BIO PLASTICS EUROPE

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

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

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Vocabulary of definitions

Definition	Meaning
Chemical recycling	Technologies that use physicochemical 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 nd/or steam.
Kerbside collection	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.
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.
Waste stream	Specific types of waste found in a customer's disposal (trash, cardboard, aluminum, metal, etc.) or a broader definition of a disposal type. (e.g. MSW, C&D, hazardous, etc.)
Waste-to-energy plant	Facilities consisting 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.

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Executive summary

Plastic pollution, including through single-use plastics, continues to plague natural environments around the world. The use and consumption of plastic products is increasingly high, therefore, the goal to find viable options for reuse, recycling and disposal as well as sustainable management of this type of waste is on the rise. The variety of solutions that can solve the plastic pollution problem cover local, national and regional levels. Some of the proposed interventions focus on post-consumption management and require considerable investment and an improvement of waste management infrastructure. Other interventions prioritize the reduction of plastic use 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 food packaging. 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 topics on bio-based and biodegradable plastics for a broad audience of decision-makers on national and regional level, business representatives, scientists and citizens. Topics covered include the instruction of concepts related to bio-based and biodegradable plastic, Life Cycle Assessment and Circular Economy, the assessment of the impact bio-based, biodegradable and compostable plastic have on waste management technologies and systems, and an analysis of legal and policy frameworks. In addition, the handbook covers the most promising business cases from project partner countries.

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1. Introduction

1.1 Bio-based plastic

Carbon is the main element in all plastics. Conventional, fossil-based plastics contain carbon from oil and natural gas, while bio-based plastics contain carbon derived from renewable sources. Bio-based plastics can be divided into two categories:

- Bio-based plastics that are identical to their fossil-based equivalents (for example, Bio-PE or Bio-PET). These are often called drop-ins.
- Bio-based plastics that have a completely different chemical structure than 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. In order to avoid greenwashing, it is important to communicate the bio-content of bio-based plastics to consumers.

Renewable raw materials for bio-based plastics are usually divided into first-, second- and third-generation feedstocks. First-generation feedstock is the most commonly used feedstock in bio-based plastics today. It consists of carbohydrate-rich crops suitable for human consumption or animal feed, like corn or sugar cane. Second-generation feedstock includes crops that are not suitable for human consumption or animal feed, like 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 Polyhydroxyalkanoates (PHA) sector concerning organic waste (e.g. Mango Materials).

1.2 Biodegradable and compostable plastics

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

- Natural environment – soil, water and compost require certain conditions at different periods of time, and the biodegradation process is slow.
- Industrial composting – requires an industrial composting plant or anaerobic digestion facility. Environmental conditions are stable and monitored.
- Home composting – degradation in an in-home composter, with a lower temperature than in an industrial composting plant.

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

Table 1 *Biodegradable and compostable plastics (adopted from Flury & Narayan, 2021)*

Polymer	Properties	Degradability environment
Polybutylene succinate (PBS)	Thermoplastic polymer, comparable to polypropylene, consists of polymerized units of butylene succinate.	Industrial composting
Polylactic acid (PLA)	Brittle, clear, generally suitable for food contact applications, can also be used as a foam[1]	Industrial composting, anaerobic digestion
Polyhydroxyalkanoates (PHA)	Various properties, rarely used commercially, normally used in blends[1]	Home composting, industrial composting, degradability in soil
Polybutylene adipate terephthalate (PBAT)	Various properties, can replace PP or LDPE, some grades are flexible and very tough, some grades are food contact approved, normally used in blends[1]	Home composting, industrial composting, degradability in soil
Starch blends	Wide range of different properties, can be used as a foam [1]	Home composting, industrial composting
Cellulose acetate	Rigid, some types certified according to EN 13432	Industrial composting

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

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posting and anaerobic digestion facilities.

- EN 14995 provides the same requirements as in EN13432, however, it 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. Biodegradability in marine environments

These standards provide guidelines but do not specify requirements for conditions and timeframes.

- The US standard ASTM D7081 "Standard Specification for Non-Floating Biodegradable Plastics in the Marine Environment"
- ASTM D6691 "Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum",
- ASTM D 6692 "Standard Test Method for Determining the Biodegradability of Radiolabelled Polymeric Plastic Materials in Seawater",
- ASTM D7473 "Standard Test Method for Weight Attrition of Plastic Materials in the Marine Environment by Open System Aquarium Incubations".
- OECD 306 "Biodegradability in seawater"
- ISO 16221 "Water quality – Guidance for determination of biodegradability in the marine environment"

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-life conditions are different and sometimes can hinder the degradation, especially for home composting and for biodegradability in soil and water.

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

Labels	Reference standard	Test Conditions	Biodeg Test Threshold
	EN 13432	Ambient temperature (20°C – 30°C)	90% in 12 months
	ISO 175561		90% in 2 years
	ASTM D7081 (withdrawn)		90% in 6 months
	EN 149872	20°C and 25°C	90% in 56 days
	EN 13432	58ºC ± 2ºC	90% in six months Disintegration during composting: 90% in 12 weeks

Biodegradable plastics are mostly used in the packaging sector and account for about 59% of the total market share. Other major sectors include agriculture and horticulture, and consumer goods – 13% and

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9 %, respectively (Hilton et al., 2020). Provision of the effective collection system for biodegradable and compostable materials is very essential and can significantly increase the effectiveness of bio-waste management infrastructure.

1.3 Bio-based 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 andre-cycling route.
- Depending on the polymer, bio-based and/or biodegradable plastics could be applied in the following areas (non-exhaustive).

Table 3 *Application areas of bio-based plastics*

Application Areas (Non-Exhaustive)	Description
Rigid packaging	Rigid packaging for food, household products including trays and tubs.
Soft packaging	Soft packaging made from thin and flexible foils.
Toys	Children's 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	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 certain single-use plastic items on the market.

Figure 1 *PLA applications (Source: NaturePlast)*

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 bio-based 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 include consumer goods, textiles, agriculture, automotive/transport, construction, coatings, and electronics.

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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 already used. Apart from the aforementioned application areas, researchers are studying the use of biodegradable plastics in such high performance areas as drug delivery, composite nanotubes for the automotive industry as well as in additive manufacturing (Narancic et al., 2020).

1.4 Recyclable Plastics

Conventional Plastics

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

In 1988, the US-based Plastics Industry Association (Plastics) established a classification system meant to help consumers and recyclers identify different types of plastic. Plastic types are identified via a code or number usually molded at the bottom of each plastic product.

There are seven types of plastic, and some are recycled more often than others (Howard and Lake, 2021).

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

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

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

Thanks to it being inexpensive, lightweight, and easy to recycle, PET is the most common type of plastic for single-use bottled beverages. Clear PET plastics are generally considered safe, although they can potentially absorb odors and flavors from the stored foods and liquids. These plastics can also be dangerous when exposed to heat (e.g. when a water bottle is left inside a car on a hot day). Over time, this can cause antimony (a metalloid) to leach out of the plastic and into the liquid.

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 has been emptied and rinsed of any food. Their caps and labels are usually made of a different type of plastic. Bottle labels and caps need to be removed during the recycling process.

Recycled into: Polar fleece, fiber, tote bags, furniture, carpets, paneling, straps, bottles and food containers (as long as the plastic being recycled meets purity standards and does not contain hazardous contaminants).

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

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

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, containers for motor oil, shampoos, conditioners, liquid soap, detergents, and bleaches; some trash and shopping bags.

Recycling: HDPE can 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 tiles, drainage pipes, lumber, benches, doghouses, picnic tables, fencing, shampoo bottles.

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

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

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. PVC should never be burned, 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. PVC items should be kept 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, paneling, mud-flaps, roadway gutters, flooring, cables, speed bumps, mats.

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

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

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. This is why it is mostly used for different types of bags. More recycling programs are beginning to accept LDPE plastics, but it is 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 kerbside programs, but some communities might accept it.

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

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

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

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 liquids. It's gradually becoming more accepted by recyclers.

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

Recycling: PP can be recycled through some kerbside programs, just make sure there is no food left inside.

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

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

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

PS can be made into rigid or foam products — in the latter case, it is popularly known under the Styrofoam trademark. 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, take-out containers, aspirin bottles, compact disc cases

Recycling: not many kerbside 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, packing foam, take-out containers.

Figure 10 *Miscellaneous Photo: The Star/Azman Ghani*

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

This category covers all the other types of plastic not defined by the earlier six codes. It includes polycarbonate (PC), polylactide (PLA), polyurethane (PU) and acrylonitrile butadiene styrene (ABS). Polycarbonate is a hard plastic containing the toxic chemical bisphenol A or BPA that some studies have shown 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.

1.5 Life Cycle Assessment (LCA)

According to ISO 14040, Life Cycle Assessment (LCA) comprises the compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Different impact categories are used, the greenhouse gas carbon dioxide equivalent global warming potential (GWP) being the most recognizable category.

LCA can have a wide scope measuring corporate impact or a narrow scope, i.e., product modification by replacing parts with more sustainable material. According to the Greenhouse Gas Protocol standard created by the World Resources Institute (WRI) and World Business Council for Sustainable Development

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(WBCSD) as an international standard for corporate accounting and reporting emissions, GHGs are categorized into three scopes: Scope 1 (direct emissions from company-owned and controlled resources), Scope 2 (indirect emissions from the generation of purchased energy) and Scope 3 (indirect emissions – not included in scope 2 – that occur in the value chain of the reporting company, including both upstream and downstream emissions) .

When investigating a product from the beginning to the end of its life cycle during LCA, all three scopes can be taken into account.

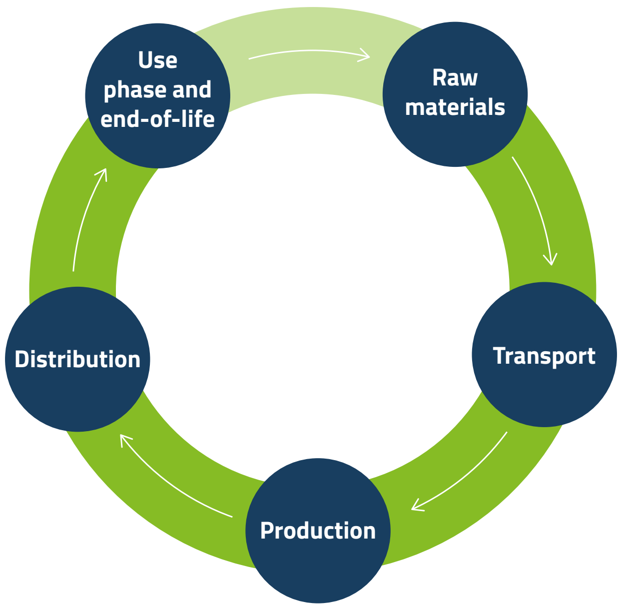

Figure 11 *LCA impact links*

Various impacts can be assessed during different phases of the cause-effect chain, at midpoints or endpoints. Midpoints are considered to be links in the cause-effect chain (environmental mechanism) of an impact category, prior to the endpoints, where 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., impact on health in terms of disability-adjusted life years for carcinogenicity, climate change, ozone depletion, photochemical ozone creation; or impact 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 provide 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, 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. Experts should be involved in comparing different individual LCAs, as the analyzed industrial ecosystems can be complex.

