Report No. 504

Sustainable, Biodegradable, Compostable and Recyclable Plastics for Packaging and End-of-life Management

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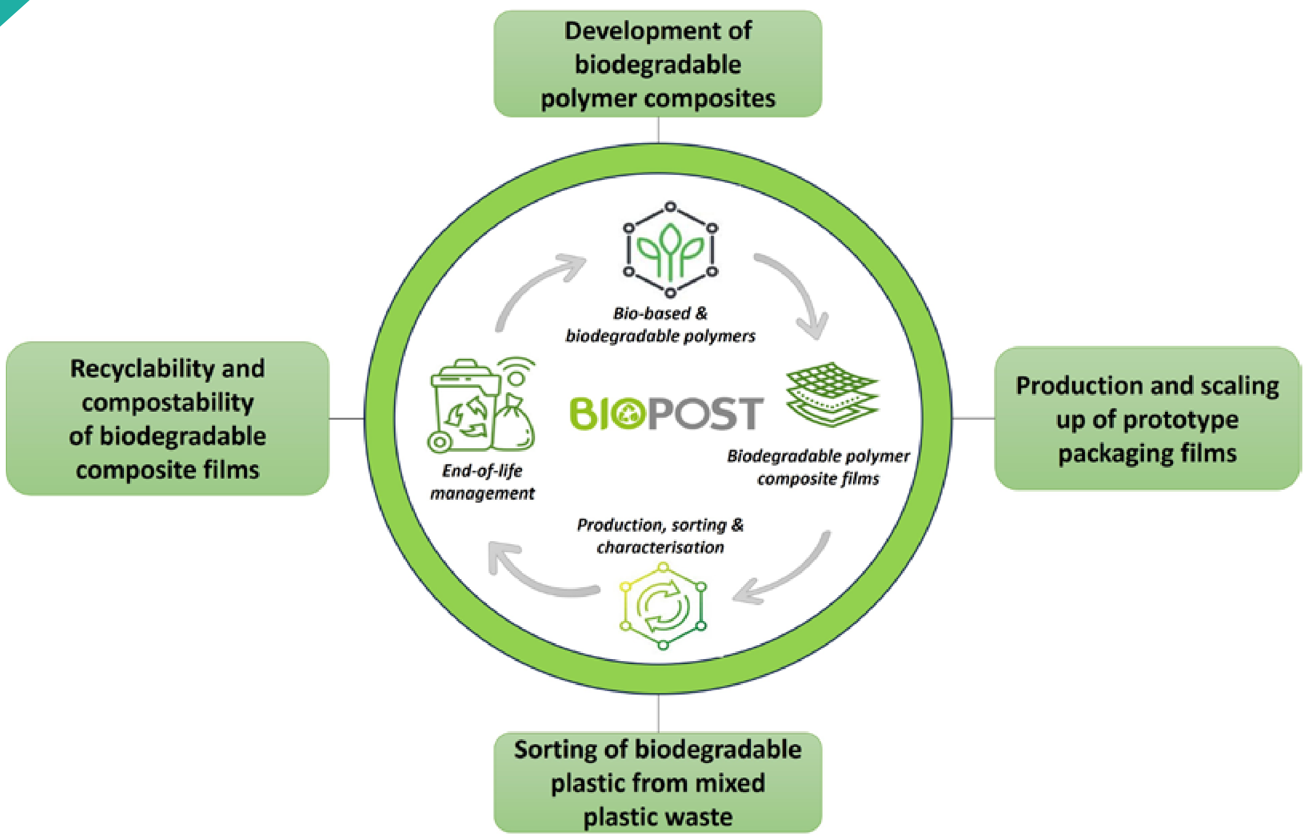
Lead organisations: Trinity College Dublin, University College Dublin and Cré Composting and Anaerobic Digestion Association Ireland



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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

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2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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What did this research aim to address?

Plastics cause significant pollution and environmental concerns. To meet the 55% recycling target for plastic packaging by 2030, sustainable alternatives like bioplastics and improved recycling systems are essential. In Ireland, plastic waste accounted for nearly 25% of total packaging waste in 2023, yet less than one-third of this waste was recycled. Bioplastics are emerging as promising sustainable alternatives, and the global production is projected to grow from less than 1% to 20% in 5 years. Therefore, developing robust waste management and recycling infrastructure will be essential to comply with the EU's new packaging and packaging waste regulations. This project focused on creating biodegradable plastic prototypes based on commercial biodegradable polymers, testing sorting systems and exploring sustainable recycling options on a pilot scale. This project aimed to demonstrate a sustainable ecosystem for biodegradable plastic prototypes. Key objectives included producing biodegradable composites and blends using commercial and natural polymers. In addition, the project involved conducting pilot studies to evaluate the feasibility of separating biodegradable plastic waste from mixed plastics using current or enhanced sorting systems, and to explore sustainable recycling options.

