently handle only material inputs that are largely homogenous in nature.
- Often requires stringent pre-sorting and or pre-treatment steps to prepare for purification.
- Typically necessitates high energy requirements, in particular the post-purification drying stages.
- Typically, cannot remove contaminants entirely.
- Has not been demonstrated to provide food-grade outputs.
- Lack of clarity regarding the solvent types and toxicities for larger scale examples.
- Does not allow for limitless recycling of the material, due to thermal degradation of the chains during reprocessing and conversion to form new plastic products.
- Current lack of clarity regarding environmental performance.
- Yet to demonstrate economic viability on a commercial scale.

Solvent purification

The basis of solvent purification is to use the principle of solubility to selectively separate any contaminating substances from the plastic waste. These contaminants typically consist of:

- Additives such as flame retardants, stabilisers, impact modifiers, colourants and pigments;
- Non-target polymers;
- Non-Intentionally Added Substances (NIAS), which are compounds both absorbed and produced within the plastic material during use. This can include side products from the manufacturing process, as well as degradation products, both from partial breakdown of the polymer itself as well as the additives contained within the plastic.

The plastic is shredded and dissolved within a solvent exhibiting a high solubility of the polymer whereases contaminants have low solubility. Contaminants will remain solid and will be separated off form the liquid phase.

Once the purification process is complete, the polymer is extracted from the solution by placing it in a non-solvent to re-solidify the polymer, in a process known as precipitation. Further treatment of the polymer follows, including filtration, washing and drying, to remove the non-solvent.

As the effectiveness of this technology is dependent on solubility, it can be theoretically be applied to almost any polymer, provided a suitable solvent can be found.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

The table below shows the current application for solvent purification by polymer type and waste streams.

Table 6 *current application for solvent purification by polymer type and waste streams*

Polymer	Waste stream
Polystyrene (PS)	Expanded polystyrene foam (EPS) Household PS waste
Polyethylene Terephthalate (PET)	Polyester/cotton textile Packaging
Polythylene (PE)	Multilayer bags
Polyamide (PA)	Multilayer bags
Polypropylene (PP)	Carpets

The effectiveness of polymer purification is very dependent on the exact composition of the waste input in terms of contaminants. Regretfully, there is a lack of clarity for the majority of technologies regarding the impurities dealt with.

Ideally, if all the types of polymers contained within the plastic waste are known, as well as the full range of contaminants, the process could be used to purify multi-material waste streams, provided there were sufficient stages of solvent selection.

Theoretically, this could avoid the costs associated with segregated collection and advanced sorting infrastructure required to separate specific polymer types. However, the added complexity required to ensure selectivity for each polymer type leads to higher environmental and economic costs from increased solvent, energy and time inputs.

Screening and sorting of the materials is a common pre-treatment step to separate external contaminants such as stickers, glue, tape, and so on. Even following purification, the risk of residual impurities is still often an issue due to the reduction in the material properties compared with the virgin polymer.

Another important limitans is that the process may have a stressing influence on the polymer structure, as thermal and physical stresses do during the reprocessing of the plastic. This means that the method will not likely allow an infinite recycling of a plastic material.

A study funded by the Dutch government, conducted several studies screening **LCA** studies of chemical recycling technologies with the aim of determining whether they may fit within the Dutch waste management system. Although the results of the study are not detailed enough to make general assumptions, comparison of waste-to-energy methods with solvent purification of expanded polystyrene (EPS) found significant climate change benefits for the latter. However, as this technology is yet to reach commercial scale, it is difficult to draw solid conclusions. Studies up to date have been based on scenarios defining very specific waste stream inputs to ensure successful purification.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

According to the report on Chemical Recycling by Hann and Connock (2020) here you are a summary of the advantages and disadvantages of solvent purification.

Advantages:

- Has been demonstrated to separate polycotton textile blends.
- Environmentally benign solvents have been tested successfully at a lab scale.
- Generally, allows recovery of the solvent for reuse.
- The process has been demonstrated to recover non-target by-products for valorisation.

Disadvantages:

- Can currently handle only material inputs that are largely homogenous in nature.
- Often requires stringent pre-sorting and or pre-treatment steps to prepare for purification.
- Typically necessitates high energy requirements, in particular the post-purification drying stages.
- Typically, cannot remove contaminants entirely.
- Has not been demonstrated to provide food-grade outputs.
- Lack of clarity regarding the solvent types and toxicities for larger scale examples.
- Does not allow for limitless recycling of the material, due to thermal degradation of the chains during reprocessing and conversion to form new plastic products.
- Current lack of clarity regarding environmental performance.
- Yet to demonstrate economic viability on a commercial scale.

2.2.4 Anaerobic digestion and composting

Biological Treatment: Composting and Anaerobic digestion

It is important to note that biodegradable plastic is not always compatible with composting or anaerobic digestion. Both treatment processes require that the compostable plastic material degrade sufficiently within a **restricted time frame** and **specific environmental conditions**.

Figure 34 shows a route in which biodegradable material could be valorized igestibley through industrial composting or anaerobic digestion. There are a few conditions that need to be met for successful valorization.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

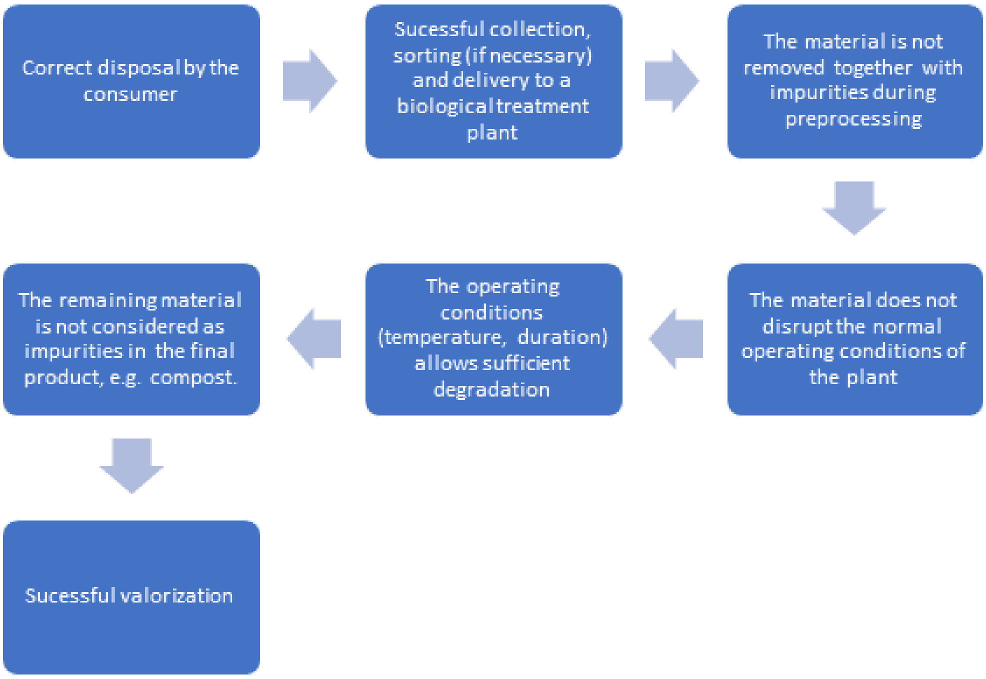

Figure 34 *An example of a possible route of valorizing compostable plastics through biological treatment*

The producer should thus always ensure that there is a **suitable collection system** in place that is able to route compostable plastic to suitable composting or anaerobic digestion plants. In addition, it is imperative that the **local plant operator is contacted** to check if local conditions allow safe and sufficient treatment of compostable plastics in the plant. In addition, the risks in the table below should be taken into account.

Table 7 *Risk factors for the successful valorization of biodegradable plastic in composting or anaerobic digestion*

Risk	Explaination
Variation between industrial composters	Different plants, even in the same country, can have different equipment, biowaste inputs and operating conditions. Local conditions need to be checked by communicating with local operators before implementing a biodegradable plastic product.
Variation of the shape and size of compostable products	The shape, size and residence time all affect the ultimate degradation of a compostable material. In a given region, each product's suitability for industrial composting will have to be evaluated on a case-by-case basis.

Summary

For biodegradable plastic material to be successfully valorized through the composting or anaerobic digestion route, they should meet the following conditions:

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

- The product is certified compostable or anaerobic digestible with the current standards AND is treatable within the normal operating conditions of the local treatment facility in its current shape and form
- There exists a segregation, collection and/or sorting route in the region where biodegradable plastics are funnelled to the respective facilities
- The labels on the product guide the consumers to dispose of the product in the correct route
- The facility has the necessary equipment or process to differentiate and separately process and/or pre-treat conventional and biodegradable plastics
- The product does not pose a problem for the normal operation of the plant
- The interest of the facility is aligned with the use of the biodegradable plastic product
- The material does not affect the quality of the plant outputs and is not considered as impurities according to local standards

Composting

Composting is the process of treating biowaste through controlled biological decomposition of organic matter in the presence of oxygen producing hummus-rich compost. Composting can either be done via home composting or industrial composting. The differences in conditions are significantly different and thus the degradation rate of compostable plastic might be different in each case. Unlike home composting, industrial composting is able to achieve thermophilic temperatures, above 45°C up to around 70-75°C (Barrena et al. 2014; Rudnik 2008; Sundberg et al. 2004). Simple composting systems might present a cost-effective treatment option for biodegradable waste (Hoornweg et al. 2000; Couth and Trois 2012).

EN 13432 stipulates the requirements for industrial compostable packaging. The disintegration requirement states that not more than 10 wt% of the material can remain (>2mm) after a maximum of 12 weeks. The product needs to be tested in the form of its desired application. Industrial composting plants treat and sanitize separately collected biowaste and turn it into stable compost, which is then often sold for the use on agricultural land. They have a major interest in treating biowaste efficiently and to produce high quality compost. Thus, the duration of active composting and maturation can significantly differ from the standard. For example, the active composting time ranges only from around 4 to 8 weeks in Germany producing fresh compost that can be used on agricultural land (Stadtreinigung Hamburg 2019; Hann et al. 2020).

The degree of disintegration of biodegradable plastics also depends on the polymer type, blend composition and product shape (Kliem et al. 2020). For example, the thickness of PLA, as well as the composting temperature is found to influence the degradation rate (Ruggero et al. 2021). The shape is considered in composting certification, as the products need to be tested for disintegration in the form of the desired application. Other components that might be present in biodegradable plastic blends such as mineral fillers and plasticizers are reported to influence the degradation rate (Tolga et al. 2020; Arrieta et al. 2014). Lastly, the longer-term effects of remaining biodegradable plastic particles after composing is still unclear (Folino et al. 2020; Polman et al. 2021).

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Anaerobic digestion

Anaerobic digestion (AD), similarly to composting is not suitable for all types of biodegradable plastics. AD is the process of decomposition of organic material in oxygen free environment. During anaerobic degradation, carbon from bioplastics consumed by microorganisms and main products such as methane and carbon dioxide are produced. Anaerobic digestion of bioplastics can be performed in mesophilic (37°C) or thermophilic (55°C) conditions.

There are different standards exist to assess the anaerobic degradation of the bioplastics ASTM D5511–18 (2020) and ASTM D5526–18 (2020) for high solids content (15-45%) and (ASTM D5511–18, 2020; ASTM D5526–18, 2020) for mixed conditions. For wet or semi wet conditions ISO 14853:2016 and ISO 13975:2019 (ISO 14853, 2016; ISO 13975, 2019) can be employed within 90 days degradation period (Battista et al., 2021). To assess anaerobic treatability of bioplastics harmonized European standard EN 13432 can be used either. According to this standard anaerobic biodegradation and disintegration can be verified as an option. For biodegradation, 50% is required after two months as anaerobic fermentation is followed by aerobic composting, during which biodegradation can further continue.

The degradation rate of bioplastics under anaerobic conditions is different and very much depends on the type of the polymer and environmental factors such as temperature, moisture, pH, and aerobic/anaerobic conditions (Abraham et al.,2021). According to Cucina et al., 2021, anaerobic degradation of bioplastics under thermophilic conditions have shown significant reduction in time needed for degradation in comparison with mesophilic conditions. Regarding the recent studies, most promising materials degrading in anaerobic conditions are bio-based and biodegradable plastics such as PLA, PHB and PHA (Benn and Zitomer, 2018; Federle et al., 2002; Yagi et al., 2009, 2010, 2013, 2014; Wang et al., 2018; Zhang et al., 2018). Petroleum-based biodegradable plastics such as PBS and PBAT showed lower levels of biodegradation (Abraham et al.,2021).

Due to the high content of carbon in the bioplastic polymers, bioplastics can be co-digested with other materials such as food waste or sludge which have low C:N ratio. The co-digestion process of bioplastics, can increase the C:N ratio and result in increased biogas production (Stroot et al., 2001).