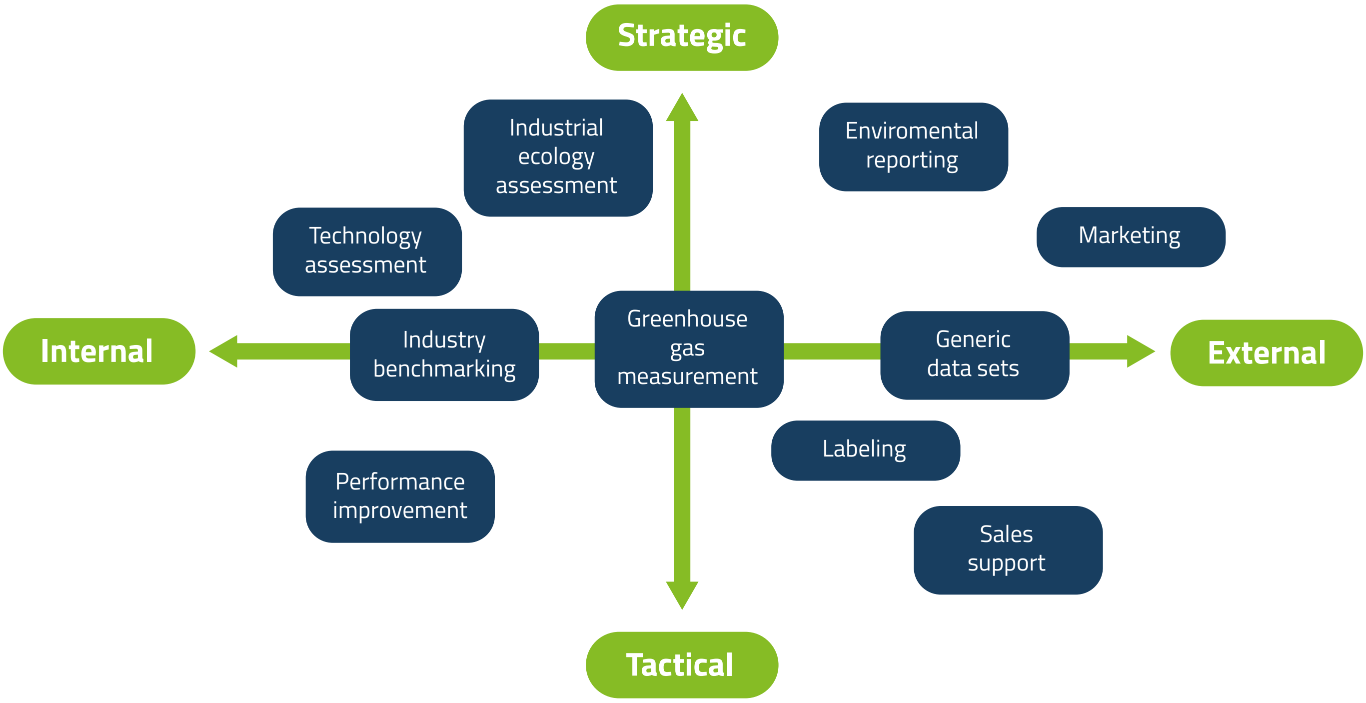

Figure 12 *Applications for LCA, Figure adapted from Saur, K. (2002)*

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 the same dimension, weight or functionality (barrier, load bearing capability etc.).

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

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

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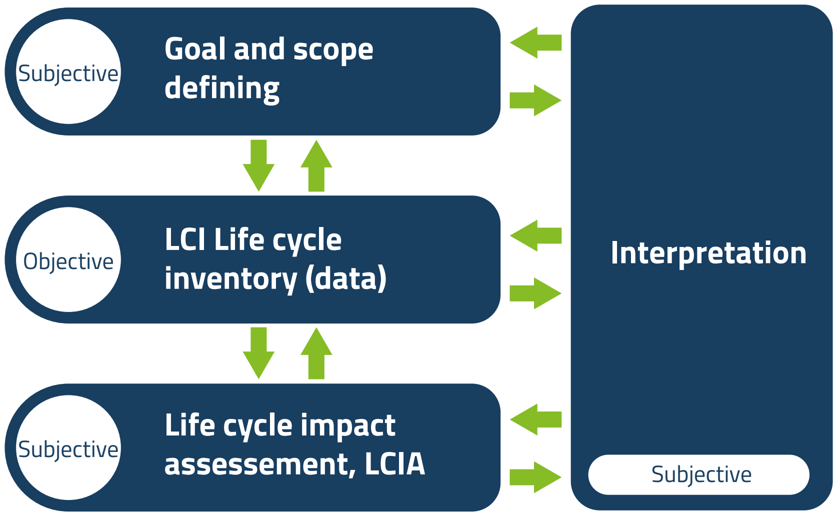

Figure 13 *Stages of an LCA according ISO 14040 standard*

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

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

Simplified LCA – comprehensive assessment using generic datasets covering the whole life cycle of a product/system of processes. It requires significantly less time and resources, which is a significant difference from detailed LCA. Simplified LCA covers the screening of life cycle stages, simplification of LCA results for future recommendation and assuring the reliability of the analysis results. This methodology is also sometimes called 'Streamlined LCA'.

Detailed LCA – this type of LCA is comprehensive, with the full consideration of every life cycle stage with system-specific datasets, analyzed in detail for further process improvement. (Farjana et al., 2021).

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

1.6 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 European 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 (EP, 2021). 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 (Foundation, 2019).

The purpose of these changes is to transform the currently existing linear economic model into a circular economy model that aims to reduce the amount of waste generated and have resources circulate. Circular economy is based on three main principles: design out waste and pollution, Circulate products and materials (at their highest value), regenerate nature (Foundation, 2019).

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, circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources (Foundation, 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 value as little as possible, renewable energy sources are used and systems thinking is at the core (Kaarten, 2020).

The purpose of a 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 'Outline of a Circular Economy' definition, which illustrates the continuous circulation of different materials. These cycles can be divided into technical and biological circles (Figure 14) (Foundation, 2019; Nurmi, 2020).

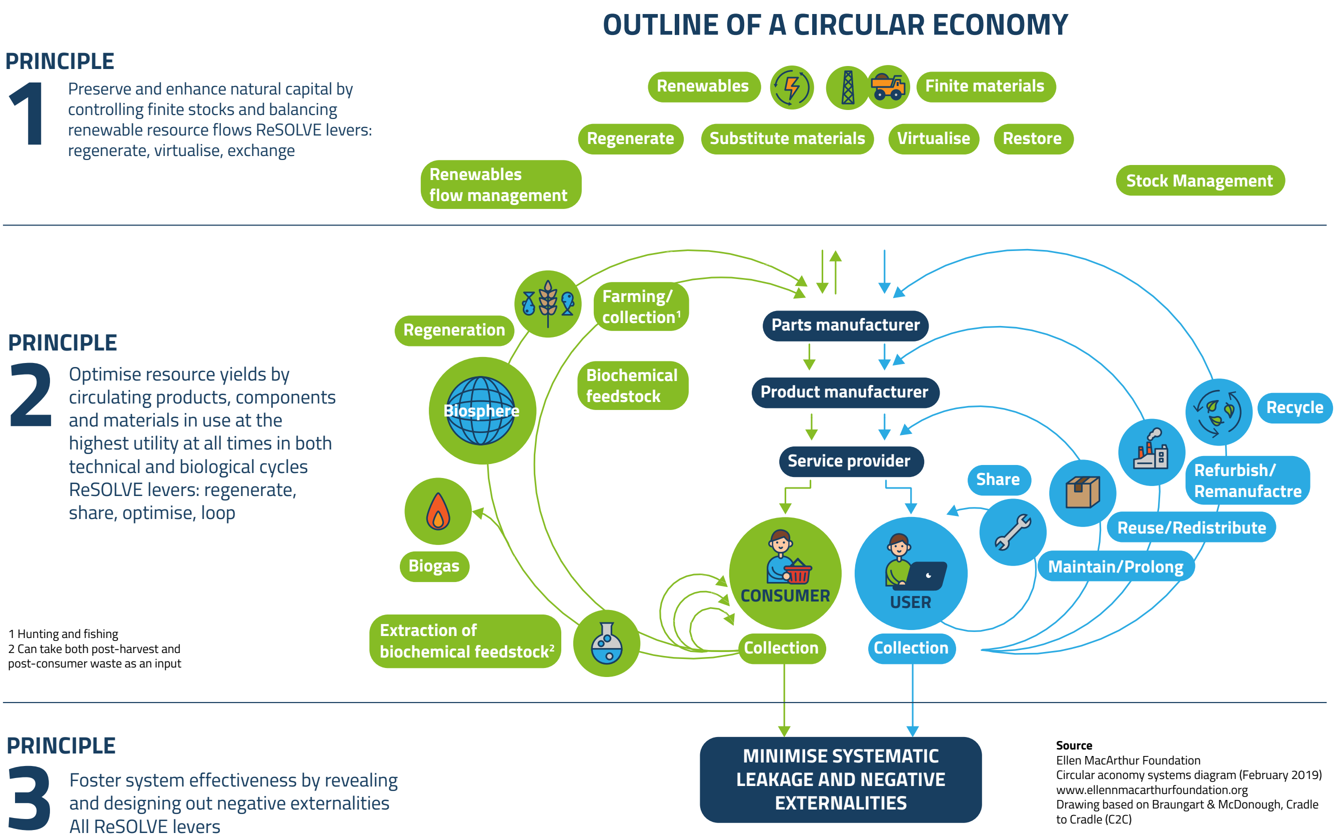

Figure 14 *Outline of a Circular Economy, as defined by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2019)*

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Based on the circular economy, different models can be implemented 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 individuals and small businesses to large organizations (Foundation, 2019).

In the linear economy, raw natural resources are taken, transformed into products, and disposed of. This "take-make-consume-throw away" pattern relies on large quantities of cheap, easily accessible materials and energy (Kaarten, 2020, Karttunen, 2020). Planned obsolescence, when a product is designed to have a limited lifespan in order to encourage consumers to buy it again, is also a part of this model. A circular economy model aims to close the gap between production and natural ecosystem cycles, on which humans ultimately depend. Circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible. This way, the life cycle of products is extended (Kaarten, 2020). Such products can be efficiently used again and again, thereby creating further value.

In a circular economy, economic activity builds and rebuilds overall system health. It is based on three principles (Foundation, 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 gasses 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 favors activities that preserve value in the form of energy, labor, 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.

1.7 Highlights

Plastics have become one of the most ubiquitous materials used globally, and it is recognized that managing the plastic pollution problem is a big global challenge. Therefore, it is important to develop a sustainable plastics economy that would reduce the persistence and accumulation of plastics. The European Union 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 European 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.

Recyclable plastic. There are five essential steps in the recycling of plastic materials: collection of waste plastic, sorting according to plastic types, shredding and resizing to a form that can be recycled, washing to remove impurities, and compounding. In 1988, the US-based Plastics Industry Association (Plastics), introduced a classification system to help consumers and recyclers identify different types of plastic via a code or number that is usually molded at the bottom of each plastic product. It is necessary to develop 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 contain carbon derived from renewable sources. It is rare for plastic marketed as bio-based to be fully comprised of bio-based feedstock, as it is usually produced 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, including aerobic (compost), soil or anaerobic conditions. Therefore, biodegradable and compostable plastics provide a promising alternative to conventional plastics, as they can degrade in the presence of microorganisms in water, carbon dioxide and microbial biomass. Depending on the polymer, bio-based and biodegradable plastics can be used in a variety of applications, just like their fossil counterparts. 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 include consumer goods, textiles, agriculture, automotive/transport, building and construction, coatings, and electronics. That said, currently (2020), bioplastics have a very low share in the total production of plastics, and represent only about 1% of the approx. 368 million tonnes of plastic produced annually.

2. The impact of bio-based, 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 that are currently available. In addition, the potential impacts of bio-based and/or biodegradable plastics on the current waste management systems are described.

As shown in Figure 15, a waste management system includes the following elements: source separation, collection and transport, sorting, and, finally, reuse, recycling, energy recovery, treatment and disposal.

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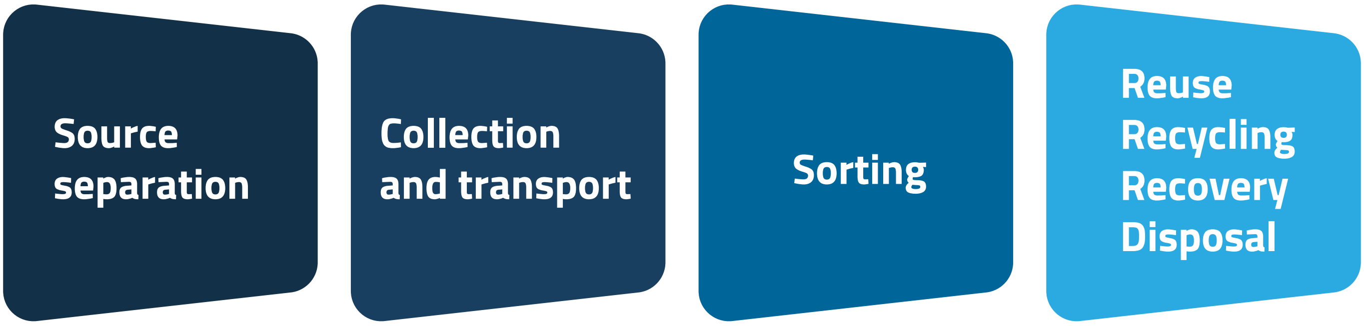

Figure 15 *Elements in a waste management system*

Source separation is commonly done in order 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 may be carried out to separate different materials collected that have commingled. 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 disposed of.

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 used. Plastic waste can be collected either commingled 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 at a certain frequency, for example weekly or bi-weekly (Weißenbacher et al., 2015). For example, plastic packaging waste can be collected door-to-door in a commingled stream of plastics and metal packaging, which is sometimes also mixed with paper and/or glass.