What did this research find?

The BioPOST project conducted pilot-scale trials to assess the segregation of biodegradable plastic packaging films from mixed waste using optical sorting technology in Irish recycling plants, achieving a segregation rate of 60–90%. It evaluated 60 blends of biodegradable polymers for biodegradation under Irish industrial composting conditions and selected formulations for mechanical recycling. Key findings include the following:

- Segregated prototype biodegradable plastics were suitable for mechanical recycling.
- Most tested blends, except those containing polybutylene succinate, were fully compostable in Irish industrial composting processes.
- Ireland currently lacks infrastructure for effective segregation and recovery of bioplastics, hindering recycling efforts.
- Establishing systems for labelling, collection, segregation and recycling in line with the EU Packaging and Packaging Waste Regulation is essential for promoting bioplastic circularity and sustainability.

Therefore, it is crucial to establish a system for the labelling, collection, segregation, recycling and disposal of biodegradable plastics in accordance with the new Packaging and Packaging Waste Regulation. The collection and segregation infrastructure is vital for promoting the circularity of bioplastics, especially biodegradable types, to ensure the benefits of compostability and sustainable recycling and recovery options.

How can the research findings be used?

The BioPOST project has demonstrated the feasibility of producing, sorting and recycling biodegradable plastic composites under Irish conditions. To implement these findings, the focus should shift to scaling segregation trials, retrofitting material recovery facilities and improving collection systems to separate biodegradable plastics from conventional plastics. The research supports Ireland's Climate Action Plan and the EU's circular economy goals by promoting closed-loop plastic waste management through recycling and composting, reducing environmental impacts.

The findings are relevant to policymakers, waste management authorities and industry stakeholders, offering guidance for developing the Packaging and Packaging Waste Regulation and setting standards for biodegradable plastic products. By 2030, all packaging must be recyclable or designated for composting. Key challenges include scalability, economic viability, and consumer behaviour and waste segregation. Emerging opportunities lie in chemical and enzymatic recycling, and in leveraging compost as a value-added product in the agricultural sector. It is envisaged that continued collaboration across research, industry and policy will be vital to ensure bioplastics contribute effectively to Ireland's transition to a circular economy.

Project code: 2019-RE-LS-4

EPA RESEARCH PROGRAMME 2021–2030

Sustainable, Biodegradable, Compostable and Recyclable Plastics for Packaging and End-of-life Management

(2019-RE-LS-4)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Trinity College Dublin, University College Dublin and Cré – Composting and Anaerobic Digestion Association of Ireland

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ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2021–2030. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment, Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research. This project was also co-funded by the Department of Agriculture, Food and the Marine.

The authors would like to acknowledge the members of the project steering committee, namely Professor Yvonne Van der Meer (Maastricht University, the Netherlands), Joe Reilly (EPA), Tony Quinn (Department of Agriculture, Food and the Marine) and Vivienne Ahern (Department of the Environment, Climate and Communications); and Oonagh Monahan (EPA Research).

DISCLAIMER

This report is based on research carried out/data from 2019 to 2024. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2021–2030
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-80009-330-0 January 2026

Price: Free Online version

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Executive Summary

Plastic waste generation is a global problem that contributes to severe ecological pollution and climate change. With effective management of plastic waste, greenhouse gas emissions related to plastic production and end-of-life management can be significantly reduced. Extensive reliance on fossil fuel-based plastics puts significant pressure on the available fossil fuel resources, and the non-biodegradable nature of this plastic waste creates major challenges, including ecosystem damage, marine pollution and climate change. Plastic waste in Ireland represented nearly 30% of total packaging waste in 2021 and the recycling rate for plastic is falling behind rising plastic waste generation, standing at less than one-third of generated plastic waste.[1] Hence, it is crucial for Ireland to address the growing plastic waste crisis by developing sustainable plastic alternatives to foster its climate action plan and circular economy.