***Table 8** Advantages and disadvantages of anaerobic digestion and composting of bioplastics*

Biological treatment	Advantages	Disadvantages
Anaerobic digestion	• Will improve the carbon to nitrogen (C/N) ratio of the mixture • Biogas production • Faster degradation under thermophilic conditions • Digestate production	• Not all types of biodegradable plastics suitable for anaerobic degradation. • Degradation efficiency depends on the type of the polymer, microorganisms and environmental conditions.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

	• Co-digestion with food waste or sludge	• Before treatment bioplastics have to be reduced in size. • The risk for microplastic in soil and digester.
Composting	• Simple composting systems could be a cost effective solution for treating biodegradable waste	• Degradation highly depends on local operating conditions, polymer type, product design and shape • Compostable plastics may be removed together with conventional plastics during pre-treatment in industrial plants • The risk of small plastic particles remaining after composting is unclear

2.3 Highlights

To efficiently recycle large amounts of plastic wastes, a circular economy requires suitable technologies. Therefore, the innovative recycling and recovery technologies have enormous economic value in transforming post-use and difficult-to-recycle plastic into their original building blocks that can be continually reintegrated to supply chains as feedstocks for new plastics and chemicals or other raw materials for manufacturing.

Elements of a waste management system include source separation, collection and transport, sorting and finally reuse, recycling, energy recovery, treatment and disposal. Source separation is commonly done to separate recyclables from non-recyclable waste for recycling. After consumption, the source separated waste will need to be collected and transported to waste management facilities. After collection, sorting might be carried out to separate different materials collected comingled. In the case of plastics, further sorting based on polymer types is needed for recycling. Lastly, waste can either be sent to be reused, recycled, treated energetically or disposal. Automated sorting technologies have their limitations and the resulting heterogeneity and contamination are some of the reasons contributing to a difference in properties of mechanically recycled plastics compared to virgin material (Alassali et al., 2021; Eriksen et al., 2019). In addition, most conventional sorting systems currently do not distinguish between food and non-food packaging, this limits the use of mechanically recycled plastic in food applications.

Chemical recycling turns plastic waste into chemical products, avoiding their production from fossil feedstock in the first place. Therefore, chemical recycling is expected to decrease the demand for the planets' finite fossil resources as well as the emissions of greenhouse gases. However, the chemical recycling is still in early development and has not been fully assessed environmentally. It

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

is therefore timely to assess if and to which extent chemical recycling of plastic packaging waste can achieve environmental benefits before research funds and time are invested.

Mechanical recycling of plastics is a well-known valorisation technique, vastly used in commodities such as PET and PE. It allows to reduce the amount of wastes, and also to reduce the consumption of raw materials and emissions. The structural and thermal degradation are the main drawbacks of the mechanical recycling. It affects the overall performance of final recycled plastic products.

Bio-based biodegradable plastics

In general, bio-based and biodegradable plastics are either:

-separately collected with organic waste with the aim of composting, when the labels on the products guide the consumers to do so;

-separately collected with conventional plastics (recyclable waste), especially for biobased "drop-in" plastics that are chemically similar to conventional petroleum-based plastics;

-disposed of in residual waste.

Biodegradable plastic destined for biological treatment requires a sorting or pre-treatment system that is able to differentiate them from general impurities, including conventional non-biodegradable plastics.

The biodegradable plastic is not always compatible with composting or anaerobic digestion. Both treatment processes require that the compostable plastic material degrade sufficiently within a restricted time frame and specific environmental conditions. Therefore, biodegradable plastic material to be successfully valorized through the composting or anaerobic digestion route, they should meet certain conditions.

The most important barrier for the recycling of post-consumer waste coming from bio-based and biodegradable plastics is their still small market. This makes unfeasible to implement conventional and centralized recycling schemes, although, distributed recycling could provide currently an alternative suitable for this kind of materials. Another problem is that the acceptance of biodegradable plastics in biological treatment plants vary significantly from region to region.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

3 Analysis of the legal and policy framework

3.1 Current policy and legislation (plastics vs biobased and biodegradable plastics)

In the light of the Climate Crisis there were numerous legislative acts adopted around the world. Some of them were new, responding to the newly arisen issues or situations requiring a solution, other were made as amendments to the previously adopted acts, as those covered the main principles, but needed some alteration and update to meet the demand of the current environment concerned society and policy makers. Below is a review of the acts pertaining to the plastics, plastic waste, waste management, marking and bio-based plastics, starting with the main pillars of the legislative framework shaping EU policy on plastics and plastic waste.

Basel Convention – global legally binding instrument

Adopted in on 22 March 1989 in Basel, Switzerland, the Basel Convention is the most comprehensive global environmental treaty on hazardous and other wastes. It aims at protection of human health and environment against the adverse effects of hazardous wastes, defined based on their origin and/or composition and their characteristics. The aim is addressed through a number of general provisions requiring States to observe the fundamental principles of environmentally sound waste management (Article 4). Parties to the Convention pledge themselves to take measures ensuring that the generation of waste is reduced to a minimum, and provide for the adequate disposal facilities. The Convention also provides for the establishment of regional or sub-regional centres for training and technology transfers regarding the management of hazardous wastes and other wastes and the minimization of their generation to cater to the specific needs of different regions and subregions (article 14).

Up until recently, the Convention did not specifically cover plastics and plastic waste, however in 2019, the Conference of the Parties to the Basel Convention (COP-14, 29 April–10 May 2019) adopted amendments to Annexes II, VIII and IX to the Convention to address plastic waste and include in a legally-binding framework, referred to as:

- The Plastic Waste Amendment (decision BC-14/12),
- A decision setting out a range of further actions (decision BC-14/13)[2].

As soon as they become effective on 1 January 2021, these amendments will have a significant impact on the rules governing the movement of plastic waste across international boundaries.

As with regard to further actions, decision BC-14/13 provides for further immediate actions by the Parties, namely:

- efforts at the domestic level with timebound targets for minimization/prevention of plastic waste,

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

- efforts to create new technology and processes to reduce the use of hazardous constituents in the production of plastics,
- update to the technical guidelines for the identification and environmentally sound management (ESM) of plastic waste and for their disposal,
- establishment of Partnership on plastic waste with a goal to improve and promote the ESM of plastic waste at the global, regional and national levels and prevent and minimize their generation, to significantly reduce and in the long term eliminate the disposal of plastic waste into the environment.

Sustainable Development Goals (SDGs)

Resolution adopted by the United Nations General Assembly on 25 September 2015[3]

The 2030 Agenda for Sustainable Development,[4] adopted by all United Nations Member States in 2015, sets the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries in a global partnership. Therein it is recognized that ending poverty and other deprivations must go along with strategies tackling climate change. Strong commitment by all the United Nations Member States to implement the global goals is key, to make the Agenda a reality.

As with regard to the plastics, the waste is addressed in the SDG 12, aimed at ensuring sustainable consumption and production patterns. Among the other undertakings it targets to "achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment" by 2020 (SDG 12.4), to substantially reduce waste generation through prevention, reduction, recycling and reuse by 2030 (SDG 12.5), and most importantly, to "rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities" (SDG 12.c).

EU Action Plan for Circular Economy

The European Commission launched a Circular Economy Plan in 2015[5] including measures helping to stimulate Europe's transition towards a circular economy, boost global competitiveness, foster sustainable economic growth and generate new jobs. Measures foreseen in the Act cover the whole cycle: from production and consumption to waste management. Notably, it also included the implementation timeline. Among the other results of the Act implementation, there is a set of documents passed in 2018 setting legislative framework on waste: Directive (EU) 2018/851 on waste, Directive (EU) 2018/852 on packaging and packaging waste, etc. Thereby targets for reduction of waste and provisions for waste management and recycling were set:

- A common EU target for recycling 65% of municipal waste by 2035,

• A common EU target for recycling 70% of packaging waste by 2030 (namely, plastic: 55%)

As most of the targets set in the Act have been reached, on 11/03/2020 the European Commission has adopted a new Circular Economy Plan being the part of the European Green Deal[6].

The new Circular Economy Action provides for measures aiming to make sustainable products the norm in the EU, focus on the sectors that use most resources and where the potential for circularity is high (including packaging and plastics), ensure less waste.

GREEN DEAL is an integral part of the Commission strategy to implement the United Nation's 2030 Agenda and the sustainable development goals and provides a roadmap with actions therein. "While the circular economy action plan will guide the transition of all sectors, action will focus in particular on resource-intensive sectors such as textiles, construction, electronics and plastics. The Commission will follow up on the 2018 plastics strategy focusing, among other things, on measures to tackle intentionally added micro plastics and unintentional releases of plastics, for example from textiles and tyre abrasion. The Commission will develop requirements to ensure that all packaging in the EU market is reusable or recyclable in an economically viable manner by 2030, will develop a regulatory framework for biodegradable and bio-based plastics, and will implement measures on single use plastics. "[7]

EU Strategy for Plastics In The Circular Economy

The EU Action Plan for the Circular Economy envisages the transition to a circular economy which is one of the major EU priorities. As it addresses plastics and plastic waste, in 2018 a European Strategy for Plastics was introduced as a follow-up to it[8]. Strategy for Plastics provides for actions and measures in order to transform the way products are designed, produced, used, and recycled in the EU:

- introduction of new rules on packaging to improve the recyclability of plastics used on the market, including standardised system for the separate collection and sorting of waste;
- legislation on single-use plastics;
- guidance for national authorities on how to minimise plastic waste at source;
- cooperation on Global level to curb plastic pollution both in EU and beyond it, etc.

Current actions by Member States target various plastic products and adopt different approaches, hence there is a risk of market fragmentation caused by uncoordinated measures differing in scope. European Commission in its Communication introducing the Strategy for Plastics emphasized the need harmonized approach when it comes to plastics and plastic waste and planned respective legislative measures engaging regional and national authorities.

EU directives on plastics and plastic waste

Directive 2008/98/EC on waste

„This Directive lays down measures to protect the environment and human health by preventing or reducing the generation of waste, the adverse impacts of the generation and management of waste

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

and by reducing overall impacts of resource use and improving the efficiency of such use, which are crucial for the transition to a circular economy and for guaranteeing the Union’s long-term competitiveness.“ (Article 1)

The Directive sets the legislative framework, providing for waste management, covering producers‘ responsibility, aiming at reduction of generation of waste, in particular waste that is not suitable for preparing for re-use or recycling, setting the recycling targets for municipal (household and similar waste) waste (increase by 55% by 2025 and by 60% by 2030). It foresees requirements to Member States for a separate collection of at least paper, metal, plastic, and glass waste (Article 11), produce waste management plans and introduce waste prevention programmes.

Directive 94/62/EC on packaging and packaging waste

The aim of the Directive is to harmonize national measures concerning the management of packaging and packaging waste in order to prevent or reduce any impact on the environment. The first priority is to prevent the production of packaging waste and, to reuse or recycle packaging, hence, to reduce the final disposal of such waste.

The main measures listed in the Directive include national programmes, incentives through extended producer responsibility schemes, reduction in the consumption of lightweight plastic carrier bags, increase in the share of reusable packaging placed on the market and of systems to reuse packaging in an environmentally sound manner (e.g. deposit-return schemes, economic incentives). The Directive specifies recycling targets for Member States:

- by 31 December 2025 a minimum of 65 % by weight of all packaging waste (50 % of plastic)
- by 31 December 2030 already a minimum of 70 % by weight of all packaging waste (55% of plastic).

Member States should also ensure that systems are set up to provide for the return and/or collection of used packaging and/or packaging to channel it to the most appropriate waste management alternatives.

Under the Directive each Member State on a harmonized basis shall establish databases on packaging and packaging waste. It is also an obligation of Member States to ensure that consumers are explicitly informed about the return, collection and recovery systems available to them, their role in contributing to reuse, recovery and recycling of packaging and packaging waste, the meaning of markings on packaging existing on the market.

Annex II of the Directive sets requirements on the composition and recycling nature of the packaging.

Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment

Directive targets the single-use plastic products. The main objective of the Directive is to prevent and to reduce the impact of certain plastic products on the environment: “to prevent and reduce

Horizon 2020
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

the impact of certain plastic products on the environment, in particular the aquatic environment, and on human health, as well as to promote the transition to a circular economy with innovative and sustainable business models, products and materials, thus also contributing to the efficient functioning of the internal market." (Article 1) This is to be achieved by defining specific waste prevention and waste management objectives and measures in relation to single-use plastic products.

Article 3 of the Directive defines plastic as „ a material consisting of a polymer as defined in point 5 of Article 3 of Regulation (EC) No 1907/2006, to which additives or other substances may have been added, and which can function as a main structural component of final products, with the exception of natural polymers that have not been chemically modified", and biodegradable plastic as a plastic capable of undergoing physical, biological decomposition, such that it ultimately decomposes into carbon dioxide (CO2), biomass and water, and is, in accordance with European standards for packaging, recoverable through composting and anaerobic digestion".

Directive addresses single-use plastics as they have a disproportionate impact on the environment when comparing the time of their use and the time of their decomposition.

Member States are obliged to prepare description of the measures in order to meet the goals set by the Directive, by July 31, 2021.