Figure 16 *Figure 16 Bring points (Source: Lis Burke, 2007)*

Figure 17 *Figure 17 Kerbside or door-to-door collection (Source: Bernard Spragg, 2013)*

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Figure 18 *Figure 18 Recycling center (Source: Dave Crocer, 2008)*

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, plastic packaging waste can be collected in commingled streams or separately. The third collection option is civic amenity sites or manned recycling centers, which collect not only plastic waste but also bulky waste, hazardous waste, WEEE, and other recyclables. Usually, a combination of the above options is used for plastic waste collection in a given 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 common, whereas the separate collection of small plastic household items like toys or clothes hangers is uncommon.

Figure 19 *Reverse vending machines for deposit return systems (Source: Bidgee, 2018)*

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

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	Commingled 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 centers, pick-up services or civic amenity sites.

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Impact of bio-based, biodegradable and compostable plastics on waste management technologies and systems

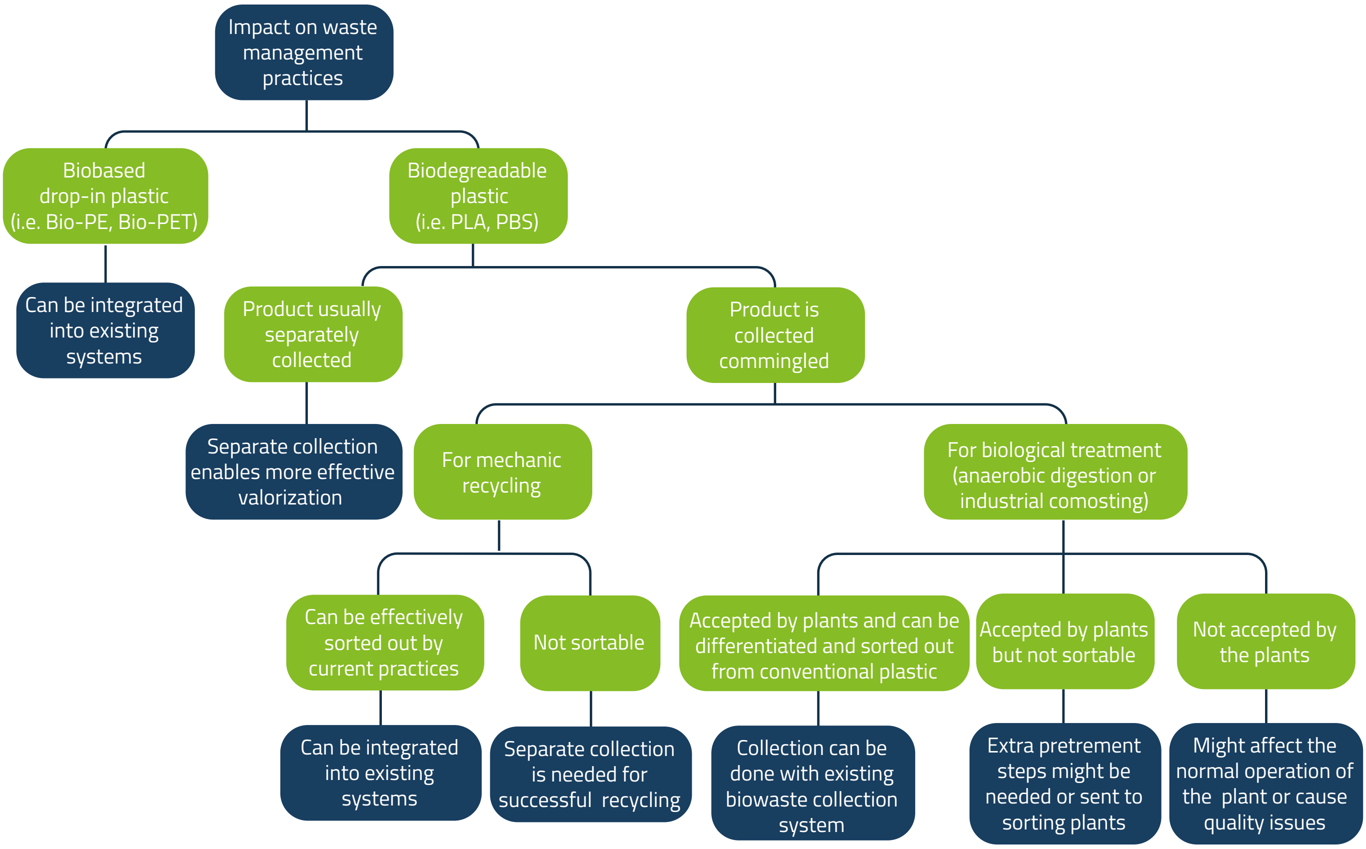

Figure 20 *Decision tree on the impact of bio-based and biodegradable plastics on waste collection, separation and sorting*

The potential impact of bio-based and biodegradable plastics will depend on:

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

Bio-based drop-in plastic

Bio-based drop-in plastics 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 as they treat 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 into separate streams. If degradable material enters the conventional plastics stream and fully degrades during 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.

PET and PE are non-biodegradable and their precursors are fossil fuel derived. It is entirely possible to obtain the monomers from renewable resources and therefore synthesize Bio-PET and Bio-PE. Bio-based alternatives such as Bio-PET and Bio-PE have identical properties to their petroleum derived plastic counterparts, and can be processed using the same equipment and the 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 et al., 2020).

Polylactide (PLA) is a bioplastic that is potentially recyclable but for which no separate recycling stream has yet been established. Mechanical recycling causes downgrading of PLA quality. When mechanically recycling PLA, it is possible to add a chain extender which helps to partially recover the impaired molar mass and other mechanical properties, making the recycled PLA more comparable to virgin PLA (Andrade et al., 2018).

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). These monomers can then be re-polymerised, resulting in a circular production economy (Lamberti et al., 2020).

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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. There is only a small amount of Polyglycolide (PGA) in circulation, and it 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 the fermentation of mixed microbial cultures to generate new PHA (Lamberti et al., 2020).

The technology and literature for bio-versions of commodity plastics and chemical recycling routes are already well established. All that remains then is for the chemical recycling infrastructure to develop, and for 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 differs. For example, conventional household packaging can be collected via commingled kerbside systems, while large household plastic items can be collected via recycling centers or civic amenity sites.

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 commingled collection (Eriksen et al., 2019; Hahladakis and Iacovidou, 2019). Thus, if chemically distinct biodegradable plastics such as PLA and PBS are 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 as being a problem for PET recycling in the case of cross contamination (Schyns and Shaver, 2021; Åkesson et al., 2021).

Automated sorting of commingled 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 commingled with other polymer types) might be needed to reduce cross contamination of different polymers, which would incur extra effort.

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 varies 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 recycling bins. The collection of biodegradable plastic packaging together 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 that are made predominantly from bio-based sources and used for the separate collection of biowaste. These are allowed in the bio waste bin on the condition that the local waste operator, which has the ultimate decision-making power, 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, it is predicted that they are 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 depends hugely on the different schemas of the collection. To better understand sorting plants, one of the standards for sorting plans (the one established in Spain for the 96 facilities receiving domestic light packaging financed by Ecoembes) will be explained in detail. In addition, the differences between this standard and other standards are also included. New collection systems that include biodegradable packaging commingled with other plastic packaging in the recycling bin will force the inclusion of a new line for this new fraction at the sorting plant.

The Spanish sorting-plants model

Waste treated in lightweight 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 cartons. The yellow 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 a mixed plastic fraction, which is composed of materials made of PS (polystyrene), PP (polypropylene) and other plastics; aluminum and steel packages are also included, 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.

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Figure 21 Lightweight 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 management of rejected waste.

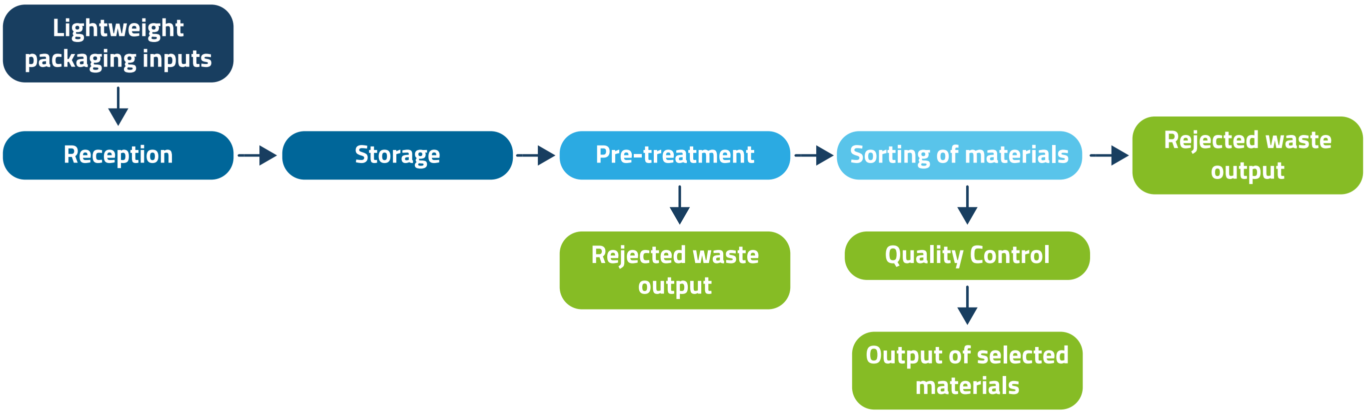

Figure 22 Outline of sorting process. (Source: Elaborated by ECOEMBES, 2021)

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.

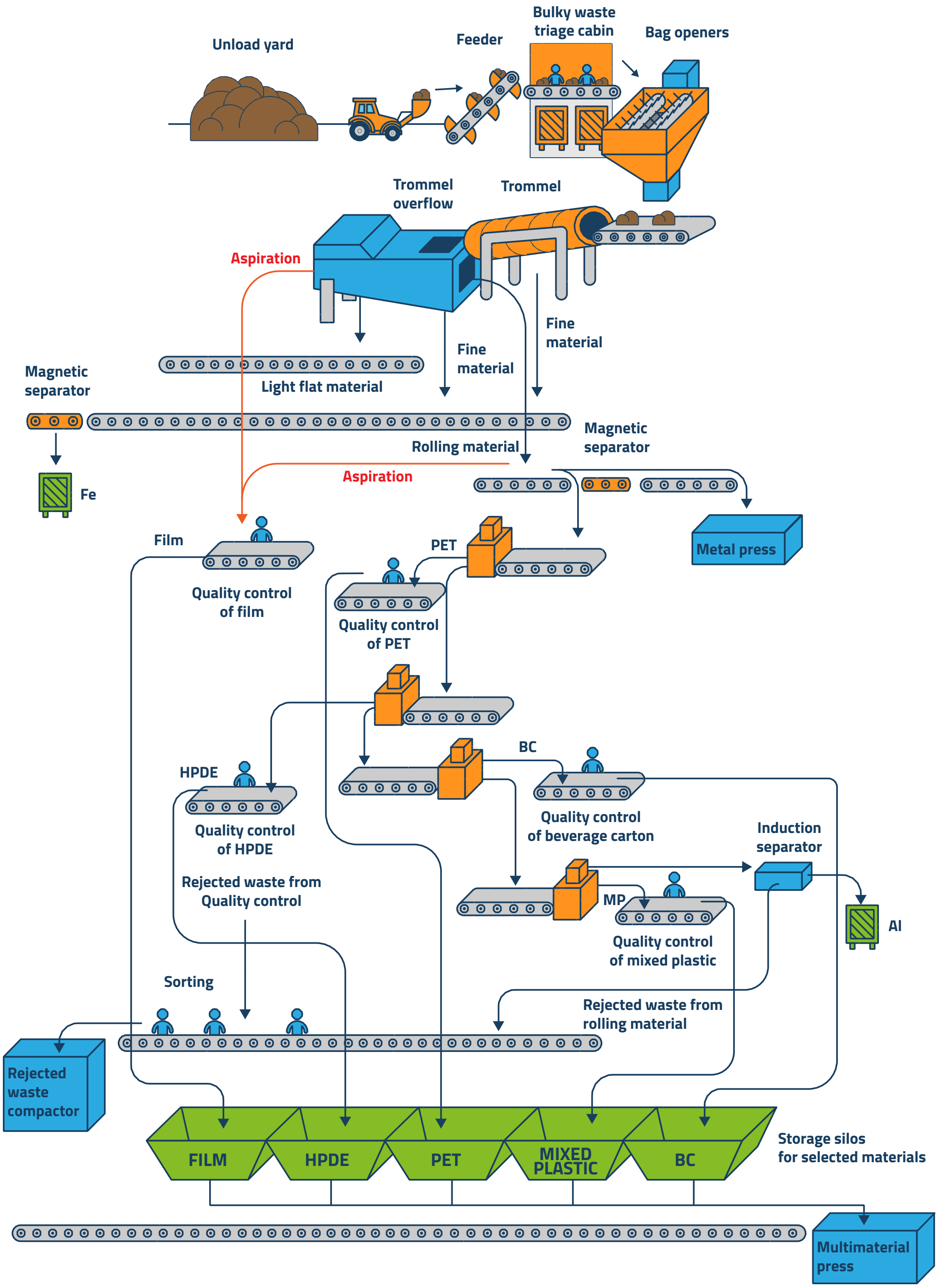

Figure 23 *Diagram of an automated sorting process. (Source: Elaborated by ECOEMBES, 2021)*