The Sustainable, Biodegradable, Compostable and Recyclable Plastics for Packaging and End-of-life Management (BioPOST) project demonstrates a regenerative model by offering biodegradable, recyclable and compostable bioplastic composites that have the potential to enhance the sustainability of Ireland's plastic packaging and waste management system. The research framework of BioPOST involves the typical life cycle of plastic products, starting from sourcing suitable biodegradable polymers, processing them into prototype products and assessing end-of-life management, such as sorting, recycling and composting, to evaluate the entire value chain of biodegradable composites and its environmental impacts. During the course of the project, the team engaged with a broad range of stakeholders through online meetings and an end-of-project dissemination event.

The key milestones of the BioPOST project and their respective outcomes include the following:

- This project developed and investigated the processing of biodegradable polymer blends using commercial and laboratory-made polymers such as polylactic acid (PLA), polybutylene succinate (PBS), polyhydroxybutyrate (PHB) and polyhydroxyoctanoate (PHO). These blends, technically called biodegradable polymer composites, have shown superior elongation properties and demonstrated scalability and capability to be produced and processed into prototype packaging films and products.
- Upon determining the mechanical and thermal properties crucial for packaging films, it has been found that the melt blending of PHO and PHB with PLA, a brittle polymer with high mechanical strength, exhibited improved elongation. PHO offered enhanced compatibility with the PBS and polycaprolactone (PCL) blend compared with virgin PCL, and this was evident from the improved elongation rate and tensile strength (holding capacity) of PBS-PCL composites, which are key desirable attributes of packaging films.
- Effective segregation and recycling of materials is crucial for integrating biodegradable plastic products into the circular economy. The development of efficient collection and sorting mechanisms has become a significant challenge, affecting the end-of-life management of biodegradable plastic waste owing to its current low volume ($<1\%$). Hence, a commercial sorting system on a pilot scale was utilised to understand the detectability of various biodegradable polymer composites and blends produced through the BioPOST project. Interestingly, the sorting efficiency of all biodegradable polymer composites ranged from 60% to 90%, and the highest efficiency, of 90%, was observed for PLA and PLA-based blends. This suggests the feasibility of automatic detection and sorting of biodegradable plastic products with the current waste segregation infrastructure. Further trials with real-world biodegradable plastic products are

1 EPA (Environmental Protection Agency), 2023. Waste packaging statistics for Ireland. Available online: https://www.epa.ie/our-services/monitoring--assessment/waste/national-waste-statistics/packaging/ (accessed 14 March 2025).

required to understand segregation efficiency in commercial settings.

- Mechanical recycling is a closed-loop recycling approach and includes steps such as sorting, washing, grinding and compounding to produce recycled biodegradable polymer composites and facilitate biodegradable plastic economy value chains. All segregated BioPOST prototype products were found to be suitable for mechanical recycling. However, recycled films exhibit inferior mechanical properties, necessitating the addition of 10–20% of virgin polymers to compensate for the mechanical properties.
- Biodegradable composites can decompose in industrial composting processes, resulting in finished compost with numerous benefits, such as improving soil quality, replacing conventional fertiliser products and fixing carbon dioxide emissions through soil sequestration. Our study has demonstrated that blends based on commercial biodegradable polymers, such as PLA, PCL, PHB and PHO, are compostable under Irish industrial composting conditions. However, composites and blends containing PBS failed disintegration tests in industrial composting conditions, despite PBS being certified for both home and industrial composting, as per EU standard EN 13432.
- A preliminary life cycle impact assessment study of biodegradable polymer composite film production and end-of-life management has identified global warming and ecotoxicity as the primary environmental concerns. Mechanical recycling exhibited relatively lower environmental impacts compared with industrial composting, highlighting the circularity potential of post-consumer bioplastic waste. However, composting accounts for lower impacts in terms of key performance indicators of the resource efficiency parameters, such as fossil fuel depletion, water consumption and land use categories. It is worth noting that, compared with mechanical recycling, composting was associated with lower environmental impacts when accounting for carbon credits from the application of finished compost and biogenic carbon as a renewable source for feedstock production.