Also, the Directive sets the recycling targets: by 2025, of an amount of waste single-use plastic products equal to 77 % by weight, and by 2029 - 90 %. In order to make the collection effective, Member States may establish deposit-refund schemes, or establish separate collection targets for relevant extended producer responsibility schemes.

In order to eliminate wrongful interpretations, by 3 July 2020, the Commission shall publish guidelines, including examples of what is to be considered a single-use plastic product for the purposes of this Directive.

As of the year 2022, Member States shall report the data on single-use-plastics to the Commission.

Notable, that the Member States should transpose the requirements under the Directive to the local legislation by 3 July 2021.

EU legislation designed for bio-based plastics

Currently developed and available bio-based plastics have substantially the same properties as plastics and overcome these when it comes to their degradability. It is obvious, that in times when Policy makers aim at reducing plastic waste, bio-based plastics serves as an environment friendly alternative to plastic products (packaging) the latter being cheap production wise and convenient for the society to use, however more and more unacceptable due to their lifecycle and adverse impact on environment.

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Nevertheless, currently there are no legal acts on EU level providing regulation specifically to bio-based plastics, but provisions of both EU ACTION PLAN FOR CIRCULAR ECONOMY and EU STRATEGY FOR PLASTICS IN THE CIRCULAR ECONOMY form opportune grounds for their adoption.

Meanwhile, there are some provisions in the legislation reviewed above, pertaining to biodegradable and compostable packaging:

- the revised Directive 2008/98/EC on waste allows biodegradable and compostable packaging to be collected together with the bio-waste and recycled in industrial composting and anaerobic digestion.
- the revised Directive 94/62/EC on packaging and packaging waste Directive defines compostable and biodegradable packaging: „packaging waste processed for the purpose of composting shall be of such a biodegradable nature that it does not hinder the separate collection and the composting process or activity into which it is introduced" and "biodegradable packaging waste shall be of such a nature that it is capable of undergoing physical, chemical, thermal or biological decomposition such that most of the finished compost ultimately decomposes into carbon dioxide, biomass and water. Oxo-degradable plastic packaging shall not be considered as biodegradable." (Annex II par.3) thus acknowledging them being a sustainable solution helping to minimize environmental impact of plastic packaging.

3.2 Labelling

Commission decision12 of 28 January 1997

Established the identification system for packaging materials pursuant to European Parliament and Council Directive 94/62/EC on packaging and packaging waste. The Decision covers all packaging covered by Directive 94/62/EC and aims to establish the numbering and abbreviations on which the identification system is based, indicating the nature of the packaging material(s) used and specifying which materials shall be subject to the identification system. Table 1 of the Decision defines numbering and capital letters abbreviations to be used with plastics:

Table 9 *Numbering and abbreviation system*

Material	Abbreviations	Numbering
Polyethylene terephthalate	PET	1
High density polyethylene	HDPE	2
Polyvinyl chloride	PVC	3
Low density polyethylene	LDPE	4
Polypropylene	PP	5
Polystyrene	PS	6

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

It should be noted that Article 3 of the Decision provides for a voluntary and not mandatory use of the abovementioned identification on the materials and packaging, stating that a decision whether to introduce on a binding basis the identification system for any material or materials may be adopted in accordance with the procedure laid down in Article 21 of Directive 94/62/EC. While revising the Directive in 2015, it was stated in par.1 of Article 8 that "Council shall, in accordance with the conditions laid down in the Treaty, decide no later than two years after the entry into force of this Directive on the marking of packaging ". However, by the date no decision on marking of the packaging has been made. That confronts with the requirement laid down in Article 7 the Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment, stating that "Member States shall ensure that each single-use plastic product listed the Annex placed on the market bears a conspicuous, clearly legible and indelible marking on its packaging or on the product itself informing consumers of the following: (a) appropriate waste management options for the product or waste disposal means to be avoided for that product, in line with the waste hierarchy; and (b) the presence of plastics in the product and the resulting negative impact of littering or other inappropriate means of waste disposal of the product on the environment."

This aspect of a voluntary identification use may trigger additional aggravation for an implementation of effective plastic waste collection and sorting for recycling or re-use purposes – identification of the material can be difficult not to consumer only, but also to the sorting facilities.

Worth to mention, that even if it chosen to mark a bio-based product (packaging) using the abovementioned identification system, it would be marked with number 7 "Other" alongside with the plastics containing Bisphenol A, which has an adverse effect on the living.

Regulation (EC) No 66/2010 on the EU Ecolabel

Regulation provides for another again voluntary marking (labelling) of the products, however applicable just to these that meet requirements set forth therein. It is awarded in case of meeting high environmental standards throughout the Life-cycle: from raw material extraction, to production, distribution and disposal. The EU Ecolabel works in accordance with the ISO standard 14024.

This Regulation shall apply to any goods or services which are supplied for distribution, consumption or use on the Community market whether in return for payment or free of charge (Article 1). In order to hold the Ecolabel, the products should conform to the criteria based on the environmental performance of products, taking into account the latest strategic objectives of the Community in the field of the environment. EU Ecolabel criteria shall be determined on a scientific basis considering the whole life cycle of products. According to the Regulation, each Member State shall designate the body responsible the product verification process.

Currently the Ecolabel is granted to the products only, not referring to the packaging. However, given the fact that the criteria include „(a) the most significant environmental impacts, in particular

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

the impact on climate change, the impact on nature and biodiversity, energy and resource consumption, generation of waste, emissions to all environmental media, pollution through physical effects and use and release of hazardous substances; (b) the substitution of hazardous substances by safer substances, as such or via the use of alternative materials or designs, wherever it is technically feasible; (c) the potential to reduce environmental impacts due to durability and reusability of products; (d) the net environmental balance between the environmental benefits and burdens, including health and safety aspects, at the various life stages of the products" (par. 3 Article 6), it should be relevant to extend it towards bio-based plastic packaging.

3.3 Highlights

Directions towards circular economy in EU set forth in the EU Action Plan for Circular Economy and EU Strategy for Plastics clearly indicate the need for conventional plastic use and plastic waste reduction and welcome environment friendly alternatives. However, complexity of the alternative materials, hence ambiguity in their recycling and waste management makes the achievement of the set goals rather sophisticated. Not to mention, that ambiguity is not only with producers or entities responsible for waste management, but also with consumers, who have lost the track on the variety of alternative plastics on the market, lack knowledge on materials marking and are often confused when it comes to sorting of waste.

Therefore, below are the recommended regulatory responses to the identified barriers on effective use of bio-based plastics and their waste management.

Lack of legislative framework for bio-based plastics: there is a need for a legal regulation, harmonizing definitions, terminology and methodologies on identification of bio-based plastics, their clear and ultimate distinction from other materials, hence leading to tailor made treatment (e.g. production, marking, use, collection, recycling, monitoring, and reporting) both by Member States, regional and national authorities, producers, sorting and recycling entities, as well as the end consumers. Legislation should outline the latest tendencies in materials replacing conventional plastic, in order to promote innovative solutions both on materials and their collection/sorting/waste management systems.

Ambiguity in marking/ labelling bio-based plastics and products: lack of a comprehensive and legally binding bio-based plastics (among others) identification system (marking) leads to their wrongful treatment and, hence often leads them to landfill waste. Therefore, there should be introduced standardized obligatory marking/labelling of bio-based plastics, that would help to clearly distinct them from other materials, driving consumer's choice of the packaging when relevant, and allowing both consumer and sorting/recycling/waste management entities contribute to plastic waste minimizing by proper management of the used bio-based plastics. Marking/labelling should clearly separate bio-based plastics from other materials, as these can be visually look-alike, and stress on the less harmful impact on environment (e.g. currently, under the identification system for packaging set by the Commission Decision (1997) they should be marked "7. Other" along with harmful materials, such as bisphenol A and that is unacceptable).

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Loopholes in bio-based plastics waste management: currently, there are no legal provisions providing for the separate collection of bio-based plastics, leading to them ending either with hazardous waste, conventional plastics, or municipal waste. There is a need on standardising waste collection systems and creating harmonized waste collection infrastructure, which would lead to effective sorting for bio-based plastic waste. Local and regional authorities have to have a key role to play in implementation, administration and monitoring of such systems. In order to promote bio-based plastics and products thereof, certain financial incentives could be introduced.

4 The most promising business cases (good practices)

4.1 Different systems

4.1.1 Deposit refund system (DRS)

A deposit-refund combines a subcharge on product consumption with a rebate when the product or its packaging is returned (Walls, 2011). The deposit system applied mainly to the different packaging materials especially beverages and is a sustainable solution to move toward circular economy in which materials and products are reused or recycled minimising the waste generation.

The deposit-refund system (DRS) effectively works in 40 countries around the world. 10 of those countries are in Europe (Calabrese, et al. (2021).

- National deposit Law in place and already running:
- Croatia (2006), Denmark (2002), Estonia (2005), Finland (1996), Germany (2003), Iceland (1989), Lithuania (2016), Netherlands (2005), Norway (1999), and Sweden (1984).
- National deposit Law in place waiting for implementation:
- England (2023/24), Latvia (2022), Portugal (2022), Malta (2021), Scotland (2021), Belarus (2020), and Romania (2022).
- No national deposit law but it is under consideration:
- Austria, Bulgaria, Cyprus, Chech Republic, France, Greece, Hungary, Ireland, Italy, Liechtenstein, Luxemburg, Poland, Slovakia, Slovenia, Spain.
- In Belgium the law is passed but it is delayed indefinitely
- In Switzerland deposit will only be triggered if the recycling rate falls below 75%.

Deposit return systems currently deal mostly with beverage packaging made from glass (beer, juice, soft drinks and strong alcoholic beverages), plastic or aluminium and steel cans.

There are three typical types of deposit refund schemes utilized:

Type I

The most common type utilized in seven European countries: Croatia (HR), Denmark (DK), Estonia (EE), Finland (FI), Lithuania (LT), Norway (NO), and Sweden (SE). The type I system main difference

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

lays in the cost burden which is paid for by producers and in operating mode burden where DRS operator has a dominant role in all processes (Calabrese, et al. (2021):

- Retailer buys containers and pays the deposit to the beverage producer
- Customer buys from the retailer and pays the deposit
- Customer brings back container to the retailer and receives the deposit back
- DRS operator collects empty containers from retailers and are now responsible for resale or recycle of the containers

According to (Calabrese, et al. (2021), the collection and disposal of empty packaging is financed from three sources: handling revenues by the producers, packaging sold; and unredeemed deposits.

Country examples:

Estonia

In Estonia, the responsible producers' organization Eesti Pandipakend (EPP), is responsible for organizing the recycling of packaging marketed by producers, importers and traders. EPP is acting with accreditation of the Ministry of the Environment since 2005. EPP organizes collection, transport, sorting, counting and recycling of packaging items to deposit throughout Estonia. For consumer the packaging deposit refund system means that it is possible to return a packaging with special marking of EPP everywhere where beverages are sold, or to some nearby collection point. At the moment around 1260 collection points exist over the Estonia, form which 800 are manual and 460 are automated (Urke, 2019).

Finland

PALPA (Suomen Palautuspakkaus Oy) is a Finnish company that handles bottle return. PALPA's recycling system includes both glass and plastic beverage bottles and aluminium beverage cans. Some of the bottles are reused, some of the material is recycled. PALPA is one example of national level sorting systems in Finland. The sorting is based on a deposit-based return system that efficiently recycles bottles and cans. PALPA, which maintains the system, is a non-profit organization. The pledge of packaging encourages consumers to return empty beverage containers to recycling. Then they will not remain in the environment or end up in mixed waste. Manufacturers and importers of beverage packaging pay a membership fee and per-unit recycling fees for being included in the refund system. Members' fees are used to cover the costs of the refund systems (PALPA 2020).

Lithuania

Bottle deposit system in Lithuania was implemented in 2016. It provided almost 3 thousand spots to return bottle packaging manually or with reverse vending machines.

Deposit System Administrator („Užstato sistemos administratorius“ (USAD)) responsible for deposit system was created in 2015. It is a non-profit organization acting as public institution, responsible

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

for administrating functions by the Packaging and Packaging Waste Management Act (E-seimas (2021).

Lithuanian beverage producers and importers, according to the law must collect and manage and sort out, recycle the packaging they place to the domestic market.

USAD was founded by:

- Lithuanian Brewers Guild;
- Lithuanian Association of Trade Companies;
- Lithuanian Association of Natural Mineral Water Producers.

The founding members are responsible for over 80% of all beverage packaging circulating in the deposit system.

Sweden

Sweden has the oldest deposit system. Deposit system for aluminium cans was started in 1984 and for Pet bottles 1994.

Recycling Rates in 2019

- 85,8% total recycling rate, both aluminium cans and PET bottles
- 2,15 Billion cans and bottles recycled
- 208 packages per person in Sweden
- 19 870 tons of aluminium
- 23 244 tons of PET material

The system for collection and recycling of PET bottles is separated from other plastic packaging due to Ordinance (2005:220) on deposit system for plastic bottles and metal cans. The ordinance is applied on PET bottles sold in Sweden with ready-to-drink beverages apart from bottles containing drinking dairy products, and drinks with a content of juice or vegetable parts exceeding 50 percent. The authority giving approval to deposit systems is The Swedish Agricultural Board.