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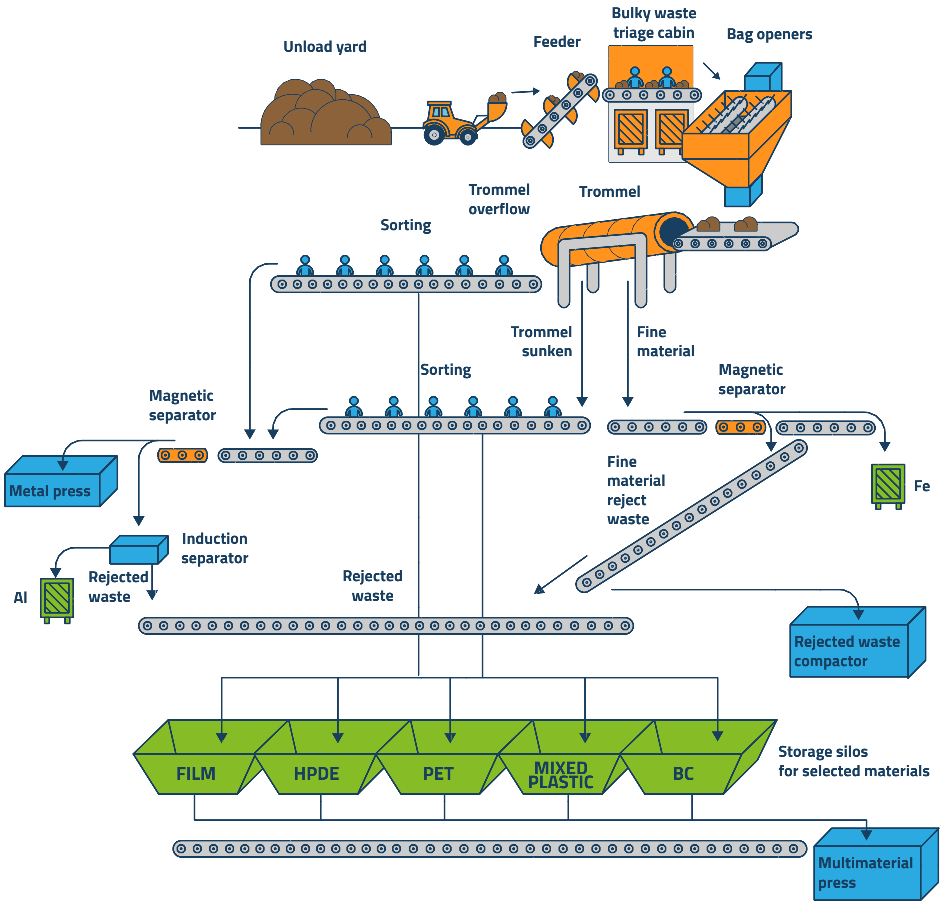

Figure 24 *Diagram of a manual sorting process. (Source: Elaborated by ECOEMBES, 2021)*

Reception and storage operations

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

- **Scales for monitoring and weighing of collection vehicles:** Vehicles with packaging waste collected from the streets arrive at the sorting facility, passing through access control and weighing (scales). In cases where the street collection vehicles need to travel great distances from the place of collection to the destination plant, in order to transport the collected material more efficiently it is convenient to unload the material at intermediate locations (transfer stations) for compacting and subsequent transport in larger containers, providing this is possible and these facilities exist. In this case, the material arriving at the plant has a higher 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, optimizing the surface available for storage prior to treatment. Several types of bulky waste, with various sizes and shapes (such as mattresses, large packages, bicycles, etc.) may be included in this process, and this could hinder the work and affect the sorting equipment to be used. Using the loading shovel, the operator must place these items in a specific container located on this or another surface.

Pre-treatment operations

In this stage, the bioplastics start to be separated into different streams, depending on the packaging type (bottles, trays, bags etc.). 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 (in the case of an unload yard) or grapple hook (in the case of a pit), then transferred and unloaded into the dosing feeder. This is done at variable speed and with a flow limiter, which is 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 (both recoverable and non-recoverable) are stored in containers located under the sorting cabin for delivery to the recycler or treatment rejects sections.

Bag opener: Non-sorted waste is downloaded by the same sorting belt into a bag opening unit, which is 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 of organic and inert material,
- Intermediate components with a high content of recyclable packages,
- Large components or sieving rejects.

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__Figure 25__ Classification in trommel by size to separate lightweight packaging (underflow) from organic matter (fine waste underflow) and bulky waste (overflow). (Source: ECOEMBES, 2021)

Classification in ballistic separator: The stream of intermediate size materials of the trommel (if one is used) or directly from the bag opener (if a trommel is not used) is subsequently subjected to ballistic classification according to size, shape and density, and again separated into three new material streams:

- A stream of heavy-rolling material formed by the majority of the heavy and/or rolling material (mainly packaging for liquids, metal packaging and beverage cartons). This falls down the inclined slope of the ballistic separator.
- A stream of light flat materials (mainly formed of cardboard, paper and other film plastics with a flat or flattened shape). This rises up the inclined plane of the separator.
- A 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. This 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 example, 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, a ballistic separator is not used. The material arriving from the trommel (if one is being used) is taken directly to the sorting cabin, where the operators sort the requested materials.

Figure 26 *Classification using a 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

Primary feeding-dosing: The waste deposited in the reception area is collected with the loading shovel (in the case of an unload yard) or grapple hook (in the case of a pit), then transferred and unloaded into the dosing feeder. This is done at variable speed and with a flow limiter, which is 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 a trommel) and the ballistic separator are subjected to magnetic material sorting before being sent to the rejected waste fraction.

Optical separation: The rolling material stream on this line that has not been selected by either pneumatic aspiration or 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 performance and quality in the sorting of these materials, the magnetic and pneumatic sorting must take place prior to the optical separation.

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In the case of the 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 optical separation is subjected to a sorting of non-magnetic metals (aluminum) by an eddy current separator.

Figure 28 *Induction separators remove aluminum 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 may 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, 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 material type (intermediate storage silos) while 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. aluminum), the production is stored in auxiliary containers for subsequent compaction.

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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), with the exception of metals, and particularly steel, which require different bale sizes and features as well as specific presses.

Rejected waste management at the facility: All rejected waste in the sorting facility is typically concentrated on a single output conveyor belt that discharges it 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 efficient disposal to the landfill site. This can involve several alternative systems:

- Self-compactors,
- Static compactor,
- Rejected waste press,
- Containers (for low-volume facilities).

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

Figure 31 *The rejected waste material at the facility is compacted or stored in containers for delivery to the landfill site. (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 this standard exactly; there are differences among the different plants. The operations in a sorting plant will vary depending on the level of automation at that sorting plant. Some differences that may be found are as follows:

- Some facilities have discharge pits and some facilities have unloading yards as reception areas.
- Treatment lines with discharge pits are fed by grapple hooks.
- Treatment lines with unloading yards are fed by loading shovels.
- Some sorting plants are fitted with trommels.
- The size mesh of the ballistic separator used may vary between 50 and 70 mm.
- Some plants have incorporated optical separation for film.
- There are many different configurations of optical separator chains.
- Induction separation with a different intensity is used for the sorting of beverage carton packaging in some plants.
- Quality control of the selected materials is performed mostly by an operator, but in some cases we can find optical separator quality control.

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Figure 32 *A classification trommel: this divides the material stream into two or more categories according to grain size using specific size sieves. (Source: ECOEMBES, 2021)*

Other European models for sorting-plants

According to the Circular Economy Action Plan (EC, 2020), the Commission will propose to harmonize the (currently separate) waste collection systems across all of Europe. In the future, all requested materials will be harmonized so a European sorting-plan model should be established.

Typical sorting-plant models in Europe involve several similar sorting steps to those presented in the above example from Spain. These include both manual dismantling and sorting by automated processes, separation according to density and size, and optical or magnetic separation. However, the exact processes can vary according to consumer behavior and collection systems. For example, in the Nordic countries, consumer behavior and market availability mean that less beverage carton packaging (Tetra Pak) is used than in Spain, so 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 while requiring 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 used in Greece, Ireland, Malta and Romania.
2. Dual-stream collection: 'fibers' (i.e. paper and cardboard) and 'non-fibers' (i.e. plastic, metal and glass) are collected separately. This is the main collection system in Finland and the UK.

3. Mono-stream collection: each material is collected separately (i.e. paper and cardboard, glass, and lightweight packaging), and treated in an MRF. The Spanish model described above fits into 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: there is no separate collection of recyclables. This leads to high contamination rates and the need for intensive treatment. While the Waste Framework Directive (2008/98/EC) required the 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 a 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, which can then be reintegrated into 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 waste, a circular economy requires suitable technologies, such as chemical recycling (Meys et al., 2020). Chemical recycling turns plastic packaging waste into chemical products, thus removing the need to manufacture these products from fossil-based feedstock in the first place. Consequently, chemical recycling is expected to decrease the demand for the planet's finite fossil resources as well as the emissions of greenhouse gasses (Foundation, E.McA., 2017). At the same time, chemical recycling provides products that are chemically identical to those they replace. In this way, chemical recycling avoids the performance losses currently observed for mechanical recycling of plastic packaging (so-called "downcycling") (Hong and Chen, 2017). When downcycling, products ultimately have to be incinerated or end up in landfills after shorter use cycles.

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However, there is a mismatch between the 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 what 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, thus creating positive economic, environmental, and societal impacts. The four strategic system enablers where technology can accelerate solutions to the waste crisis and serve as a model for broader circular economy initiatives are (Sullivan and 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 r eplace 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% recycled consumer waste by 2020. In addition, hundreds of consumer packaged goods (CPG) companies have made public statements about their goals of achieving 100% recyclable or reusable materials by 2025. However, one of the challenges faced by companies is that their data exists in silos, which makes 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 to enable this through traceability apps and by providing deep insights into citizen sentiment or 'product experience', thus helping brands to better engage with their customers and provide insights into product design based on product needs and shared values.

- **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 the 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 problems resulting from the incorrect management of plastic waste, such as environmental pollution and the generation of micro and nanoplastics found in water, soil and air (that, in turn, 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 and reprocessing of plastic waste 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 to conventional, petroleum-based plastics such as PET or HDPE. Different collection and recycling systems are implemented in different countries. However, the mechanical recycling of bio-based 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 role to play in the market, such as PLA, PHAs or TPS. Non-biodegradable bio-based plastics known as drop-in bioplastics, such as Bio-PE or Bio-PET, which are identical to, and recycled like, petroleum-based PE and PET, 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 Figure 33, the mechanical recycling of plastics basically consists of the collection, sorting, separation and purification of waste (which can include washing steps), and its crushing and reprocessing, usually by melt-compounding (Niaounakis, 2013) The result is recycled plastic with which new products can be made.

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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 high temperatures and shear stresses since some bio-based and biodegradable plastics, such as PLA and PCL, present low melting and glass transition temperatures, making them especially susceptible to thermomechanical degradation (Niaounakis, 2013, Al-Salem, 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 bio-based 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, but it has been reported that FT-NIR led to 98% efficiency in the sorting process (NatureWorks LLC, 2009).

The washing stage plays a key role in the 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 (Firas et al. 2004). In the case of bio-based and biodegradable plastics, since most of them are polyesters (such as PLA and PHAs), they are very susceptible to 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, for 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 decontamination of recycled PET used in food packaging applications. The process consists of 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 bio-based and biodegradable plastics, since some studies with thoroughly washed PLA wastes showed that SSP led to the increase of the intrinsic viscosity of PLA (Beltrán, 2020).

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

Overall, mechanical recycling is a very interesting method for the treatment of plastic waste because it allows for the elimination of 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), even in the case of bio-based plastics (Scaffaro et al. 2019).

It is important to distinguish between post-industrial waste and post-consumer waste. In the first case, unused waste generated in the plastic manufacturing process is collected and reprocessed. In post-consumer recycling, it is waste that is collected after the product is consumed (Niaounakis, 2013, Al-Salem, 2009.)