1 Introduction

1.1 Plastic Waste and the Environment

Plastic, a material known for its versatility of applications and mass production capabilities, plays an indispensable role in our modern society. Conversely, plastic can have severe detrimental effects on the environmental and ecological balance in terms of resource extraction from fossil fuels, incorrigible contact with the food chain and pollution. These plastic materials exist in the technical half of the circular economy as they are made from fossil-based resources, and are not biodegradable but are recyclable (Pandey *et al.*, 2023). Despite the latter characteristic, plastic recycling rates have been stubbornly low for decades and sit at less than 12% globally (Geyer *et al.*, 2017). The fate of today's plastic typically involves disposal, incineration and landfill. This results in effects such as (1) ecosystem damage, (2) leakage of degradation products into oceans, and (3) greenhouse gas emissions. Plastic packaging waste is emerging as a major concern for Ireland, and therefore it is critical to reduce single-use plastic waste, as per the waste hierarchy, and increase the recycling rate to meet the recycling target of 60% by 2030. Ireland must tackle the growing plastic waste crisis and develop alternative sustainable plastics to minimise the damage to citizens' health and the environment (Singh and Sharma, 2016).

1.2 Biodegradable Plastics

Bioplastics produced from renewable resources (biomass, corn, sugar cane, etc.) can offer a sustainable option for the development of economically and ecologically attractive materials. Bioplastics are broadly divided into two categories: bio-based plastics and biodegradable plastics. Bio-based plastics are fully or partially made from renewable resources and are not necessarily biodegradable or compostable. However, biodegradable plastics can be produced from either fossil-based or renewable resources and can offer complete biological degradability, a reduction in the volume of waste and compostability when they are managed appropriately (Song *et al.*, 2009). Commercially available biodegradable polymers like thermoplastic starch, polyhydroxyalkanoates (PHAs), polylactic acid (PLA) and polycaprolactone (PCL) can be biodegraded completely into biomass, carbon dioxide and water by means of microbial activity (Dalton *et al.*, 2022). Switching from conventional fossil-based plastics to sustainable, biodegradable ones, where appropriate, will minimise plastic waste disposal and reduce waste problems. The annual market report of European Bioplastics has predicted that the global production capacity of bioplastics will rise at a considerable pace, from around 2.18 million tonnes in 2023 to 7.43 million tonnes in 2028 (European Bioplastics, 2023). Figure 1.1 shows the global production of bioplastics. The term "biodegradable plastic" is used to refer to a plastic that is biodegradable, while "bioplastic" refers to any plastic produced from biomass, either biodegradable or non-biodegradable (Cakmak, 2024).

1.3 Challenges with Biodegradable Plastics

Although the current production level of biodegradable polymers is low, when considering packaging, 31% of current fossil-based products can be replaced by biodegradable polymer products (Havstad, 2020). However, introducing new biodegradable polymers as a one-to-one replacement for fossil-based polymers is an enormous challenge. This is mainly due to the restricted applications for, and cost of, emerging biodegradable polymers. Most biodegradable polymers have excellent properties when compared with fossil-based plastics. However, some of their properties, such as a low heat distortion temperature, insufficient mechanical properties, high gas permeability and low melt viscosity for further processing, restrict the use of biodegradable polymers for a wide range of applications (Filiciotto and Rothenberg, 2021). One approach to solving this problem is the nano-reinforcement of pristine polymers to prepare nanocomposites and blend them with other bio-based materials, which has already been proven to be an effective way to improve these properties (Yu and Flury, 2024). Under the EU's Single-use Plastics Directive (Directive (EU) 2019/904), biodegradable

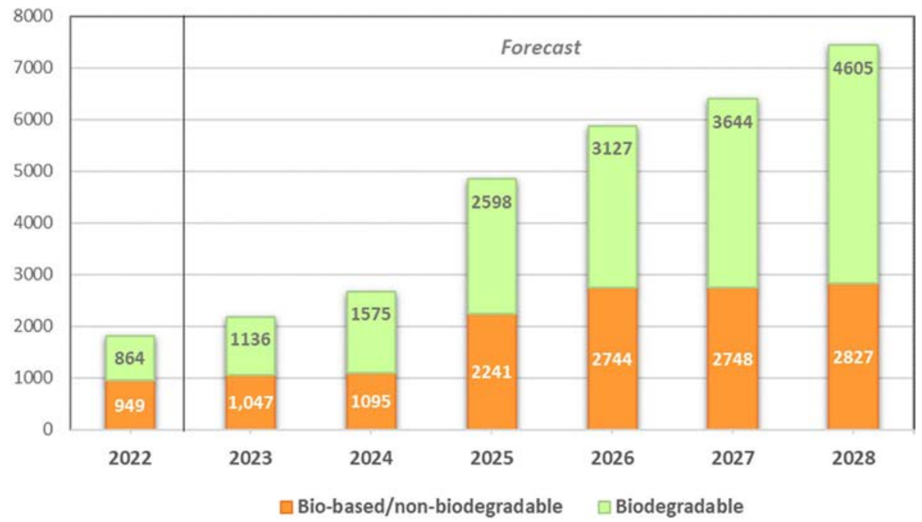

Figure 1.1. Global production capacities of bioplastics, 2022–2028 (in 1000 tonnes). Source: European Bioplastics (2023).