Type 2

The type 2 deposit refund system is utilized in Germany. In this type of the system producers and retailers pay the system costs. Retailers are responsible for packaging collection and disposal (Calabrese, et al. (2021).

Country examples:

Germany

In Germany, two distinct deposit systems are applied to beverage packaging, a system for reusable packaging (Mehrwegpfand) and a system for single-use or disposable packaging (Einwegpfand).

For reusable packaging, associations were formed by beverage companies (e.g. Association of German Wells (Genossenschaft Deutscher Brunnen eG)) resulting in standardized bottle pool systems and uniform deposit amounts. A deposit of 0.15 € is charged for glass bottles, PET bottles, and bottles with clip closure, while 0.08 € are charged for beer bottles (glass). In addition, the plastic crate in which the reusable bottles are usually sold is also charged with a deposit (1.50 €). The used bottles are collected at participating supermarkets and are transported to the nearest bottler of the specific pool system.

The deposit system for disposable beverage packaging is mandated through the German Packaging Act (VerpackG). The German Packaging Act dictates that every beverage company using disposable packaging has to charge a deposit of at least 0.25 € per packaging from the retailers who in turn have to charge this amount from the consumer. Moreover, retailers are obligated to take the disposable bottles back and refund the customer, regardless where the bottle was sold and regardless whether the retailer sells the specific brand or type of bottle.

In order to achieve compensation between the participating companies, sophisticated clearing systems such as the German Deposit System GmbH (Deutsche Pfandsystem GmbH (DPG)) were installed. Although the Einwegpfand has to be charged for every disposable beverage packaging, some exceptions are made based on the packaging material and the beverage type. For instance, the mandatory deposit only applies to packaging volumes between 0.1 and 3.0 L. In addition, certain alcoholic beverages (sparkling wine, wine, and mixed drinks with >15‰) as well as non-sparkling juices, milk-based drinks (>50% milk content), and dietetic drinks are excluded from the obligation (VerpackG, § 31, (4)).

Type 3

The type 3 deposit refund system is utilized in Netherlands. In this type of the system producers and retailers pay the system costs. Producers are responsible for packaging collection and disposal (Calabrese, et al. (2021).

Country examples:

Netherlands

Deposit is called in Dutch statiegeld. Automatic collection system for the bottle is used. In this scheme the producers are owners of the empty containers and are responsible for the collection and disposal. Since July 2021 the deposit scheme expanded to small plastic bottles with a volume of 1 l or less. 0,15 EUR deposit will be added for the bottle smaller than 1l and 0.25 Eur for the bottle larger than 1l (Plasteurope, 2020).

In Netherlands, the deposit refund system established for the large PET bottles (with the volume larger than 0.75 l), where about 95% of the bottle are collected through DRS system. The return rate of glass bottle is about 90%. Almost all collected bottles are recycled into new bottles (Spasova, 2019).

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

4.1.2 Pay as you throw and Incentive

The Pay-as-you-throw and the Incentive systems, both have some similarities and some differences, but both are following the same principle focused on the citizen. In opposition to the Deposit system that looks to admonish the citizens that do not recycle, the Pay-as-you-throw and the Incentive systems looks to benefit to the citizens that recycle.

The deposit systems only cover one type of plastics (just bottles) and these two systems could benefit other kinds of plastics as trays, bags, wraps, bins, etc.

Regarding the promoting of plastic recycling inside the citizenship, in the “carrot-and-stick policy”, the deposit will be the “stick” option and the pas-as-you-throw and the incentive systems are the “carrot” option.

The **Pay-as-you-throw system** is based on the policy “the one that contaminates, the one that pays”. Citizens are not paying directly the waste management of the light packaging waste (those are paying by the companies through the Extended Producer Responsibility -EPR-).

Citizens, inside the municipal taxes for waste, they are paying the waste management of the Urban Solid Waste. Most of the countries has an open system where citizens that generate more waste pay the same as the ones that generate less waste. Thanks to the pay-as-you-throw systems, the cities avoid this “flat rate” of waste generation. So, the people to generate more waste (including the people that are not separating the packaging) are paying more that the people that generates less (including the ones that sorts the waste at home and don’t mix all the waste at the RSU generic container).

Thanks to the Pay-as-you-throw system, the use of the RSU is penalized, so the use of the packaging container is encouraged indirectly. The more you sort or recycle at home, the less you pay for your waste.

The Pay-as-you-throw system can be implemented in several ways. One of them is the lock of the street containers that are opened with a citizen card or interactive key. Like this, the city council knows the number of uses of the container and can bill properly the waste taxes. The most common option is the implementation of prepaid bags. On those municipalities citizens are able to use the street containers just with these prepaid bags (including the tax in the prix of the bag).

The **Incentive system**, based on the same principles of the pay-as-you-throw looks to encourage the recycling of light packaging to generate less Urban Solid Waste thanks to incentivize the use of the packaging container.

The incentives proposed to the recycling citizens could be economic incentives (including a discount in the waste municipal tax) or not economics. En example of the non-economic incentives is the RECICLOS program implemented recently in Spain.

RECICLOS (Spanish Incentive System)

Horizon 2020
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

Spain does not have a deposit system. During the year 2020, Spain has started the implementation of an Incentive system called RECICLOS (Reciclos, 2020). This reward system is working initially for PET drinking bottles and metal cans. Bioplastics products can be easily added to the systems because it works with barcode and shape-recognition. The incentives for RECICLOS program are non-monetary incentives.

The system is being implemented in selected towns all over Spain and has two differentiated parts: the home stream and the out-of-home stream. This is how the systems works for products consumed at home involving the existing yellow containers at the streets:

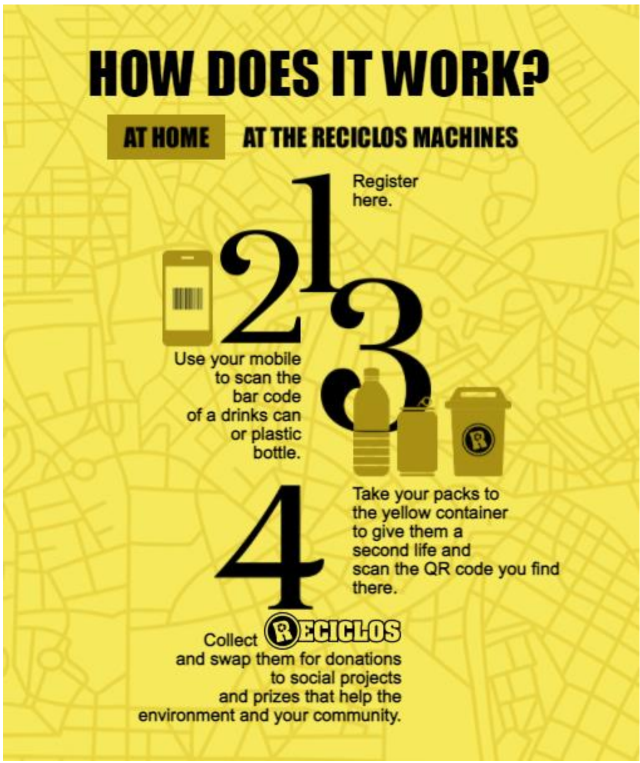

Figure 35 *Working principle of the RECICLOS system at home (Source: RECICLOS, 2020)*

This is how the systems works for products consumed at out-of-home thanks to the installation of Reverse Vending Machines:

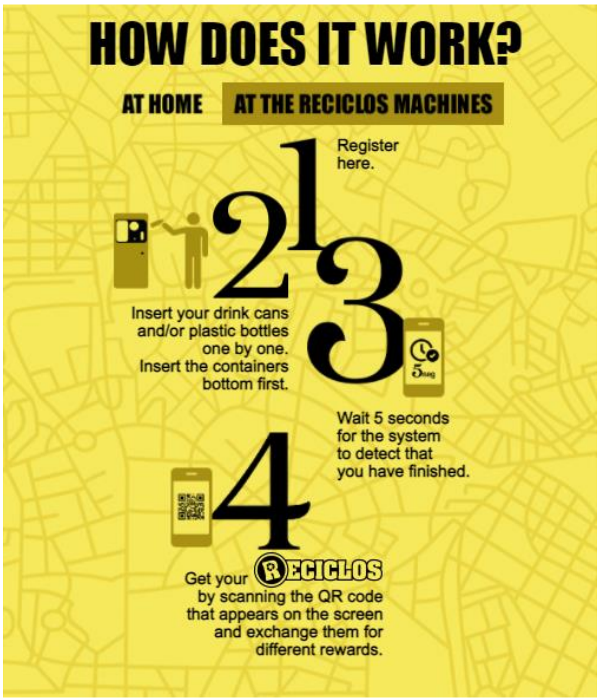

Figure 36 Working principle of the RECICLOS system at the recycle machines (Source: RECICLOS, 2020)

Citizens are receiving tokens called RECICLOS for the packaging deposited. This RECICLOS promote the environmental, economic and social sustainability of the district and the city. So, all prizes are sustainable, environmentally-friendly and beneficial for all the participants:

Figure 37 Categories where received tokens for recycling can be exchanged (Source: RECICLOS, 2020)

RECICLOS system is based (for home and out-of-home stream) on a mobile application where users can create an account and start generating RECICLOS (tokens) recycling PET drinking bottles and metal cans:

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

***Figure 38** RECICLOS App main screen (Source: RECICLOS, 2020)*

RECICLOS encourages recycling and rewards the citizens' efforts. With RECICLOS, users will learn to recycle the waste that is deposited in the yellow container and at the reverse vending machines, and people will also get RECICLOS for each beverage can or plastic bottle recycled.

Thanks to the RECICLOS obtained, people can take part in draws for organic products and donate RECICLOS to join in collaborative projects and make initiatives in their municipality or neighbourhood a reality.

The draws are conducted using smart contracts. Smart contracts are computer programs that execute, control and document registered agreements between two or more parties. Users receive entries, to which one or more prizes are randomly assigned. Smart contracts provide a secure, agile solution based on blockchain technology for conducting draws that is more secure than having a third party verify this process manually.

Citizens can easily locate thanks to the app the yellow containers on the streets for home packaging or the reverse vending machine if they are drinking out-of-home.

In summary, both systems, Pay-as-you-throw and Incentives, encourage the recycling for citizens, both can use the current infrastructures of waste management (not need to involve shops and supermarkets) and both can be extended to all kinds of plastics, including bioplastics (not only focused on PET bottles like the deposit system).

Reusable packaging

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

According to Ellen McArthur foundation reusable packaging is a critical part of the solution to eliminate plastic pollution. As part of the New Plastics Economy Global Commitment, over 350 organisations have recognised that, wherever relevant, reuse business models should be explored to reduce the need for single-use plastic packaging. (Ellen McArthur, 2019)

Reusable packaging is designed for reuse in the same or similar application, or for another purposeful packaging use in a supply chain. The packaging is durable to function properly in its original condition for multiple trips and its lifetime is measured in years. The packaging operates in a system that prevents it from solid waste, replaces single use plastic applications and recovery and recycling of the product at its end of life is aimed in product design. (Reusable packaging association, 2021)

Because most financial benefits of reusable packaging come from avoided production, the rate at which a package is replaced is a key element. Savings are not seen immediately, but in the long run. To ensure that the packaging lasts for multiple rounds of product deliveries, it should be durable and made of materials that are more expensive than cheap plastic. (Packaging Europe, 2021)

Typical case for reusable packaging and fast-moving consumer packaging is a holistic system around food packaging where packaging provider offers the tracking by means of different tokens or deposits.

Recup company: Recup +Rebowl is nationally widespread system in use in Germany with over 8400 service providers. Recup is a plastic cup that comes with 1 € deposit. Once you return the cup to recup partner customer gets the deposit back. Customer can refill cup between returns. Food/ beverage provider is responsible for cleaning of reusable cup. Recup replaces up to 1000 disposable cups in the course of its life and is made out of 100% recyclable polypropelyne plastic (ReCup, 2021)

Kamupak company: Operating in Finland uses tokens, kamupak credit. After selecting using takeaway food packaging customer can change it to clean one or get the deposit back or have token returned for later use, food supplier is then responsible for cleaning and hygiene. According to Kamupak the main environmental impact comes from the plastic raw material of the Kamupak container; A KamuDish or KamuCup, that can be used on average around a hundred times. When a KamuDish has reached the end of its life cycle we return it to the manufacturer to be recycled as raw material. Recycling 100% of the material saves a significant amount of new raw material, which significantly reduces the environmental impacts. Kamu products are made of different kinds of polypropene plastics. The types of material are known so they can be returned to the manufacturer to be used again as material for new products. This is of great importance for the life cycle impact of the KamuDish, as the carbon footprint of recycled polypropylene is even more than 70% smaller compared to virgin raw materials.