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). Consequently, 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 a 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, bio-based and biodegradable polymers are especially susceptible to chain-breaking processes (Briassoulis, 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 abovementioned SSP stage (which is frequently used in the mechanical recycling of PET), the plastic is heated for several hours at the appropriate temperature to promote polymerization reactions that counteract degradation (Firas et al, 2004, Cruz and Zanin, 2005).

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2.2.2.3. The current situation in the mechanical recycling of bio-based and biodegradable plastics

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

However, the recycling of post-industrial waste is commonly used in the plastics industry (EREMA, 2020; 2021). In fact, PLA post-industrial waste is currently one of the cases of mechanical recycling of bio-based and biodegradable plastics being applied at the industrial level (Maga et al., 2019).

As was previously stated, bio-based and biodegradable plastics are especially susceptible to degradation during reprocessing at high temperatures. Several studies have reported considerable decreases in the molecular weight of PLA after several reprocessing cycles, as a result of the different degradation processes that take place during melt processing (Badia and Ribes-Greus, 2016). This decrease of the molecular weight comes along with a change in the properties of PLA. For instance, melt-flow index, a parameter crucial for the plastic processing industry, increases after each reprocessing cycle (Żenkiewicz et al., 2009, Carrasco et.al., 2010), which is problematic for the design of processes at the industrial level. The thermal properties of PLA were also affected by reprocessing, which led to an increase in the crystallization ability and a slight decrease in the thermal stability of the materials (Brüster et al., 2018, Agüero et al., 2019). Lastly, it is worth noting that reprocessed materials showed poorer mechanical properties, such as lower tensile strength and stress at break (Żenkiewicz et al., 2009, Pillin et al., 2008).

This data reflects the fact 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, so 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 allowed for in blends with virgin plastic (for example, 20% in the case of many high-consumption grades of PLA), without significantly impairing the properties of the final product.

Regarding the mechanical recycling of post-consumer waste from bio-based 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 yet for this type of plastic.
- There is a special alternative for the treatment of this waste, which does not exist for plastics derived from petroleum. Many varieties of this type of plastic are compostable under the right conditions, for example under industrial conditions. Composting, which is analyzed in another chapter of this document, makes it possible to eliminate the problem of waste, although the possibility of reusing materials is also lost.

- Many people believe that biodegradable plastics decompose and disappear quickly in the environment. So, they believe that the abandonment of their waste is not a major environmental concern. 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 - that is, at around 60 °C, at the right pH, and 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 sea. Furthermore, under these conditions the degradation of these plastics can release potentially toxic additives and generate microplastics like conventional plastics do.
- Some bio-based 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 bio-based 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) recycle their own plastic waste, is gaining a lot of interest with the growth of additive manufacturing technologies (e.g.: 3D printing). This approach could allow the recycling of 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 the transportation of waste is reduced.

The most common example of the distributed recycling approach can be found in the mechanical recycling of 3D printing waste inside a university campus. Some studies have pointed out that it is possible to obtain recycled materials with acceptable properties, although special care has to be paid to the homogeneity of the waste, since waste 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 was pointed out in the previous sections, bio-based and biodegradable plastics are susceptible to a wide variety of degradation agents, which can act during both their service and during mechanical recycling. However, the lack of a separate stream for bio-based and biodegradable plastics, such as PLA, has made it difficult to evaluate the degradation in use and after recycling of real post-consumer samples. Nevertheless, some researchers have simulated, at laboratory scale, the degradation during service and during the recycling of PLA. For instance, accelerated ageing over 7 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 a subsequent decrease in some important properties such as thermal stability (Beltrán et al., 2018).

The degradation of bio-based and biodegradable plastics during service and mechanical recycling, with the consequent decrease in performance that comes with it, could threaten the feasibility of mechanical recycling for these materials. Therefore, in recent years, several cheap and environmentally sound

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methods to upgrade the performance of recycled bio-based and biodegradable plastics have been published. For instance, the use of different additives such as stabilizers, chain extenders or crosslinking agents during extrusion is one of 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., 2019, Cosate de Andrade et al., 2017, Tuna and Ozkoc, 2017). Another approach consists in the improvement of the properties of recycled bio-based and biodegradable plastics by using fillers such as cellulose (Laadila et al. 2017, Laadila et al. 2020), silk fibroin nanoparticles (Beltrán et al., 2020), lignocellulosic nanoparticles (Beltrán et al., 2020) or clays (Beltrán et al., 2018). Lastly, the utilization of solid-state polymerization (SSP) in adequately chosen conditions led to an increase in the molecular weight of recycled PLA samples (Beltrán et al., 2020). 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 which is widely used today, has been specially considered. Many of the issues that have been discussed are common to all biodegradable and bio-based 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 they are characterized by their low thermal stability. They present a melting temperature close to degradation temperature (Arrieta et al., 2017). Thus, they can undergo thermal degradation at processing temperatures (Vu et al. 2019). Regarding mechanical recycling, PHAs undergo significant thermal degradation in the reprocessing stage of the 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 pure PLA and pure PHB (Plavec et al., 2020).

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

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

2.2.2.6. Concluding remarks

The mechanical recycling of plastics is a well-known valorization technique, and is used substantially in commodities such as PET and PE. It allows for a reduction in the amount of waste as well as in the consumption of raw materials and emissions. It is worth noting that mechanical recycling does not come without drawbacks. These include structural and thermal degradation, with the consequent decrease of the overall performance of final recycled plastic products, to which some bio-based and biodegradable plastics (e.g.: PLA and PHAs) are especially susceptible. Nevertheless, it is possible to mitigate these problems using different methods, allowing for recycled materials with acceptable properties.

However, currently 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 it unfeasible to implement conventional and centralized recycling schemes, although distributed recycling could currently provide an alternative suitable for this kind of materials.

2.2.3. Chemical recycling

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

Chemical depolymerisation

Chemical depolymerisation consists of breaking down polymer chains through the use of chemicals. It can also be referred to in the 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 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 (polymerisation 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.

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.

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Table 5 Chemical inputs and outputs of the reaction

Chemical input	Reaction pathway	Monomer output	Other product(s)
Glycol	Glycolysis	bis(2-Hydroxyethyl) 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 currently 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 utilization of **catalysts**, which are chemical compounds that aid the reaction process by helping to increase the rate of the reaction.

The use of these substances, 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 made to assess the **environmental performance** of chemical depolymerisation processes. In general, chemical depolymerisation is still too demanding in terms of energy requirements, and so mechanical recycling is still considered the most favorable technology overall.

However, chemical depolymerisation allows for the addressing of the issue of 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), the following is a summary of the advantages and disadvantages of chemical depolymerisation.

Advantages:

- Monomer outputs can be utilized 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 fiber inputs.

Disadvantages:

- Can currently handle only material inputs that are largely homogeneous 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 solvent types and toxicity 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, stabilizers, impact modifiers, colorants and pigments;
- Non-target polymers; and
- Non-Intentionally Added Substances (NIAS), which are compounds both absorbed and produced within the plastic material during use. This can include secondary products from the manufacturing process, as well as degradation products, both from partial breakdown of the polymer itself and the additives contained within the plastic.

The plastic is shredded and dissolved within a solvent, exhibiting high solubility of the polymer, whereas contaminants have low solubility. Thus, contaminants remain solid and are separated from 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 theoretically be applied to almost any polymer, provided a suitable solvent can be found.

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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
Polyethylene (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 the 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 input.

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 material properties compared with the virgin polymer.

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

Research funded by the Dutch government conducted several studies screening **LCA** studies of chemical recycling technologies with the aim of determining whether they might 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 now have been based on scenarios defining very specific waste stream inputs to ensure successful purification.

According to the report on Chemical Recycling by Hann and Connock (2020) the following is 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 homogeneous in nature.
- Often requires stringent pre-sorting and or pre-treatment steps to prepare for purification.
- Typically necessitates high energy requirements, in particular during the post-purification drying stages.
- Typically cannot remove contaminants entirely.
- Has not been demonstrated to provide food-grade outputs.
- Lack of clarity regarding solvent types and toxicity 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 under **specific environmental conditions**.

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

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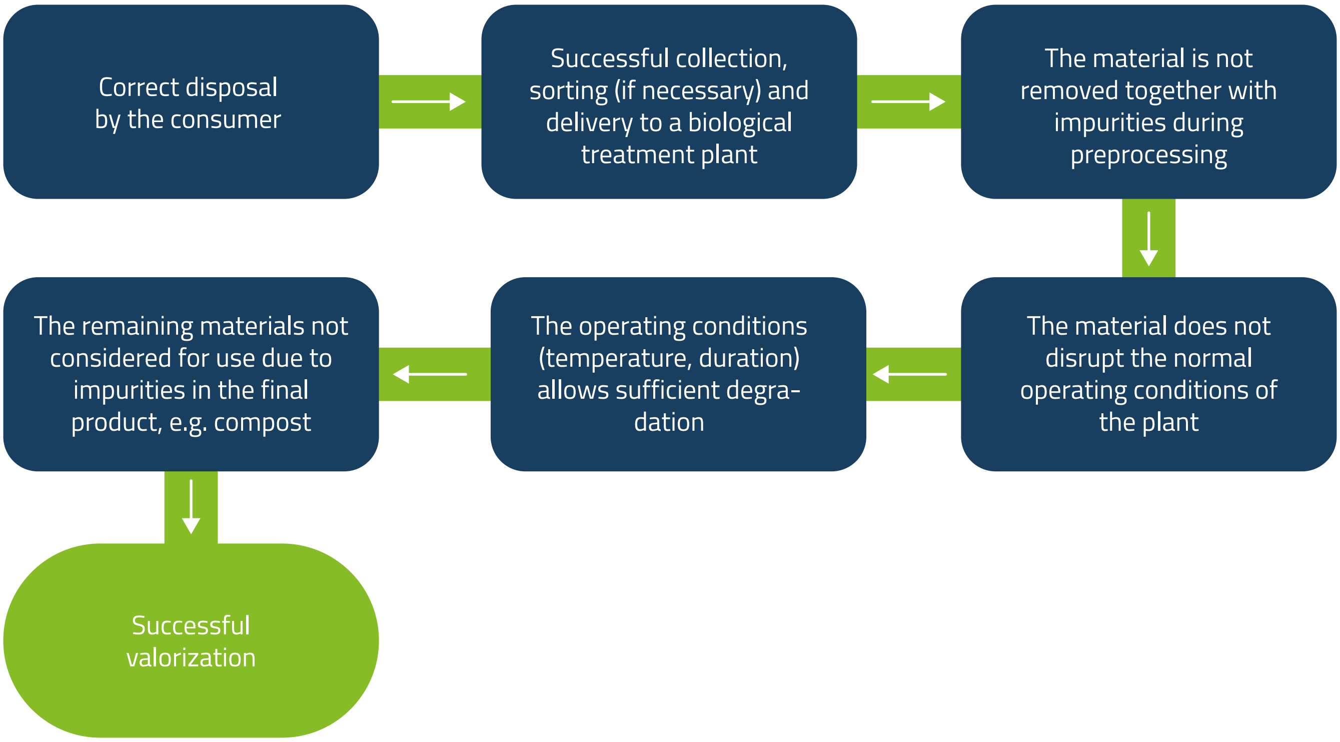

Figure 34 *An example of a possible route of valorizing compostable plastics through biological treatment*

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	Explanation
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 materials to be successfully valorized through the composting or anaerobic digestion route, they should meet the following conditions:

- 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 funneled to the respective facilities,
- The labels on the product guide consumers to dispose of the product in the correct manner,
- The facility has the necessary equipment or process to differentiate and separately process and/or pretreat conventional and biodegradable plastics,
- The product does not pose a problem to 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 an impurity 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 humus-rich compost. Composting can either be done via home composting or industrial composting. The differences in conditions are significant, 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, from 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 degradation requirement states that not more than 10 wt% of the material can remain (>2 mm) after a maximum of 12 weeks. Industrial composting plants treat and sanitize separately collected biowaste and turn it into stable compost, which is then often sold for use on agricultural land. They have a major interest in treating biowaste efficiently and producing high quality compost. Thus, the duration of active composting and maturation can significantly differ from the standard. For example, the active composting time ranges 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). Other components that might be present in biodegradable plastic blends, such as mineral fillers and plasticizers, are re-

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ported to influence the degradation rate (Tolga et al., 2020; Arrieta et al., 2014). Lastly, the longer-term effects of remaining biodegradable plastic particles after composting is still unclear (Folino et al., 2020; Polman et al., 2021).

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 an oxygen free environment. During anaerobic degradation, carbon from bioplastics is consumed by microorganisms and primary 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.