and bio-based plastics are classified as plastics, as there are no accredited technical standards to certify the complete biodegradability of plastics in the marine environment within a short time frame and without causing environmental harm.

Given the rapid pace of research and development in the area of bioplastics, a review of the Single-use Plastics Directive in 2027 will include an evaluation of the scientific and technical progress regarding standards for marine biodegradability. As part of the EU's new Circular Economy Action Plan (European Commission, 2020), a policy framework is being developed to assess the criteria for biodegradable and compostable plastic applications and their benefits to the environment (European Commission, 2024).

1.4 Sorting of Biodegradable Plastics

Currently, there are no commercial segregation systems in Ireland that separate biodegradable and non-biodegradable plastic waste. General plastic waste across Europe contains only 0.5–1.0% biodegradable plastics (European Bioplastics, 2023), which are mainly made of PLA, polyhydroxybutyrate (PHB), polybutylene succinate (PBS) and thermoplastic starch, depending on the region. Biodegradable plastics are designed for treatment in industrial composting plants. If they enter mechanical recycling streams due to misthrows, they can be sorted using current near-infrared technologies. Studies from around Europe carried out under real-life operating conditions in recycling plants confirm that mandatory separate collection for post-consumer biodegradable plastic waste is necessary to improve the recycling of biodegradable plastics (Moshood *et al.*, 2022). As the demand for biodegradable plastic products continues to grow, more and more products based on biodegradable polymers will enter the market. Currently, there are significant gaps between the demand, production and supply of biodegradable polymers (Havstad, 2020). However, the recent EU Biotech and Biomanufacturing Initiative, the EU Bioeconomy Strategy, the European Green Deal and other EU initiatives will accelerate a rapid increase in biodegradable polymer production in the EU. Developing an efficient infrastructure for sorting, collecting and recycling biodegradable polymers is critical to prioritising the use of biodegradable polymers to establish a circular value chain for biodegradable plastic products (Kawashima *et al.*, 2019).

1.5 End-of-life Options for Biodegradable Plastics

The waste management practices for biodegradable plastics can be expanded for reuse; mechanical, organic and chemical recycling; energy recovery; anaerobic digestion; and composting to renewable resources, provided that separate segregation systems are available for biodegradable plastic products (Gioia *et al.*, 2021). These options lead to closed-loop approaches for biodegradable plastic economy value chains (Figure 1.2). However, an issue that impacts the end-of-life processing of all plastics revolves around the efficiency of collection and separation of plastics for recycling (Arijeniwa *et al*., 2024).

Plastic processors require large quantities of recycled plastics for mechanical recycling. While the recycling of PLA is a well-established industrial process (Galactic have developed commercial recycling facilities), at this stage fossil-based plastics and biodegradable plastics cannot be recycled together and must be separated with current separation systems (Dalton *et al*., 2022). Given the low volumes of bioplastics on the market, the diversity of sources of waste and the high potential for contamination of plastic waste (due to the variety of plastics used), recycling can be challenging (Fredi and Dorigato, 2021).

Composting is another alternative for end-of-life disposal of biodegradable plastics. Biodegradable polymers produced by fermentation commonly undergo degradation far more easily than fossil-based plastics. PLA is considered biodegradable, although it is largely resistant to attack by microorganisms in soil or sewage under ambient conditions and needs controlled conditions to biodegrade (Gioia *et al*., 2021, Griffin-LaHue *et al*., 2022). There are currently more than 10 industrial composting facilities in Ireland. These facilities can process the segregated biodegradable plastic waste and produce compost that can be reused for the re-fertilisation of land.

Anaerobic digestion is a natural process of decomposition and decay that takes place in the absence of oxygen and by which organic matter is broken down into simpler chemical components. The digestion process produces biogas, comprised largely of methane (60%) and carbon dioxide (40%), and a “digested material”. The combination of biodegradable plastic waste with industrial sludge forms a good feedstock for anaerobic digestion, providing renewable energy with higher yields.