More cases can be found from Ellen McArthur ReUse-book availe free online.

Figure below adapted from Kamupak (kamupak 2021)

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

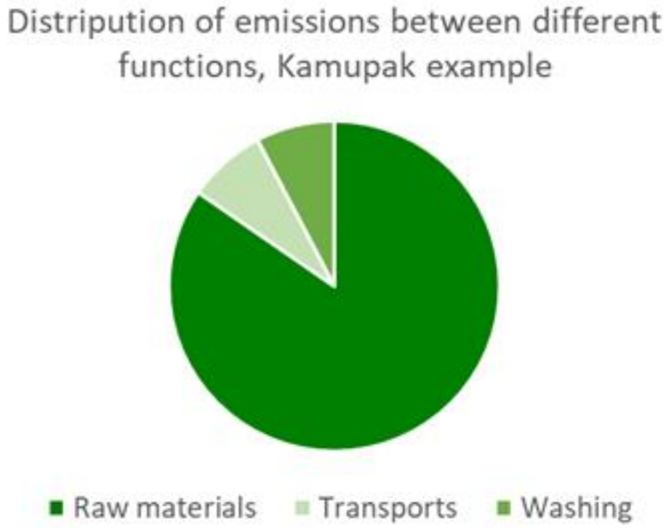

***Figure 39** Distribution of emissions between different functions (kamupak, 2021)*

4.2 "Hamburgs Werkstoff Innovative" – Regional bottle-to-bottle recycling of HDPE

The "Hamburgs Werkstoff Innovative", translation: Hamburg's Innovative Recyclables, is an example of a successful collaboration between actors in a recycling plastic packaging product value chain in order to implement a regional bottle-to-bottle recycling of HDPE (Biorepack, 2021). The HDPE bottle for laundry detergent product, sold in Hamburg, is made up of 100% HDPE recyclates extracted from separately collection post-consumer packaging waste from Hamburg. The successful implementation of the product cycle depends on each and every actor within the local recycling value chain working together and contributing.

The project started in 2019 brings together actors active in Hamburg (see Figure X):

- Stadtreinigung Hamburg (local waste management authority): Collects the recyclables (plastic packaging) in the Hamburg region and delivers it to Veolia's sorting facility.
- Veolia (recycler): Accepts the separately collected materials, carries out the sorting and recycling process in order to produce the target HDPE recyclate material.
- Unilever (producer): Designs the product and uses the produced recyclate to produce HDPE bottles for their laundry detergent product.
- Budni (drugstore chain): Sells the product on their shelves.
- Hamburg University of Technology (research institute): Supports the extensive tests conducted and the project with their scientific expertise.

Beside the actual product, the findings from the project and tests are used to optimize the sorting and recycling processes. In parallel, consumers receive information on correct waste separation at the point of sale and online.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

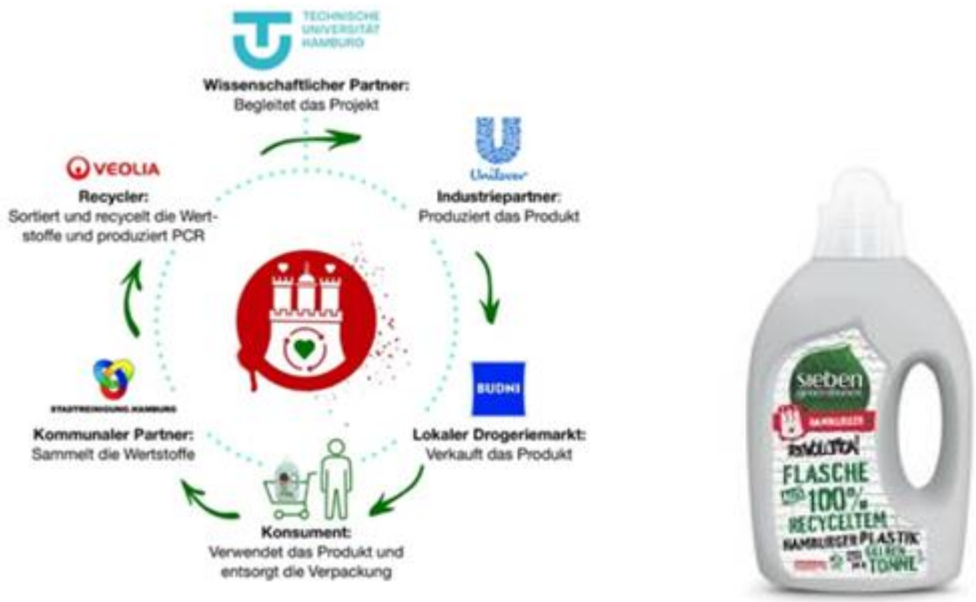

__Figure 40__ (Right) Collaboration concept of the project, (Left) Product of the collaboration (Unilever Deutschland Holding GmbH n.d. 2021)

Benefits of the collaboration:

- Increases trust in the recycling value chain
- Stimulate consumers to play their part in the implementation of a local material cycle
- Inform and improve consumer and source separate behavior
- Support the use of post-consumer recyclate and the demand for packaging made from post-consumer recyclate

4.3 The Italian good practice: BIOREPACK

Biorepack (Biorepack, 2021), the *National Consortium for the organic recycling of biodegradable and compostable plastic packaging*, is a private non-profit consortium in Italy, the measure by which packaging producers and users ensure that they achieve the recycling and recovery target of biodegradable and compostable plastic packaging waste provided for by law.

The statute of Biorepack has been approved by the Ministry of the Environment and Protection of Land and Sea in agreement with the Ministry of Economic Development by the Decree of October 16 2020 (Gazzetta Ufficiale, 2020), that recognizes it as a new consortium within the CONAI (Conai. 2021) system and provides for its operation pursuant to national environmental regulations.

Indeed, for more than 20 years, CONAI has served as an effective system for the recovery, recycling and valorisation of steel, aluminium, paper, wood, plastic, and glass packaging materials. From 2020 through Biorepack also biodegradable and compostable packaging have a recognized system of proper end-of-life management that is based on the principle of the "extended producer responsibility" (EPR) implying, in Italy, the "shared responsibility". This means the involvement of

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

all the players in waste management: from the companies who produce and use packaging, to Public Administrations which establish the rules of waste management in the territory, to citizens whose daily actions when separating waste initiate a virtuous process for the environment, all the way to the recycling companies. So, the Italian law assigned the CONAI system the task of achieving the overall target of recycling and recovery packaging across the whole of Italy and ensuring that targeted management policies are implemented, including prevention policies, through eco-innovation.

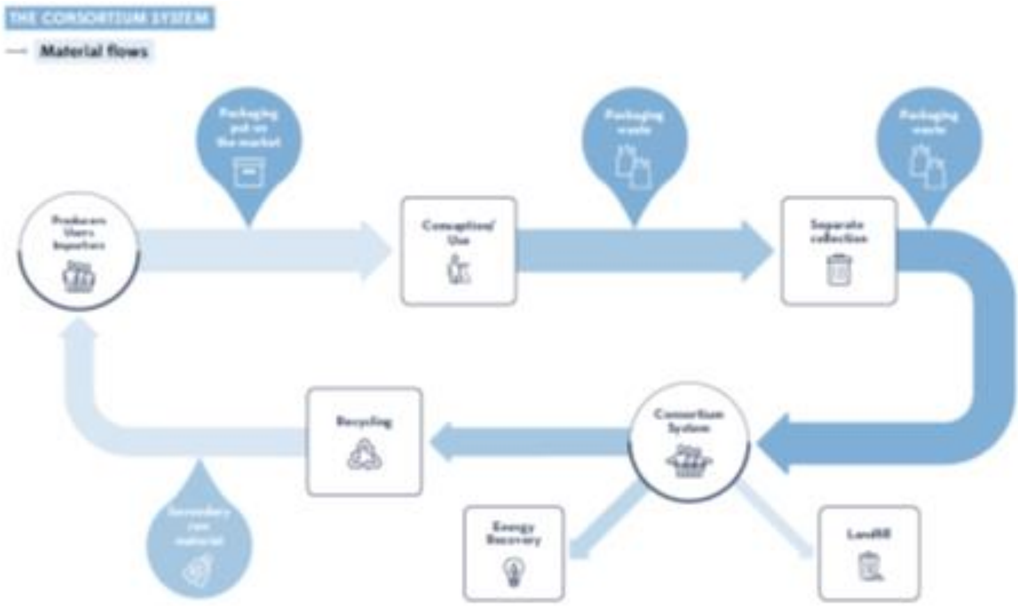

Figure 41 The CONAI system. (CONAI Sustainability Report, 2021)

The CONAI system guarantees compliance with the principle of EPR allocating the CONAI Environmental Contribution (CAC) among producers and users. CONAI retains a minimum amount to carry out its work, while a considerable part is given to the Material Consortia – also to Biorepack - which, in turn, pay a compensation to the agreement Municipalities, in accordance with the provisions of the ANCI-CONAI Framework Agreement, to cover the additional charges resulting from the separate collection of packaging.

Horizon 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

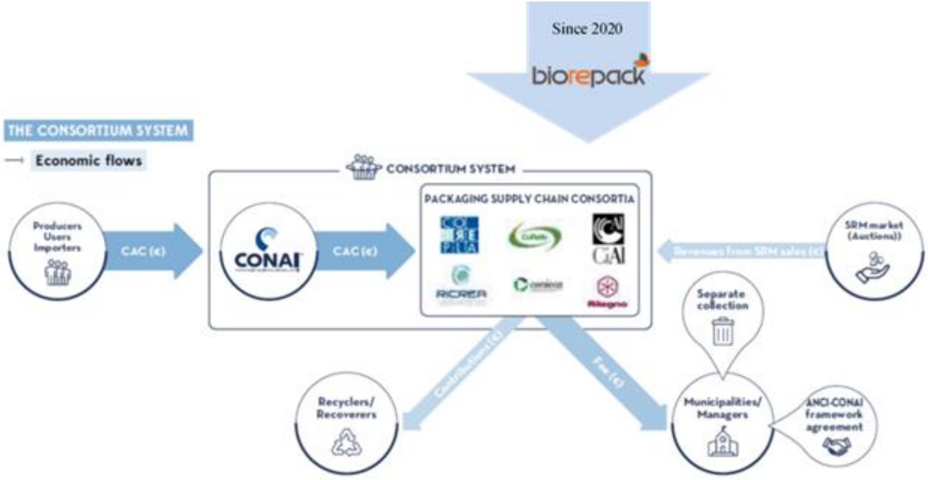

Figure 42 *(CONAI Sustainability Report, 2021)*

Biorepack is dedicated to the management of biodegradable and compostable plastic packaging for the purposes of their recycling in the separate collection circuit of the organic fraction of municipal waste. It should be specified that in Italy this type of waste collection is regulated since 2010 through specific laws that also provide for the use of biodegradable and compostable plastic bags. It should be noted that the chain of competence in which the consortium operates is that of the organic fraction of municipal waste: the main goal is to transform organic waste into resources for agriculture and soils.

Being present in the national waste management context only since early 2021 and operating in a different “sphere” than other packaging materials, representing an absolute novelty also for the CONAI system, it will be necessary to undertake innovative pathways.

Biorepack shall:

- to promote the development of the separate collection of biodegradable and compostable plastic packaging waste and similar fractions within the organic fraction of urban waste;
- to send biodegradable and compostable plastic packaging waste and similar fractions for recycling - in composting/anaerobic digestion - sent to the public collection service for the organic fraction of urban waste;
- to monitor the release for consumption of biodegradable and compostable plastic packaging and similar fractions;
- to carry out product analysis of biowaste in order to determine the performance of the interception and recycling of biodegradable and compostable plastic packaging waste and similar fractions;
- to promote communication campaigns aimed at citizens/consumers to support the correct management of biodegradable and compostable plastic packaging and similar fractions within the separate collection of the organic wet fraction of urban waste;

Horizon 2020
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

- to promote the labeling of biodegradable and compostable plastic packaging to improve recognizability and correct end-of-life management (EU regulation EN:13432 on compostable packaging).

Biorepack represents a unicum. It’s the first that a European member state has applied the EPR principle to biodegradable and compostable packaging and has identified as the guarantor actor of the correct management of the end of life in a national consortium. With Biorepack, packaging manufacturers can ensure that the 'polluter pays' principle is applied to a material that allows the creation of innovative products. In Italy, these innovative products are managed together with organic waste, forming a model that has facilitated the development of a separate collection of organic waste that targets quality and reduced pollution. To guarantee the correct management of this specific type of waste, Biorepack are planned surveys for investigate the quality of the organic waste collected.

4.4. Business Case in Malaysia Recycling Industry / Insight of Malaysia Recycling Industry

Conventional plastic has been the common raw material to most of the plastic injection or plastic products of manufacturer companies. It has been that way for many years until the trend of eco-conscious came into the picture. Every company is trying to do whatever it could to be as green or as sustainable as possible.