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 a 90-day degradation period (Battista et al., 2021). To assess the anaerobic treatability of bioplastics, harmonized European standard EN 13432 can be used as well. 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 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 has shown significant reduction in the time needed for degradation in comparison with mesophilic conditions. Regarding recent studies, the 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 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 ▪ Co-digestion with food waste or sludge	▪ Not all types of biodegradable plastics are suitable for anaerobic degradation. ▪ Degradation efficiency depends on the type of the polymer, microorganisms and environmental conditions. ▪ Before treatment, bioplastics have to be reduced in size. ▪ Risk of 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 waste, a circular economy requires suitable technologies to be in place. Therefore, innovative recycling and recovery technologies have enormous economic value in transforming post-use and difficult-to-recycle plastic into original building blocks that can be continually reintegrated into supply chains as feedstocks for new plastics and chemicals, or other raw materials for manufacturing.

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The elements of the 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, source separated waste will need to be collected and transported to waste management facilities. After collection, sorting might be carried out to separate different commingled materials. 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 disposed of.

Chemical recycling turns plastic waste into chemical products, which removes the need to manufacture these products from fossil-based feedstock in the first place. Therefore, chemical recycling is expected to decrease demand for the planet's finite fossil fuel resources, as well as the emissions of greenhouse gasses. However, chemical recycling is still in its early stages of development and has not been fully assessed environmentally. This is, therefore, the perfect moment to assess if, and to what extent, the 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 valorization technique, commonly used in commodities such as PET and PE. It allows for the reduction of waste, and also the reduction of the consumption of raw materials and emissions. Structural and thermal degradation are the main drawbacks of mechanical recycling. This affects the overall performance of the final recycled plastic products.

Bio-based and 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 bio-based "drop-in" plastics that are chemically similar to conventional petroleum-based plastics;
- disposed of within 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.

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, for biodegradable plastic materials to be successfully valorized through the composting or anaerobic digestion route, it should meet certain conditions.

The most important barrier to the recycling of post-consumer waste coming from bio-based and biodegradable plastics is their small market size at present. This makes it unfeasible to implement conventional and centralized recycling schemes, although distributed recycling could currently provide a suitable alternative for these kinds of materials. Another problem is that the acceptance of biodegradable plastics in biological treatment plants varies significantly from region to region.

3. Analysis of the legal and policy framework

3.1 Current policy and legislation (plastics vs bio-based and biodegradable plastics)

In response to the Climate Crisis, a number of legislative acts have been adopted around the world. Some of them have been enacted in response to issues or situations that have only recently presented themselves. Meanwhile, others have merely been amendments to acts that were previously adopted, as those acts already covered the main principles under consideration and only some alterations or amendments were needed to meet the demands of increasingly environmentally conscious societies and policy makers. Below is a review of those acts that have been adopted within the fields of plastics, plastic waste, waste management, marking and bio-based plastics, starting with the main pillars of the legislative framework that is shaping EU policy on plastics and plastic waste.

Basel Convention – global legally binding instrument

Adopted on 22 March 1989 in Basel, Switzerland, the Basel Convention is the most comprehensive global environmental treaty yet to be enacted on hazardous and other wastes. It aims at protecting human health and the environment against the adverse effects of hazardous wastes, as defined by their origin and/or composition, as well as their characteristics. This aim is addressed through a number of general provisions that require States to observe the fundamental principles of environmentally sound waste management (Article 4). Parties to the Convention pledge to undertake measures aimed at ensuring that the generation of waste is reduced to a minimum, and that adequate disposal facilities are provided for. The Convention also provides for the establishment of regional or sub-regional centers for training and technology transfers as regards the management of hazardous wastes and other wastes and the minimization of their generation for the purposes of catering to the specific needs of different regions and subregions (Article 14).

Until recently, the Convention's scope did not 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 regards further actions, decision BC-14/13 provides for further immediate measures by the Parties, namely:

- efforts at the domestic level with time bound targets for the minimization/prevention of plastic waste,
- efforts to create new technology and processes to reduce the use of hazardous constituents in

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the production of plastics,

- update to technical guidelines for the identification and environmentally sound management (ESM) of plastic waste and for their disposal,
- establishment of a Partnership on plastic waste whose goal it is to improve and promote the ESM of plastic waste at global, regional and national levels and prevent and minimize their generation, and 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.

The 2030 Agenda for Sustainable Development, adopted by all UN Member States in 2015, sets out 17 Sustainable Development Goals (SDGs). These goals are an urgent call for action to all of the countries in the global partnership. The document recognizes that ending poverty and other deprivations are only part of the picture, and that strategies aimed at tackling climate change are also central to the overall aim. However, for the Agenda to become a reality, a strong commitment to implement the global goals will be needed from all United Nations Member States.

For discussion of the question of plastics, we need to turn to SDG 12, which addresses waste. This particular goal is aimed at ensuring sustainable consumption and production patterns are put in place. Among other undertakings, it aims 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 which included measures aimed at stimulating Europe's transition towards a circular economy, boosting global competitiveness, fostering sustainable economic growth and generating new jobs. Measures foreseen in the Act covered the entire cycle: from production and consumption to waste management. Notably, it also included an implementation timeline. Among the other results of the implementation of the Act is the set of documents passed in 2018 that established a legislative framework for the management and reduction of waste: Directive (EU) 2018/851 on waste, Directive (EU) 2018/852 on packaging and packaging waste, etc. As a result, the following targets were put in place:

- 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 out in the Act have already been achieved, on 11/03/2020 the European Commission adopted a new Circular Economy Plan as part of the European Green Deal.

The new Circular Economy Action provides for measures aimed at making sustainable products the norm in the EU, and focus on those sectors that use most resources and where the potential for circularity is high (including packaging and plastics), thereby ensuring that less waste is produced.

The GREEN DEAL is an integral part of the Commission's strategy for the implementation of the United Nations 2030 Agenda and its sustainable development goals. It provides a roadmap for all actions needed to meet its ambitious goals. "While the circular economy action plan will guide the transition of all sectors, action will be focused in particular on resource-intensive sectors such as textiles, construction, electronics and plastics. The Commission will follow up on the 2018 plastics strategy focusing, amongst 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."

EU Strategy for Plastics In The Circular Economy

The EU Action Plan for the Circular Economy envisages the block's transition to a circular economy, which is one of the EU's major priorities. As it addresses plastics and plastic waste specifically, the 2018 European Strategy for Plastics was introduced as a follow-up to this plan. The strategy for Plastics provides for actions and measures aimed at transforming the way products are designed, produced, used, and recycled in the EU:

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

Current actions by Member States target various plastic products and adopt different approaches. Hence, there is a risk that market fragmentation may result from the implementation of measures that are uncoordinated between Member States and differ in scope. In its communication introducing the Strategy for Plastics, the European Commission emphasized the need for a harmonized approach when it comes to planned legislative measures for plastics and plastic waste that are engaged by regional and national authorities.

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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 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 establishes the legislative framework for waste management. This covers the waste producers' liability, and is aimed at reducing the generation of waste, in particular waste that is not suitable for reuse or recycling, and the setting of recycling targets for municipal (household and similar waste) waste (increase by 55% by 2025 and by 60% by 2030). It foresees that all Member States are required to provide for the separate collection of at least paper, metal, plastic, and glass waste (Article 11), the production of waste management plans and the introduction of 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, and by doing so, 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 so that it is channeled to the most appropriate waste management alternatives.

Under the Directive, each Member State is responsible for establishing databases on packaging and packaging waste that can be harmonized across the block. Member States are also obligated to ensure that consumers are explicitly informed about the return, collection and recovery systems available to them, their role in contributing to the reuse, recovery and recycling of packaging and packaging waste, and the meaning of markings on packaging existing on the market.

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

BIO PLASTICS EUROPE

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

The Directive targets single-use plastic products in particular. The main objective of the Directive is: "to prevent and reduce 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".

The Directive is addressed at single-use plastics in particular as they wield a disproportionate impact on the environment when you compare the short time frame of their usage with their long period of decomposition.

Member States are obliged to prepare a description of the measures they intend to implement 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 the risk of misinterpretation, the Commission committed to publishing guidelines by 3 July 2020 that will include examples of what is to be considered a single-use plastic product within the context of this Directive.

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

Notably, all Member States are required to transpose the requirements under the Directive into their local legislation by 3 July 2021.

EU legislation designed for bio-based plastics

All currently developed and available bio-based plastics have substantially the same properties as conventional plastics. It is in the area of bio-plastic degradability that they supersede their antecedents. It is obvious that, in times when policy makers are aiming to reduce plastic waste, bio-based plastics serve as an environmentally friendly alternative to conventional plastic products (packaging). After all, although the latter is cheap production wise, and convenient to use, it is increasingly becoming more unacceptable within the wider culture to use it due to its lifecycle and adverse impact on the environment.

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

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

- the revised Directive 2008/98/EC on waste allows biodegradable and compostable packaging to be collected together with 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 thus: "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) Through such a definition, the revised Directive acknowledges compostable and biodegradable packaging as a sustainable solution that minimizes the environmental impact of plastic packaging.

3.2 Labeling

Commission decision 12 of 28 January 1997

This 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 9 of the Decision defines numbering and abbreviations (expressed in capital letters) 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

It should be noted that Article 3 of the Decision provides for a voluntary and non-mandatory use of the aforementioned identification on materials and packaging, stating that a decision on 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 that date no such decision on the marking of the packaging had been made.

The provisions of Article 3 conflict 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 that states 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 question of the voluntary use of identification may impede the implementation of effective plastic waste collection and sorting for recycling or reuse purposes – as the identification of such material may be difficult not only for the consumer, but for the sorting facilities also.

It is also worth mentioning that even if the choice is made to mark a bio-based product (packaging) using the abovementioned identification system, it would be marked with the number 7 "Other", thus categorizing it alongside plastics containing Bisphenol A, which have adverse effects on the living.

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

This Regulation provides for another, once again voluntary, marking (labeling) of products. However, this is applicable to those products that meet the requirements set forth therein. It is awarded in cases where the products in question meet high environmental standards throughout their Life-cycle: from raw material extraction, to production, distribution and disposal. The EU Ecolabel works in accordance with the ISO standard 14024.

This Regulation applies 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 the products, taking into account the latest strategic objectives of the Community in the field of the environment. EU Ecolabel criteria is to be determined on a scientific basis that takes into account the entire life cycle of the product. According to the Regulation, each Member State is responsible for designating the body responsible for the product verification process.

Currently the Ecolabel is granted to products only, and does not refer to their packaging. However, given the fact that the criteria include "(a) the most significant environmental impacts, in particular the impact on climate change, the impact on nature and biodiversity, energy and resource consumption, generation

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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

The pivot towards a circular economy in the EU that is set forth in the EU Action Plan for the Circular Economy and the EU Strategy for Plastics clearly indicates the need for reduction in the use of conventional plastic plastic waste and welcomes environmentally friendly alternatives. However, the complexity of the alternative materials, and the concomitant complexity of their recycling and waste management makes the achievement of those goals rather laborious and circuitous. And this lack of clarity extends not only to the producers or entities responsible for waste management, but also to consumers, who have lost track of the variety of alternative plastics on the market, lack knowledge of the meaning of how materials are marked, and are often confused when it comes to sorting of waste.

With a view to remedying these issues, some recommendations for regulatory responses to the identified barriers on the effective use of bio-based plastics and their waste management are listed below.

Lack of legislative framework for bio-based plastics: there is a need for legal regulation, and the harmonization of definitions, terminology and methodologies applied to the identification of bio-based plastics. The distinction between bio-based plastics and other materials must be clearly and definitively established, as this would allow for the creation of tailor made treatment (e.g. production, marking, use, collection, recycling, monitoring, and reporting) by Member States, regional and national authorities, producers, sorting and recycling entities, as well as end consumers. Legislation should outline the latest innovations in materials that are intended to replace conventional plastic, so that equally innovative solutions both in materials and their collection/sorting/waste management systems can be promoted.

The Unclear marking/ labeling of bio-based plastics and products: the lack of a comprehensive and legally binding bio-based plastics (amongst others) identification system (marking) leads to them being treated wrongfully, with the result that they are often wrongly deposited as landfill waste. Therefore, a standardized obligatory marking/labeling system for bio-based plastics should be introduced to help clearly distinguish them from other materials, driving consumer choice for packaging where relevant, and allowing both consumer and sorting/recycling/waste management entities to contribute to plastic waste minimization through the proper management of the bio-based plastics used. Marking/labeling should clearly separate bio-based plastics from other materials, as these can be visually similar, and place stress on bio-based plastics less harmful impact on the 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).

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 up alongside hazardous waste, conventional plastics, or municipal waste. There is a need to standardize waste collection systems and create a harmonized infrastructure for waste collection, which would lead to the effective sorting of bio-based plastic waste. Local and regional authorities have to have a key role to play in the 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 surcharge on product consumption with a rebate that is issued when that product or its packaging is returned (Walls, 2011). The deposit system is applied mainly to different packaging materials, especially beverages, and is a sustainable solution aimed at kickstarting the circular economy in which materials and products are reused or recycled in order to minimize waste.

The deposit-refund system (DRS) works effectively 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 has been delayed indefinitely
- In Switzerland deposits 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 aluminum and steel cans.

There are three typical types of deposit refund schemes that are being utilized:

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Type 1

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

- Retailer buys containers and pays a deposit to the beverage producer
- Customer buys from the retailer and pays a deposit
- Customer returns the 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 producers' organization Eesti Pandipakend (EPP), is responsible for organizing the recycling of packaging marketed by producers, importers and traders. The EPP has been acting under accreditation from the Ministry of the Environment since 2005. The EPP organizes the collection, transportation, sorting, counting and recycling of packaging items for deposit throughout Estonia. For consumers, the packaging deposit refund system means that it is possible to return packaging with EPP special marking everywhere where beverages are sold, or to some nearby collection point. At the moment, around 1260 collection points exist throughout Estonia, of 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 aluminum beverage cans. Some of the bottles are reused, some of the material is recycled. PALPA is one example of a national level sorting system 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 on the packaging encourages consumers to return empty beverage containers to recycling, as by doing so 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. Almost 3 thousand spots were set up nationally where bottle packaging can be returned manually or via reverse vending machines.

The Deposit System Administrator (Užstato sistemos administratorius (USAD)) that is responsible for the deposit system was created in 2015. It is a non-profit organization that acts as a public institution, and is responsible for administrating functions set forth in the Packaging and Packaging Waste Management Act (E-seimas, 2021).

According to the law, Lithuanian beverage producers and importers must collect, manage, sort, and recycle the packaging they supply 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. The deposit system for aluminum cans was begun in 1984 and for Pet bottles 1994.

Recycling Rates in 2019:

- 85.8% total recycling rate, both aluminum cans and PET bottles
- 2.15 billion cans and bottles recycled
- 208 packages per person recycled in Sweden
- 19,870 tons of aluminum
- 23,244 tons of PET material

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

Type 2

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

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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.the 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 closures, while 0.08 € is charged for beer bottles (glass). In addition, the plastic crate in which the reusable bottles are usually sold is also subject to a deposit (1.50 €). The used bottles are collected at participating supermarkets and are transported to the nearest bottler participating in the 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 to the consumer. Moreover, retailers are obligated to accept returned disposable bottles and refund the customer, regardless of where the bottle was sold and regardless of whether the retailer sells the specific brand or type of bottle.

In order to ensure that the required level of compensation is achieved between the participating companies, sophisticated clearing systems such as the German Deposit System GmbH (Deutsche Pfandsystem GmbH (DPG)) have been installed. Although the Einwegpfand is required to be charged for every disposable beverage packaging, some exceptions are permitted 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 the Netherlands. In this type of system, the producers and retailers themselves are required to pay all of the system's operational costs. Producers are responsible for packaging collection and disposal (Calabrese, et al. 2021).

Country examples:

Netherlands

The Dutch term for deposit is statiegeld, and in the Netherlands an automatic collection system for bottles is in place. In this scheme, producers are the owners of the empty containers that are generated, and are responsible for their collection and disposal. Since July 2021 the deposit scheme has expanded to include small plastic bottles with a volume of 1 l or less. A 0.15 EUR deposit is added for a bottle smaller than 1l and 0.25 € for a bottle larger than 1l (Plasteurope, 2020).

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

4.1.2. Pay as you throw and Incentive

Although the Pay-as-you-throw and the Incentive system share some similarities and some differences, they both follow the same citizen-focused principle. In contrast to the Deposit system that looks to admonish citizens that do not recycle, both the Pay-as-you-throw and the Incentive systems look to benefit those citizens that recycle.

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

Broadly speaking we can divide the promotion of recycling into systems that fall collectively under a "carrot-and-stick policy". The deposit system here would be the "stick". While pay-as-you-throw and the incentive systems are the "carrot" option.

The **Pay-as-you-throw system** is based on a "the one who contaminates is the one who pays" approach. Citizens do not pay directly for the waste management of light packaging waste (those costs are paid by the companies through the Extended Producer Responsibility -EPR-).

As part of their municipal taxes for waste, citizens pay for the waste management of Urban Solid Waste. Most countries have an open system where citizens that generate more waste pay the same as those that generate less waste. Thanks to pay-as-you-throw systems, cities are able to avoid this "flat rate" for waste generation. This means in effect that those people who generate more waste (including people that do not separate packaging) pay more than those who generate less (including those that sort the waste at home and don't mix all their waste together inside a RSU generic container).

The Pay-as-you-throw system penalizes the use of an RSU; thus creating the knock on effect of indirectly encouraging the use of packaging containers. The more you sort or recycle at home, the less you pay for your waste.

A Pay-as-you-throw system can be implemented in several ways. One such way is to install a lock on street containers that can only be opened through the use of a citizen card or interactive key. As a result, the city council can then monitor and keep a record of how often a container is used, allowing them to then more accurately bill waste taxes. The most common option, however, is the implementation of prepaid bags. Within municipalities that select such an approach, citizens are only able to use street containers if they have used prepaid bags to collect their waste (tax is included in the price 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 incentivizing the use of packaging containers.

Amongst the incentives offered to citizens who recycle, economic incentives could be offered (including a discount in municipal waste tax). But such incentives need not be purely economic. An example of such

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an approach is the RECICLOS program that has been recently implemented in Spain.

RECICLOS (Spanish Incentive System)

Spain does not have a deposit system. During 2020, the country began implementing the RECICLOS incentive system (RECICLOS, 2020). This reward system was initially introduced 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 the RECICLOS program are non-monetary incentives.

The system is currently in the process of being implemented in selected towns all over Spain and has two distinct parts: a home stream and an out-of-home stream.

Below is an illustration of how the system works for products consumed at home and how it involves the use of existing street located yellow containers:

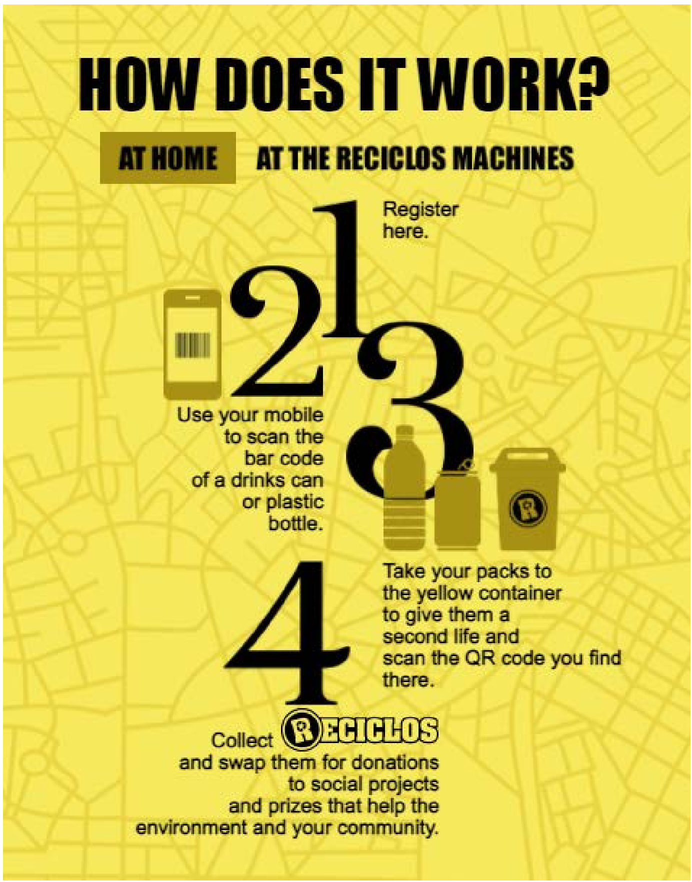

__Figure 35__ Working principle of the RECICLOS system at home (Source: RECICLOS, 2020)

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

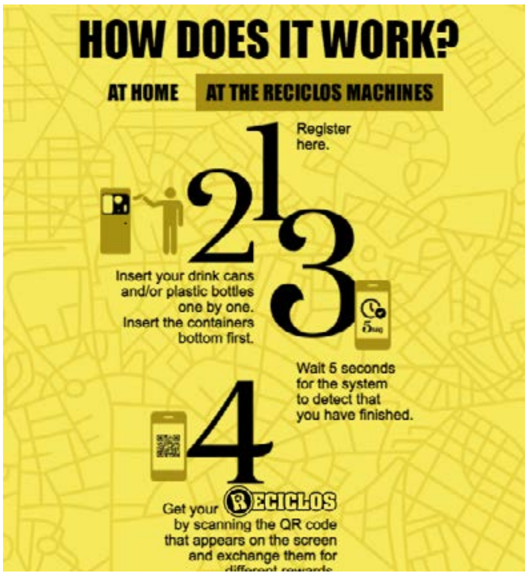

Figure 36 Working principle of the RECICLOS system at the recycle machines (Source: RECICLOS, 2020)

Citizens receive tokens called RECICLOS for all of the packaging they have deposited. The RECICLOS program is designed to promote the environmental, economic and social sustainability of the district and the city. So, all awards are sustainable, environmentally-friendly and beneficial for all participants:

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

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

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

The RECICLOS program encourages recycling and rewards the citizens' efforts in this regard. With RECICLOS, users learn to recycle the waste that is deposited in yellow containers and in vending machines, and people will also receive a RECICLOS token for each beverage can or plastic bottle that is recycled.

Meanwhile, with these RECICLOS, people can take part in draws for organic products or donate their RECICLOS to join in collaborative projects and make initiatives in their municipality or neighborhood a reality.

Prize 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, allowing for a way of conducting draws that is more secure than having a third party verify this process manually.

Using the app, citizens are able to easily locate yellow street containers or reverse vending machines.

In summary, both systems, Pay-as-you-throw and Incentives, encourage citizens to recycle. Both can use the current infrastructures of waste management (without the 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

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

Reusable packaging is designed for reuse in the same or similar application, or for other purposeful packaging uses in supply chains. Such packaging has the durability needed to function properly in its original condition across multiple applications and its lifetime is measured in years. This packaging operates in a system that prevents it from becoming solid waste, replaces single use plastic applications, and the recovery and recycling of the product at its end of life is envisaged in initial product design (Reusable packaging association, 2021).

Because most of the financial benefits of reusable packaging come from circumventing 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)

A typical use case for reusable packaging and fast-moving consumer packaging would be the construction of a holistic system around food packaging wherein the packaging provider supplies tracking by means of different tokens or deposits.

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

Kamupak company: This reusable takeaway container program operates in Finland and uses tokens and kamupak credit. Kamupak offers reusable containers for food takeaway and beverages across a range of food and drink serving locations. Once customers have used Kamupak they can then go to any participating Kamupak provider and either have it replaced for a clean container, receive their deposit back, or receive a token for later use. According to Kamupak, the main environmental impact of their solution comes from the raw materials Kamupak containers are made of – a KamuDish or KamuCup can be used on average around a hundred times. When a KamuDish has reached the end of its life cycle, it is returned to its manufacturer to be recycled as a raw material. By recycling 100% of the material, a considerable amount of new raw material is saved, which significantly reduces environmental impact. Kamu products are made of different kinds of polypropene plastics, and the types of material used are clearly identified 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, which is available free online.

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Figure below adapted from Kamupak (Kamupak, 2021)

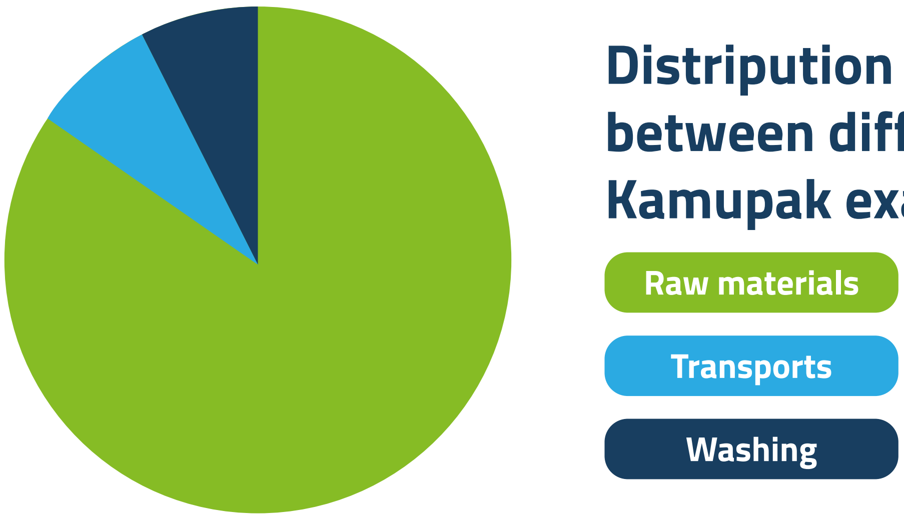

Figure 39 *Distribution of emissions between different functions (Kamupak, 2021)*

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

The "Hamburgs Wertstoff Innovative", Hamburg's Resources Innovative, is an example of a successful collaboration between actors in a plastic value chain in order to implement a regional bottle-to-bottle recycling of HDPE (Hamburgs Wertstoff Innovative, 2019). The HDPE bottle for laundry detergent product, sold in Hamburg, is made up of 100% HDPE recyclates extracted from post-consumer packaging waste from Hamburg. The successful implementation of the product cycle depends on each actor within the local recycling value chain working together and contributing.