For instance, Heng Hiap Industries (HHI), a recycling company which located in Malaysia encounters various request from our customer over the past few years. The customer from Italy & Japan started off with conventional plastic and seeking solutions to minimize the usage of such material. Hence, biomass was used to mix with the conventional recycled plastic to produce their end products. From this case, we can see that they are very willingly and patient during the entire development stage as the customer takes this very seriously.

After the development has more progress, we believe the customer will eliminate the usage of conventional plastic and replace it with bioplastic to produce their products. It is not an easy decision to eliminate conventional plastic but the journey to this stage is overwhelming that recycle plastic do able to perform at such with biomass addition.

It is being done gradually that customers will slowly increase the % of material to be replaced. Lastly, the customer will then move on to bioplastic for the products. The entire journey is not simple and is to be complete within a few years time. The will and desire are very high as shown by the customer during the development stages which makes the entire journey even interesting.

4.5. Highlights

Sustainable waste management means reducing and avoiding the amount of single-use plastic products along with increasing the amount recycled at the same time.

Horizon 2020

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

The countries concerned apply waste prevention measures based on the responsibility for the product they produce or import. These measures are based on the idea that waste prevention is organized effectively where producers and importers are responsible for the management of the waste they generate, thus promoting responsible product design to increase the conditions for re-use or at least recycling, treatment/disposal.

The most successful extended producer responsibility schemes have several features in common: (1) a joint, fully private body set up, operated and supported by the obligated producers; (2) the requirement for producers to fully fund the collection and recycling program; (3) specific and measurable objectives to be achieved. According to research results, the success of the system is also determined by other factors: the promotion of eco-design; greater application of individual producer responsibility; close cooperation between all stakeholders and exchange of good practice; the variable part of the fees is determined according to specifically defined criteria (companies belonging to associations of manufacturers and importers, EU countries usually pay a connection fee, a fixed and variable fee depending on various criteria, such as product eco-design level, product recycling level, etc.); proper involvement of governments, municipalities and waste management operators and other stakeholders throughout the system.

5 References

1.2. Biodegradable and compostable plastics

De Wilde, B., Babou,M., Briassoulis, D., Hiskakis, M., Mistriotis, A, Mortier, N., Verstichel, S., A. 2013. Report on current relevant biodegradation and ecotoxicity standards, Deliverable 6.1, OWS, Ghent, Belgium. https://www.biobasedeconomy.eu/app/uploads/sites/2/2017/03/Report-on-current-relevant-biodegradation-and-ecotoxicity-standards.pdf [accessed 9 September 2021].

European Environment Agency (EEA), 2020. Biodegradable and compostable plastics — challenges and opportunities. https://www.eea.europa.eu/publications/biodegradable-and-compostable-plastics/biodegradable-and-compostable-plastics-challenges . [accessed 9 September 2021].

Flury, M. & Narayan,R., 2021. Biodegradable plastic as an integral part of the solution to plastic waste pollution of the environment, current opinion in green and sustainable chemistry, volume 30, 100490, ISSN 2452-2236, https://doi.org/10.1016/j.cogsc.2021.100490

Hilton, M., Geest Jakobsen. L., Hann, S., Favoino, E., Molteno, S., Scholes, R., 2020. Relevance of biodegradable and compostable consumer plastic products and packaging in a circular economy, Project conducted under Framework Contract No ENV.B.3/FRA/2017/005 for the European Commission DG Environment. https://op.europa.eu/en/publication-detail/-/publication/3fde3279-77af-11ea-a07e-01aa75ed71a1 [accessed 9 September 2021].

Nova, 2021. Biodegradable Polymers in Various Environments According to Established Standards and Certification Schemes – Graphic (PNG). https://renewable-carbon.eu/publications/product/biodegradable-polymers-in-various-environments-according-to-established-standards-and-certification-schemes-graphic-png [accessed 30 January 2023].

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Van den Oever, M., Molenveld, K., van der Zee, M., Bos H., 2017. Bio-based and biodegradable plastics: facts and figures — focus on food packaging in the Netherlands, Report No 1722, Wageningen University, Wageningen. https://edepot.wur.nl/408350 [accessed 9 September 2021].

1.3. Biobased plastics application areas

European Bioplastics e.V. (n.d.): Bioplastics market data. European Bioplastics e.V. Available online at https://www.european-bioplastics.org/market/.

Narancic, Tanja; Cerrone, Federico; Beagan, Niall; O'Connor, Kevin E. (2020): Recent Advances in Bioplastics: Application and Biodegradation. In Polymers 12 (4). DOI: 10.3390/polym12040920.

Vom Saal FS, Vandenberg LN. Update on the Health Effects of Bisphenol A: Overwhelming Evidence of Harm. Endocrinology. 2021 Mar 1;162(3):bqaa171. doi: 10.1210/endocr/bqaa171. PMID: 33516155; PMCID: PMC7846099.

1.4. Bioplastics recycling

Bioplastics Guide. Bioplastics – End-of-life options.2021. http://www.bioplastics.guide/ref/bioplastics/end-of-life-options#:~:text=Bioplastics%20can%20be%20recycled%20but,material%20it%20is%20mixed%20with.

Fabio M. Lamberti, Luis A. Román-Ramírez & Joseph Wood. Recycling of Bioplastics: Routes and Benefits. *Journal of Polymers and the Environment* . **28**, pages2551–2571 (2020)

https://link.springer.com/article/10.1007/s10924-020-01795-8

Cosate de Andrade MF, Fonseca G, Morales AR, Mei LHI (2018) Mechanical recycling simulation of polylactide using a chain extender. Adv Polym Technol 37:2053–2060. https://doi.org/10.1002/adv.21863

1.5. Recyclable Plastics

BRIAN CLARK HOWARD AND AMINA LAKE. Exactly What Every Plastic Recycling Symbol Actually Means GOOD HOUSEKEEPING INSTITUTE. 2021 https://www.goodhousekeeping.com/home/g804/recycling-symbols-plastics-460321/

1.6. Life Cycle Assessment (LCA)

Bare, J.C., Hofstetter, P., Pennington, D.W. *et al.* ,2000, Midpoints versus endpoints: The sacrifices and benefits. *Int. J. LCA* **5,** 319 (2000). https://doi.org/10.1007/BF02978665

Meijer Ellen,2021, Online article, Consider your audience when doing LCA, retrieved 19.8.2021 (https://pre-sustainability.com/articles/consider-your-audience-when-doing-lca/)

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Shahjadi Hisan Farjana, M. A. Parvez Mahmud, Nazmul Huda,2021, Life Cycle Assessment for Sustainable Mining,Ch 1 - Introduction to Life Cycle Assessment,p 1-13,https://doi.org/10.1016/B978-0-323-85451-1.00001-9.

Saur, K. 2002, Workshop Conclusions, Paper presentation at DG Environment / EUROPEN LCA Workshop, Brussels

1.7 Circular Economy

European Parlament. Circular economy: definition, importance and benefits. 2021.

https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

Ellen Macarthur. The-circular-economy-in-detail. 2019.

https://archive.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail#:~:text=A%20circular%20economy%20is%20a,the%20consumption%20of%20finite%20resources.

Kennis Kaarten. What is the definition of a circular economy?

https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/what-is-the-definition-a-circular-economy/

Ellen MacArthur Foundation. 2019. ellenmacarthurfoundation.org. 02. Accessed 08 12, 2021. https://www.ellenmacarthurfoundation.org/circular-economy/concept.

Karttunen, Maria. 2020. sitra.fi. 11 13. Accessed 08 12, 2021. https://www.sitra.fi/artikkelit/kuusi-faktaa-kiertotaloudesta/.

Nurmi, Piia. 2020. "Task 7.1.6 Circular and bioeconomy strategies in the bioplastics sector / Part of deliverable 7.1." Turku University of Applied Sciences. Accessed 08 12, 2021.

2.1 Waste management practices (Ecoembes, TUHH)

Weißenbacher, Jakob; Dollhofer, Marie; Herczeg, Márton; Bakas, Ioannis; McKinnon, David; Seyring, Nicole (2015): Assessment of separate collection schemes in the 28 capitals of the EU. Final Report. European Comission. Available online at https://op.europa.eu/en/publication-detail/-/publication/2c93de42-a2fa-11e5-b528-01aa75ed71a1, checked on 8/20/2021.

Leal Filho, Walter; Saari, Ulla; Fedoruk, Mariia; Iital, Arvo; Moora, Harri; Klöga, Marija; Voronova, Viktoria (2019): An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe. In Journal of Cleaner Production 214, pp. 550–558. DOI: 10.1016/j.jclepro.2018.12.256.

Monier, Véronique; Hestin, Mathieu; Cavé, Jérémie; Laureysens, Ilse; Watkins; Emma et al. (2014): Development of Guidance on Extended Producer Responsibility (EPR). Final Report. BIO Intelligence Service. Available online at https://ec.europa.eu/environment/archives/waste/eu_guidance/pdf/Guidance%20on%20EPR%20-%20Final%20Report.pdf, checked on 8/24/2021.

Zhou, Guangli; Gu, Yifan; Wu, Yufeng; Gong, Yu; Mu, Xianzhong; Han, Honggui; Chang, Tao (2020): A systematic review of the deposit-refund system for beverage packaging: Operating mode, key parameter and development trend. In Journal of Cleaner Production 251, p. 119660. DOI: 10.1016/j.jclepro.2019.119660.

2.1.1 Waste separation, collection and storage systems

Åkesson, Dan; Kuzhanthaivelu, Gauthaman; Bohlén, Martin (2021): Effect of a Small Amount of Thermoplastic Starch Blend on the Mechanical Recycling of Conventional Plastics. In *J Polym Environ* 29 (3), pp. 985–991. DOI: 10.1007/s10924-020-01933-2.

Alessi, Alessia; Lopes, Alice do Carmo Precci; Müller, Wolfgang; Gerke, Frédéric; Robra, Sabine; Bockreis, Anke (2020): Mechanical separation of impurities in biowaste: Comparison of four different pretreatment systems. In *Waste management (New York, N.Y.)* 106, pp. 12–20. DOI: 10.1016/j.wasman.2020.03.006.

Briassoulis, Demetres; Pikasi, Anastasia; Hiskakis, Miltiadis (2021): Recirculation potential of post-consumer /industrial bio-based plastics through mechanical recycling - Techno-economic sustainability criteria and indicators. In *Polymer Degradation and Stability* 183 (20), p. 109217. DOI: 10.1016/j.polymdegradstab.2020.109217.

Burgstaller, Marie; Potrykus, Alexander; Weißenbacher, Jakob; Kabasci, Stephan; Merrettig-Bruns, Ute; Sayder, Bettina (2018): Gutachten zur Behand-lung biologisch abbaubarer Kunststoffe. German Environmental Agency (UBA). Available online at https://www.umweltbundesamt.de/sites/default/files/medien/421/publikationen/18-07-25_abschlussbericht_bak_final_pb2.pdf, checked on 8/20/2021.

Chen, Xiaozheng; Kroell, Nils; Li, Ke; Feil, Alexander; Pretz, Thomas (2021): Influences of bioplastic polylactic acid on near-infrared-based sorting of conventional plastic. In *Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 734242X211003969. DOI: 10.1177/0734242X211003969.

Di Maria, Francesco; Micale, Caterina; Sordi, Alessio; Cirulli, Giuseppe; Marionni, Moreno (2013): Urban mining: quality and quantity of recyclable and recoverable material mechanically and physically extractable from residual waste. In *Waste management (New York, N.Y.)* 33 (12), pp. 2594–2599. DOI: 10.1016/j.wasman.2013.08.008.

Edjabou, Maklawe Essonanawe; Jensen, Morten Bang; Götze, Ramona; Pivnenko, Kostyantyn; Petersen, Claus; Scheutz, Charlotte; Astrup, Thomas Fruergaard (2015): Municipal solid waste composition: sampling methodology, statistical analyses, and case study evaluation. In *Waste management (New York, N.Y.)* 36, pp. 12–23. DOI: 10.1016/j.wasman.2014.11.009.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Eriksen, M. K.; Christiansen, J. D.; Daugaard, A. E.; Astrup, T. F. (2019): Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling. In *Waste management (New York, N.Y.)* 96, pp. 75–85. DOI: 10.1016/j.wasman.2019.07.005.

German Environmental Agency (2020): Biobasierte und biologisch abbaubare Kunststoffe [Biobased and biodegradable plastics]. German Environmental Agency (UBA). Available online at https://www.umweltbundesamt.de/biobasierte-biologisch-abbaubare-kunststoffe#11-was-ist-der-unterschied-zwischen-biobasierten-und-biologisch-abbaubaren-kunststoffen, checked on 8/20/2021.

Hahladakis, John N.; Iacovidou, Eleni (2019): An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): Focus on recycling. In *Journal of hazardous materials* 380, p. 120887. DOI: 10.1016/j.jhazmat.2019.120887.