The project started in 2019 brings together actors active in Hamburg (see Figure 40):

- 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 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.

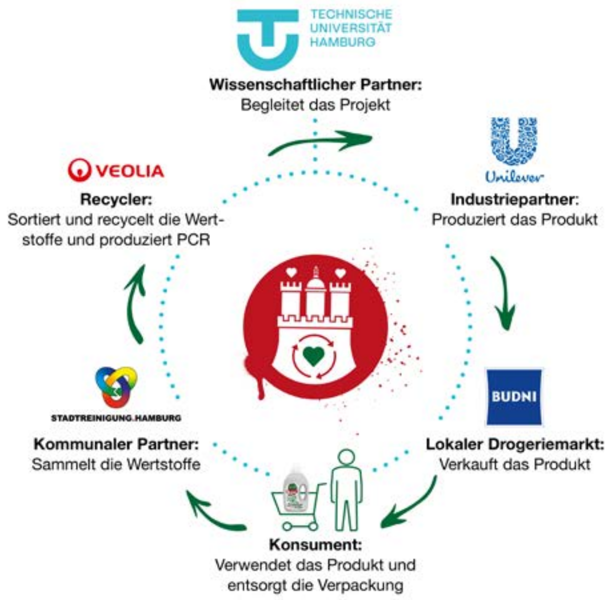

Figure 40 *(Right) Collaboration concept of the project, (Left) Product of the collaboration (Unilever Deutschland Holding GmbH n.d. 2021)*

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 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. It is 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.

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

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Indeed, for more than 20 years, CONAI has served as an effective system for the recovery, recycling and valorisation of steel, aluminum, paper, wood, plastic, and glass packaging materials. From 2020 onwards Biorepack also put in place a recognized system of proper end-of-life management for biodegradable and compostable packaging that is based on the principle of "extended producer responsibility" (EPR). This implies "shared responsibility", which means, in effect, that all players bear responsibility for waste management. This includes every stakeholder, 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. Through these measures, Italian law assigned the CONAI system the task of achieving an overall target for the recycling and recovery of packaging across the whole of Italy, and ensuring that targeted management policies are implemented, including prevention policies, through eco-innovation.

THE CONSORTIUM SYSTEM

Material flows

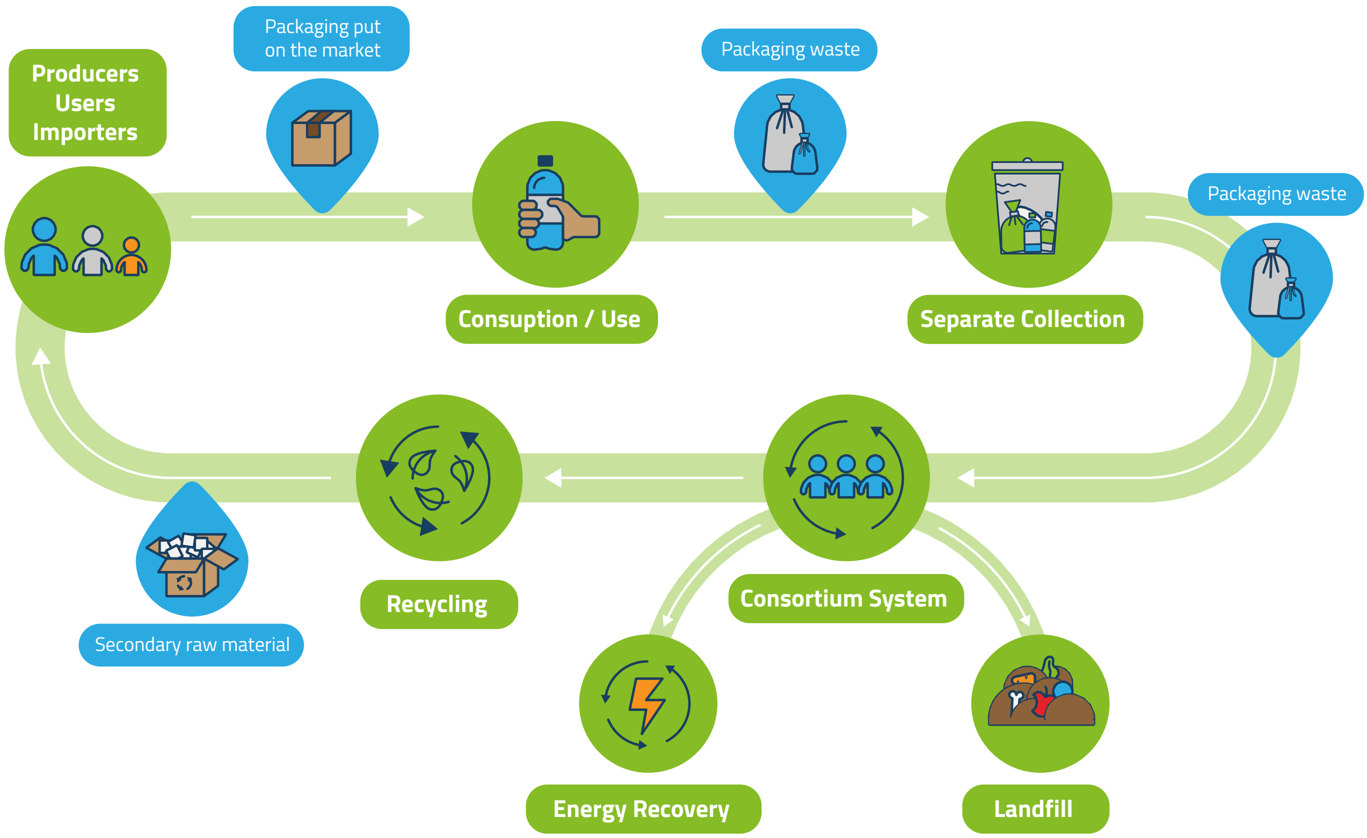

Figure 41 *Consortium system. Material flows (CONAI Sustainability Report, 2021)*

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

THE CONSORTIUM SYSTEM

Economic flows

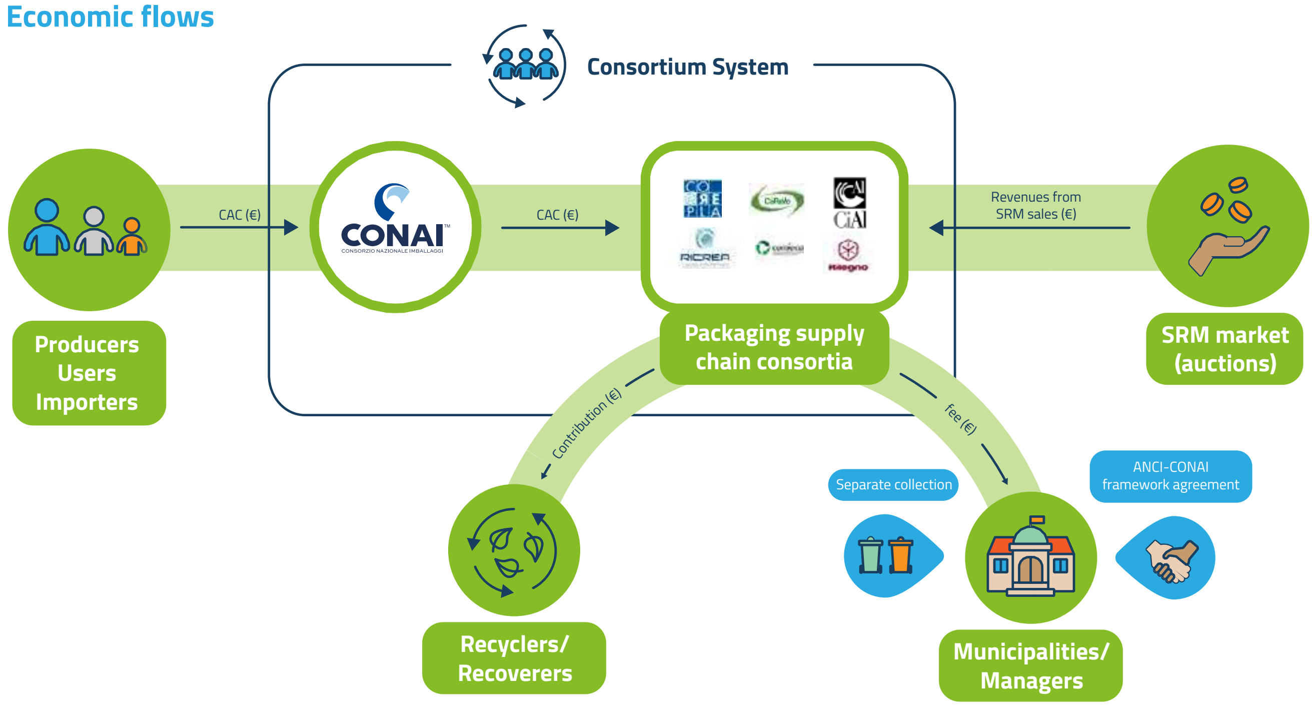

Figure 42 *Consortium system. Economic flows (CONAI Sustainability Report, 2021)*

Biorepack is dedicated to the management of biodegradable and compostable plastic packaging for the purposes of their recycling within the separate collection circuit of the organic fraction of municipal waste. It should be specified that in Italy this type of waste collection has been regulated since 2010 through specific laws that also provide for the use of biodegradable and compostable plastic bags. It should also 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.

Biorepack has only been present in the national waste management context since early 2021 and has been operating in a different "sphere" than other packaging materials. Moreover, it also represents an absolute novelty for the CONAI system. This means it will need to undertake innovative pathways.

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Biorepack shall:

- promote the development of the separate collection of biodegradable and compostable plastic packaging waste and similar fractions within the organic fraction of urban waste;
- 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;
- monitor the release for consumption of biodegradable and compostable plastic packaging and similar fractions;
- 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;
- 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;
- 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 is a truly unique proposition. It is the first European member state to have applied the EPR principle to biodegradable and compostable packaging, as well as the first to have identified a national consortium as the guarantor actor for correct end-of-life management. With Biorepack, packaging manufacturers can ensure that the 'polluter pays' principle is applied to a material that allows for 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 planning surveys to investigate the quality of the organic waste collected.

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

Conventional plastic was for a long time the most common raw material of choice for most plastic injection or plastic products. It had remained that way for many years until the trend of eco-conscious entered into the frame. Now, every company is trying to do whatever it can to be as green or as sustainable as possible.

For instance, Heng Hiap Industries (HHI), a recycling company located in Malaysia, has encountered various requests from its customers over the past few years. Customers from Italy & Japan who had started off with conventional plastic are now seeking solutions to minimize the usage of such materials. Hence, they are now mixing biomass with conventional recycled plastic to produce their end products. From this example, we can see that customers are willingly embracing more bio-based processes. Not only that, customers are willing to be patient during the entire development stage as they now take this issue very seriously.

Once these developments have more time to progress, HHI believes the customer will eliminate the usage of conventional plastic and replace it with bioplastic to produce their products. Eliminating conventional plastic is not an easy decision to make but the journey to this stage has provided overwhelming evidence that recycled plastic is able to perform with the addition of biomass.

Via gradual progress, customers will slowly increase the % of material to be replaced, with the end result being that the customer will then move on to bioplastic for their products. The entire journey is, of course, not straightforward and will be completed within a few years time. Nonetheless, will and desire are very high as shown by HIH's customers during the development stages, and this makes the entire journey even more interesting.

4.5 Highlights

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

The countries concerned apply waste prevention measures based on their responsibility for the product they produce or import. These measures are based on the idea that waste prevention is organized effectively when producers and importers are responsible for the management of the waste they generate. This sense of responsibility then promotes the pursuit of responsible product design aimed at increasing 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) a 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; a 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.); and the proper involvement of governments, municipalities and waste management operators and other stakeholders throughout the system.

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