Interseroh, Recycling und Entsorgungsoptionen für biobasierte Kunststoff-Verpackungen, 2019. Available online at https://veranstaltungen.fnr.de/fileadmin/allgemein/pdf/veranstaltungen/Fachpacktagung2019/07-Recycling-J%C3%B6ran_Reske.pdf

Niaounakis, Michael (2019): Recycling of biopolymers – The patent perspective. In *European Polymer Journal* 114, pp. 464–475. DOI: 10.1016/j.eurpolymj.2019.02.027.

Puig-Ventosa, Ignasi; Freire-González, Jaume; Jofra-Sora, Marta (2013): Determining factors for the presence of impurities in selectively collected biowaste. In *Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA* 31 (5), pp. 510–517. DOI: 10.1177/0734242X13482030.

Schyns, Zoé O. G.; Shaver, Michael P. (2021): Mechanical Recycling of Packaging Plastics: A Review. In *Macromolecular rapid communications* 42 (3), e2000415. DOI: 10.1002/marc.202000415.

Spierling, Sebastian; Röttger, Carolin; Venkatachalam, Venkateshwaran; Mudersbach, Marina; Herrmann, Christoph; Endres, Hans-Josef (2018): Bio-based Plastics - A Building Block for the Circular Economy? In *Procedia CIRP* 69, pp. 573–578. DOI: 10.1016/j.procir.2017.11.017.

Weißenbacher, Jakob; Dollhofer, Marie; Herczeg, Márton; Bakas, Ioannis; McKinnon, David; Seyring, Nicole (2015): Assessment of separate collection schemes in the 28 capitals of the EU. Final Report. European Comission. Available online at https://op.europa.eu/en/publication-detail/-/publication/2c93de42-a2fa-11e5-b528-01aa75ed71a1, checked on 8/20/2021.

Beltrán, Freddys R., Climent-Pascual, E., de La Orden, María U., Martínez Urreaga, J (2020): Effect of solid-state polymerization on the structure and properties of mechanically recycled poly(lactic acid). In: Polymer Degradation and Stability 171, S. 109045. DOI: 10.1016/j.polymdegradstab.2019.109045.

van Thoden Velzen, Eggo Ulphard; Chu, Sharon; Molenveld, Karin; Jašo, Vladislav (2022): Effect of poly lactic acid trays on the optical and thermal properties of recycled poly (ethylene terephthalate). In: Packag Technol Sci 35 (4), S. 351–360. DOI: 10.1002/pts.2633.

Joeri Vendrik (2021): PLA sorting for recycling - Experiments performed at the National Test Centre Circular. CE Delft. Netherlands. Online verfügbar unter https://policycommons.net/artifacts/2010294/pla-sorting-for-recycling/.

2.1.2 Sorting systems

Cimpan, C; Maul, A; Jansen, M; Pretz, T; Wenzel, H (2015) Central sorting and recovery of MSW recyclable materials: A review of technological state-of-the-art, cases, practice and implications for materials recycling, Journal of Environmental Management (156) p.181-199

Cimpan, C; Maul, A; Wenzel, H; Pretz, T (2016) Techno-economic assessment of central sorting at material recovery facilities – the case of lightweight packaging waste.

ECOEMBES Lightweight packaging sorting plants. https://www.ecoembes.com/sites/default/files/archivos_estudios_idi/light-weight-packaging-sorting-plants.pdf

European Commission (2020) Circular Economy Action Plan. For a cleaner and more competitive Europe. https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf

European Commission (2019) Early warning for member States at risk of missing the 2020 target of 50% preparation for re-use/ recycling for municipal waste, https://ec.europa.eu/environment/waste/framework/early_warning.htm

2.2.1 Method for Circular Economy

S Solander, A. (2021). Capitol Riot Panel Demands Records From 15 Social Media Companies In Wide-Reaching Probe. https://www.forbes.com/sites/andrewsolender/2021/08/27/capitol-riot-panel-demands-records-from-15-social-media-companies-in-wide-reaching-probe/?sh=712598544d9f

Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J., & Bardow, A. (2020). Towards a circular economy for plastic packaging wastes–the environmental potential of chemical recycling. Resources, Conservation and Recycling, 162, 105010.

World Economic Forum, Ellen MacArthur Foundation. The New Plastics Economy: Catalysing action 2017.

M Hong, EY-X. Chen, Chemically recyclable polymers: a circular economy approach to sustainability, Green Chem., 19 (16) (2017), pp. 3692-3706, 10.1039/C7GC01496A

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Sullivan, J.; Hussain, B. (2020). How technology unlocks new value from the circular economy. https://www.greenbiz.com/article/how-technology-unlocks-new-value-circular-economy

2.2.2 Mechanical Recycling

1. Niaounakis M: Biopolymers Reuse, Recycling, and Disposal , ed 1. Oxford, William Andrew Publishing, 2013

2. Al-Salem SM, Lettieri P, Baeyens J. Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Management. DOI:https://doi.org/10.1016/j.wasman.2009.06.004

3. NatureWorks LLC. Using Near-Infrared Sorting of Recycle PLA Bottles. 2009

4. Firas A, Fugen D, Edward K. Recycled poly(ethylene terephthalate) chain extension by a reactive extrusion process. Polym Eng Sci. 2004;44:1579-1587

5. Badia JD, Gil-Castell O, Ribes-Greus A. Long-term properties and end-of-life of polymers from renewable resources. Polym Degrad Stab. 2017;137:35-57

6. EFSA Panel on Food Contact Materials, Enzymes and Processing Aids,(CEP), Silano V, Barat Baviera JM, Bolognesi C, Brüschweiler BJ, Chesson A, Cocconcelli PS, Crebelli R, Gott DM, Grob K, Lampi E, Mortensen A, Riviere G, Steffensen I, Tlustos C, Van Loveren H, Vernis L, Zorn H, Castle L, Dudler V, Gontard N, Nerin C, Papaspyrides C, Croera C, Milana MR. Safety assessment of the process 'General Plastic', based on Starlinger Decon technology, used to recycle post-consumer PET into food contact materials. EFSA Journal. 2018;16:e05388

7. Beltrán FR, Climent-Pascual E, de la Orden MU, Martínez Urreaga J. Effect of solid-state polymerization on the structure and properties of mechanically recycled poly(lactic acid). Polymer Degradation and Stability. DOI:https://doi.org/10.1016/j.polymdegradstab.2019.109045

8. Schyns ZOG, Shaver MP. Mechanical Recycling of Packaging Plastics: A Review. Macromol Rapid Commun. 2021;42:2000415

9. Zhao P, Rao C, Gu F, Sharmin N, Fu J. Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. J Clean Prod. 2018;197:1046-1055

10. Scaffaro R, Maio A, Sutera F, Gulino FE, Morreale M. Degradation and Recycling of Films Based on Biodegradable Polymers: A Short Review. Polymers. 2019;11

11. Niaounakis M. Recycling of biopolymers – The patent perspective. European Polymer Journal. DOI:https://doi.org/10.1016/j.eurpolymj.2019.02.027

12. Samper MD, Arrieta MP, Ferrándiz S, López J. Influence of biodegradable materials in the recycled polystyrene. J Appl Polym Sci. 2014;131

13. Briassoulis D, Pikasi A, Hiskakis M. Recirculation potential of post-consumer /industrial bio-based plastics through mechanical recycling - Techno-economic sustainability criteria and

indicators. Polymer Degradation and Stability. DOI:https://doi.org/10.1016/j.polymdegradstab.2020.109217

14. Cruz SA, Zanin M. PET recycling: Evaluation of the solid state polymerization process. J Appl Polym Sci. 2006;99:2117-2123

15. Fredi G, Dorigato A. Recycling of bioplastic waste: A review. Advanced Industrial and Engineering Polymer Research. DOI:https://doi.org/10.1016/j.aiepr.2021.06.006

16. ERESMA. Post-Industrial Plastic Recyling Success Story. 2020;2021

17. Maga D, Hiebel M, Thonemann N. Life cycle assessment of recycling options for polylactic acid. Resources, Conservation and Recycling. DOI:https://doi.org/10.1016/j.resconrec.2019.05.018

18. Badia JD, Ribes-Greus A. Mechanical recycling of polylactide, upgrading trends and combination of valorization techniques. Eur Polym J. 2016;84:22-39

19. Żenkiewicz M, Richert J, Rytlewski P, Moraczewski K, Stepczyńska M, Karasiewicz T. Characterisation of multi-extruded poly(lactic acid). Polym Test. 2009;28:412-418

20. Carrasco F, Pagès P, Gámez-Pérez J, Santana OO, Maspoch ML. Processing of poly(lactic acid): Characterization of chemical structure, thermal stability and mechanical properties. Polym Degrad Stab. 2010;95:116-125

21. Brüster B, Montesinos A, Reumaux P, Pérez-Camargo RA, Mugica A, Zubitur M, Müller AJ, Dubois P, Addiego F. Crystallization kinetics of polylactide: Reactive plasticization and reprocessing effects. Polymer Degradation and Stability. DOI:https://doi.org/10.1016/j.polymdegradstab.2018.01.009

22. Agüero A, Morcillo DM, Quiles-Carrillo L, Balart R, Boronat T, Lascano D, Torres-Giner S, Fenollar O. Study of the Influence of the Reprocessing Cycles on the Final Properties of Polylactide Pieces Obtained by Injection Molding. Polymers. 2019;11

23. Pillin I, Montrelay N, Bourmaud A, Grohens Y. Effect of thermo-mechanical cycles on the physico-chemical properties of poly(lactic acid). Polym Degrad Stab. 2008;93:321-328

24. Peeters B, Kiratli N, Semeijn J. A barrier analysis for distributed recycling of 3D printing waste: Taking the maker movement perspective. J Clean Prod. DOI:https://doi.org/10.1016/j.jclepro.2019.118313

25. Beltrán FR, Arrieta MP, Moreno E, Gaspar G, Muneta LM, Carrasco-Gallego R, Yáñez S, Hidalgo-Carvajal D, de la Orden, María U., Martínez Urreaga J. Evaluation of the Technical Viability of Distributed Mechanical Recycling of PLA 3D Printing Wastes. Polymers. 2021;13

26. Yarahmadi N, Jakubowicz I, Enebro J. Polylactic acid and its blends with petroleum-based resins: Effects of reprocessing and recycling on properties. J Appl Polym Sci. 2016;133:n/a-n/a

Horizon 2020 This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 860407

27. Beltrán FR, Lorenzo V, Acosta J, de la Orden MU, Martínez Urreaga J. Effect of simulated mechanical recycling processes on the structure and properties of poly(lactic acid). J Environ Manag. 2018;216:25-31

28. Beltrán FR, Infante C, de la Orden MU, Martínez Urreaga J. Mechanical recycling of poly(lactic acid): evaluation of a chain extender and a peroxide as additives for upgrading the recycled plastic. J Clean Prod. DOI:https://doi.org/10.1016/j.jclepro.2019.01.206

29. Cosate de Andrade, Marina Fernandes, Fonseca G, Morales AR, Mei LHI. Mechanical recycling simulation of polylactide using a chain extender. Adv Polym Technol. 2018;37:2053-2060

30. Tuna B, Ozkoc G. Effects of Diisocyanate and Polymeric Epoxidized Chain Extenders on the Properties of Recycled Poly(Lactic Acid). J Polym Environ. 2017;25:983-993

31. Laadila MA, Hegde K, Rouissi T, Brar SK, Galvez R, Sorelli L, Cheikh RB, Paiva M, Abokitse K. Green synthesis of novel biocomposites from treated cellulosic fibers and recycled bio-plastic polylactic acid. Journal of Cleaner Production. DOI:https://doi.org/10.1016/j.jclepro.2017.06.235

32. Laadila AM, Suresh G, Rouissi T, Kumar P, Brar KS, Cheikh BR, Abokitse K, Galvez R, Jacob C. Biocomposite Fabrication from Enzymatically Treated Nanocellulosic Fibers and Recycled Polylactic Acid. Energies. 2020;13

33. Beltrán FR, Gaspar G, Dadras Chomachayi M, Jalali-Arani A, Lozano-Pérez AA, Cenis JL, de la Orden, Marí-a U., Pérez E, Martínez Urreaga J. Influence of addition of organic fillers on the properties of mechanically recycled PLA. Environmental Science and Pollution Research. 2020

34. Beltrán FR, Arrieta MP, Gaspar G, de la Orden, María U., Martínez Urreaga J. Effect of lignocellulosic Nanoparticles Extracted from Yerba Mate (Ilex paraguariensis) on the Structural, Thermal, Optical and Barrier Properties of Mechanically Recycled Poly(lactic acid). Polymers. 2020;12

35. Beltrán FR, de la Orden MU, Martínez Urreaga J. Amino-Modified Halloysite Nanotubes to Reduce Polymer Degradation and Improve the Performance of Mechanically Recycled Poly(lactic acid). J Polym Environ. 2018;26:4046-4055

36. Arrieta PM, Samper DM, Aldas M, López J. On the Use of PLA-PHB Blends for Sustainable Food Packaging Applications. Materials. 2017;10

37. Vu DH, Åkesson D, Taherzadeh MJ, Ferreira JA. Recycling strategies for polyhydroxyalkanoate-based waste materials: An overview. Bioresour Technol. DOI:https://doi.org/10.1016/j.biortech.2019.122393

38. Rivas LF, Casarin SA, Nepomuceno NC, Alencar MI, Agnelli JAM, Medeiros ESd, Wanderley AdO, Oliveira MPd, Medeiros AMd, Santos ASF. Reprocessability of PHB in extrusion: ATR-FTIR, tensile tests and thermal studies. Polímeros. 2017;27:122-128

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

39. Plavec R, Hlaváčiková S, Omaníková L, Feranc J, Vanovčanová Z, Tomanová K, Bočkaj J, Kruželák J, Medlenová E, Gálisová I, Danišová L, Přikryl R, Figalla S, Melčová V, Alexy P. Recycling possibilities of bioplastics based on PLA/PHB blends. Polym Test. DOI:https://doi.org/10.1016/j.polymertesting.2020.106880

40. Zaverl M, Seydibeyoğlu MÖ, Misra M, Mohanty A. Studies on recyclability of polyhydroxybutyrate-co-valerate bioplastic: Multiple melt processing and performance evaluations. J Appl Polym Sci. 2012;125:E324-E331

41. Zembouai I, Bruzaud S, Kaci M, Benhamida A, Corre Y, Grohens Y. Mechanical Recycling of Poly(3-Hydroxybutyrate-co-3-Hydroxyvalerate)/Polylactide Based Blends. Journal of Polymers and the Environment. 2014;22:449-459

2.2.4. Anaerobic digestion and composting

Abraham, A., Park, H., Choi, O., Sang, B.-I., (2021). Anaerobic co-digestion of bioplastics as a sustainable mode of waste management with improved energy production – A review. Bioresource Technology, 322, art. no. 124537. https://doi.org/10.1016/j.biortech.2020.124537

Battista, F.; Frison, N.; Bolzonella, D., (2021). Can bioplastics be treated in conventional anaerobic digesters for food waste treatment? Environ. Technol. Innov. 22, 101393. https://doi.org/10.1016/j.eti.2021.101393

Benn, N., Zitomer, D., (2018). Pretreatment and anaerobic co-digestion of selected PHB and PLA bioplastics. Front. Environ. Sci. 5 (93). https://doi.org/10.3389/fenvs.2017.00093

Cucina, M., de Nisi, P., Tambone,F., Adani, F., (2021). The role of waste management in reducing bioplastics' leakage into the environment: A review. Bioresource Technology, Volume 337, 125459. https://doi.org/10.1016/j.biortech.2021.125459

Federle, T.W., Barlaz, M.A., Pettigrew, C.A., Kerr, K.M., Kemper, J.J., Nuck, B.A., Schechtman, L.A., (2002). Anaerobic Biodegradation of Aliphatic Polyesters: Poly(3-hydroxybutyrate-co-3-hydroxyoctanoate) and Poly(ε-caprolactone). Biomacromolecules 3, 813–822. DOI: 10.1021/bm025520w

Stroot, P.G., McMahon, K.D., Mackie, R.I., Raskin, L., 2001. Anaerobic co-digestion of municipal solid waste and biosolids under various mixing conditions—I. digester performance. Water Res. 35, 1804–1816. https://doi.org/10.1016/S0043-1354(00)00439-5

Wang, S., Lydon, K.A., White, E.M., Grubbs 3rd, J.B., Lipp, E.K., Locklin, J., Jambeck, J. R., (2018). Biodegradation of Poly(3-hydroxybutyrate- co-3-hydroxyhexanoate) Plastic under Anaerobic Sludge and Aerobic seawater conditions: gas evolution and microbial diversity. Environ. Sci. Technol. 52, 5700–5709. https://doi.org/10.1021/acs.est.7b06688

Yagi, H., Ninomiya, F., Funabashi, M., Kunioka, M. Anaerobic biodegradation tests of poly(lactic acid) under mesophilic and thermophilic conditions using a new evaluation system for methane

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

fermentation in anaerobic sludge. (2009). Int. J. Mol. Sci. 10,3824–3835. https://doi.org/10.3390/ijms10093824

Yagi, H., Ninomiya, F., Funabashi, M., Kunioka, M., (2010). Bioplastic biodegradation activity of anaerobic sludge prepared by preincubation at 55◦C for new anaerobic biodegradation test. Polym. Degrad. Stab. 95, 1349–1355. https://doi.org/10.1016/j.polymdegradstab.2010.01.023

Yagi, H., Ninomiya, F., Funabashi, M., Kunioka, M., (2013). Thermophilic anaerobic biodegradation test and analysis of eubacteria involved in anaerobic biodegradation of four specified biodegradable polyesters. Polym. Degrad. Stab. 98, 1182–1187. https://doi.org/10.1016/j.polymdegradstab.2013.03.010

Yagi, H., Ninomiya, F., Funabashi, M., Kunioka, M., (2014). Mesophilic anaerobic biodegradation test and analysis of eubacteria and archaea involved in anaerobic biodegradation of four specified biodegradable polyesters. Polym. Degrad. Stab. 110,278–283. https://doi.org/10.1016/j.polymdegradstab.2014.08.031

Zhang, W., Heaven, S., Banks, C.J., 2018. Degradation of some EN13432 compliant plastics in simulated mesophilic anaerobic digestion of food waste. Polym. Degrad. Stab. 147, 76–88. https://doi.org/10.1016/j.polymdegradstab.2017.11.005

Arrieta, M. P.; López, J.; Rayón, E.; Jiménez, A. (2014): Disintegrability under composting conditions of plasticized PLA–PHB blends. In Polymer Degradation and Stability 108, pp. 307–318. DOI: 10.1016/j.polymdegradstab.2014.01.034.

Barrena, Raquel; Font, Xavier; Gabarrell, Xavier; Sánchez, Antoni (2014): Home composting versus industrial composting: influence of composting system on compost quality with focus on compost stability. In Waste management (New York, N.Y.) 34 (7), pp. 1109–1116. DOI: 10.1016/j.wasman.2014.02.008.

Hann, Simon; Scholes, Rosy; Molteno, Star; Favoino, Enzo; Geest Jakobsen, Line (2020): Relevance of Biodegradable and Compostable Consumer Plastic Products and Packaging in a Circular Economy. Final Report. Eunomia Research & Consulting Ltd. Available online at https://op.europa.eu/en/publication-detail/-/publication/3fde3279-77af-11ea-a07e-01aa75ed71a1, checked on 8/18/2021.

Rudnik, Ewa (2008): Compositing methods and legislation. In : Compostable Polymer Materials: Elsevier, pp. 88–110.

Ruggero, Federica; Onderwater, Rob C. A.; Carretti, Emiliano; Roosa, Stéphanie; Benali, Samira; Raquez, Jean-Marie et al. (2021): Degradation of Film and Rigid Bioplastics During the Thermophilic Phase and the Maturation Phase of Simulated Composting. In J Polym Environ. DOI: 10.1007/s10924-021-02098-2.

Stadtreinigung Hamburg (2019): Avoiding Bio-Plastics and Single-use Plastics in Industrial Composting Plants. Stadtreinigung Hamburg. Available online at https://www.connective-

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

cities.net/fileStorage/Veranstaltungen/Dialogveranstaltung_Hamburg_Plastik_2019/Dokumente/Hamburg_Stadtreinigung_Good_Practice_Presentation_SBO.pdf, checked on 8/18/2021.

Sundberg, C.; Smårs, S.; Jönsson, H. (2004): Low pH as an inhibiting factor in the transition from mesophilic to thermophilic phase in composting. In Bioresource technology 95 (2), pp. 145–150. DOI: 10.1016/j.biortech.2004.01.016.

Tolga, Sengül; Kabasci, Stephan; Duhme, Mona (2020): Progress of Disintegration of Polylactide (PLA)/Poly(Butylene Succinate) (PBS) Blends Containing Talc and Chalk Inorganic Fillers under Industrial Composting Conditions. In Polymers 13 (1). DOI: 10.3390/polym13010010.

Alassali, Ayah; Picuno, Caterina; Chong, Zhi Kai; Guo, Jinyang; Maletz, Roman; Kuchta, Kerstin (2021): Towards Higher Quality of Recycled Plastics: Limitations from the Material's Perspective. In: Sustainability 13 (23), S. 13266. DOI: 10.3390/su132313266.

Eriksen, M. K.; Christiansen, J. D.; Daugaard, A. E.; Astrup, T. F. (2019): Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling. In: Waste management (New York, N.Y.) 96, S. 75–85. DOI: 10.1016/j.wasman.2019.07.005.

3.1. Analysis of legal and policy framework

Basel convention (1989). Available online at: http://www.basel.int/TheConvention/Overview/TextoftheConvention/tabid/1275/Default.aspx

Basel convention decisions (2019). Available online at: http://www.basel.int/Implementation/Plasticwaste/Decisions/tabid/6069/Default.aspx

Resolution adopted by the United Nations General Assembly (2015). Available online at: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

Closing the loop - An EU action plan for the Circular Economy. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

A new Circular Economy Action Plan. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

The European Green Deal. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN

European Strategy for Plastics in a Circular Economy. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN

Directive 2008/98/EC on waste. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590976319071&uri=CELEX:02008L0098-20180705

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Directive 94/62/EC on packaging and packaging waste. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590977481951&uri=CELEX:01994L0062-20180704

Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590979695787&uri=CELEX:32019L0904

Commission Decision establishing the identification system for packaging materials pursuant to European Parliament and Council Directive 94/62/EC on packaging and packaging waste (97/129/EC). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31997D0129&qid=1590984045238&from=EN

Regulation (EC) No 66/2010 on the EU Ecolabel. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02010R0066-20171114&qid=1590991576604&from=EN

4.1. Different systems

Calabrese, A., Costa, R., Levialdi Ghiron, N., Menichini, T., Miscoli, V., Tiburzi, L. (2021). Operating modes and cost burdens for the European deposit-refund systems: A systematic approach for their analysis and design. Journal of Cleaner Production, Volume 288, 125600, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.125600.

E-seimas. 2021. Dėl Pakuočių ir pakuočių atliekų tvarkymo taisyklių patvirtinimo. Available at: https://e-seimas.lrs.lt/portal/legalActEditions/lt/TAD/TAIS.179369

PALPA 2020. Pantillinen järjestelmä. Available at: https://www.palpa.fi/

Plasteurope, 2020. THE NETHERLANDS. Government to implement deposit-return scheme for smaller plastic bottles. Available at: https://www.plasteurope.com/news/THE_NETHERLANDS_t245202/

Spasova, B., 2019. DEPOSIT-REFUND SYSTEMS IN EUROPE. ACRþ, Brussels. Available at: https://www.acrplus.org/images/technical-reports/2019_ACR_Deposit-refund_systems_in_Europe_Report.pdf

Urke K. L. 2019. Estonian Deposit Return System. Presentation during HISCAP 1st Virtual Meeting, BIO-PLASTICS EUROPE project.

VerpackG. 2020. Gesetz über das Inverkehrbringen, die Rücknahme und die hochwertige Verwertung von Verpackungen. (Verpackungsgesetz -VerpackG). Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). Available at: https://www.gesetze-im-internet.de/verpackg/VerpackG.pdf

Walls, M., Deposit-Refund Systems in Practice and Theory (2011). Resources for the Future Discussion Paper No. 11-47, Available at SSRN: https://ssrn.com/abstract=1980142 or http://dx.doi.org/10.2139/ssrn.1980142

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407

Ellen McArthur: ReUse book, 2019, retrieved 17.8.2021 https://www.ellenmacarthurfoundation.org/assets/downloads/Reuse.pdf

Reusable packaging association, 2021, retrieved 17.8.2021 https://www.reusables.org/what-is-reusable-packaging/

Packaging Europe, deep dive into re-usable packakgin 25.1.2021, retrieved 17.8.2021 https://packagingeurope.com/a-deep-dive-into-reusable-packaging-solutions/

Recup: retrieved 17.8.2021 https://recup.de/

Kamupak: retrieved 17.8.2021 https://en.kamupak.fi/

4.2. "Hamburgs Werkstoff Innovative" – Regional bottle-to-bottle recycling of HDPE

Unilever Deutschland Holding GmbH (n.d.): Hamburgs Wertstoff Innovative. Unilever Deutschland Holding GmbH; Hamburg University of Technology; Veolia; Stadtreinigung Hamburg; Budni. Available online at https://hamburgs-wertstoff-innovative.de/, checked on 9/15/2021.

4.3. The Italian good practice: BIOREPACK

Biorepack. 2021. https://biorepack.org/

Gazzetta Ufficiale. Della Repubblica Italiana. Approval of the statute of the National Consortium for the organic recycling of biodegradable and compostable plastic packaging. 2020.

https://www.gazzettaufficiale.it/gazzetta/serie_generale/caricaDettaglio?dataPubblicazioneGazzetta=2020-11-14&numeroGazzetta=284

Conai. 2021. https://www.conai.org/en/about-conai/

CONAI Sustainability Report. 2021. https://www.conai.org/en/communication/conai-sustainability-report/

Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860407