1.6 Objectives

The objective of the BioPOST project was to explore and understand the ecosystem for biodegradable plastic products and their role in a sustainable circular plastic economy to reduce the adverse effects of plastic waste on our environment. The BioPOST project followed the typical life cycle of plastic products, starting with sourcing the biodegradable polymers, processing them into prototype products and assessing end-of-life management, such as sorting, recycling and reusing, and performed preliminary life cycle analysis (LCA) on the full value chain to understand the infrastructure required to manage the

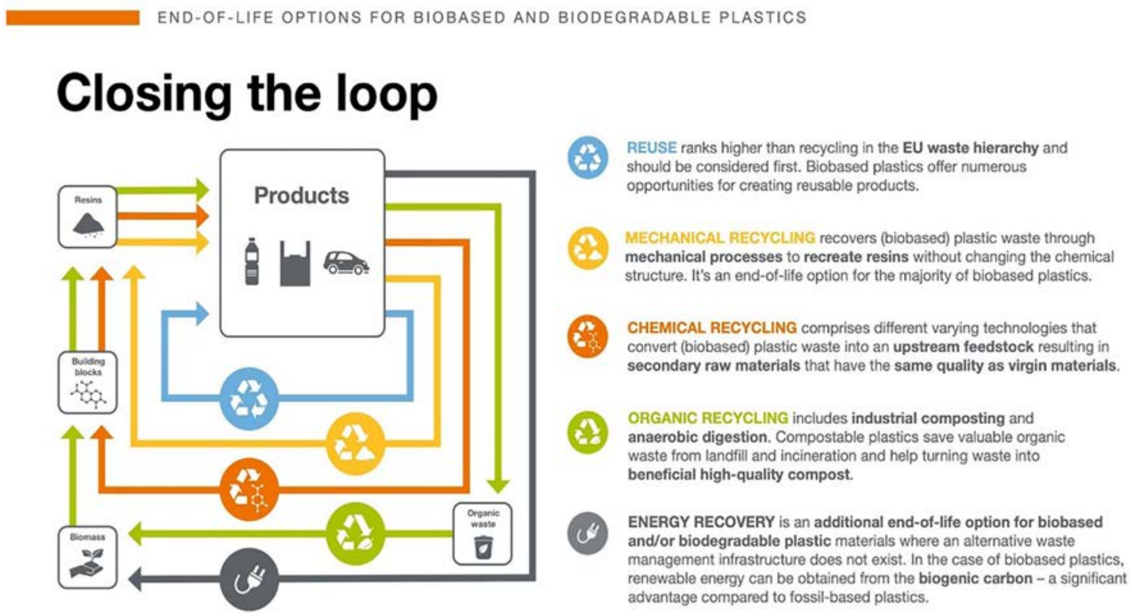

Figure 1.2. End-of-life options for bio-based and biodegradable plastics. Source: European Bioplastics (2023).

biodegradable plastic waste sustainably. The main objectives of the project were as follows:

- Produce branched PHAs from renewable biomass to blend with commercial biodegradable polymers.
- Identify and formulate biodegradable polymer composites and blends based on commercial biodegradable polymers using conventional melt processing.
- Optimise biodegradable polymer composites, blends and nanocomposites suitable for the production of prototype packaging films.
- Produce and characterise selected biodegradable composites on pilot-scale extrusion (20–50 kg), to produce prototype packaging films.
- Evaluate the recyclability of commercial biodegradable products (based on PLA, PBS, thermoplastic starch, blends of biodegradable polymers) and their mixtures obtained through the mechanical recycling process.
- Characterise the mechanical, thermal and barrier properties of recycled composites.
- Perform an LCA and evaluation of the biodegradability of virgin and recycled composites under industrial composting, in anaerobic conditions.

2 Production of Biodegradable Polymers

2.1 Materials

2.1.1 Commercial biodegradable polymers and additives

Different types of commercially available biodegradable polymers were sourced to produce an array of prototype biodegradable packaging films. In addition, three different types of indigenous medium-chain-length PHAs were produced by University College Dublin from different feedstocks to make the blends, along with commercial biodegradable polymers. Due to variation in the feedstock, the resultant PHAs differ in their properties. Table 2.1 presents the details of the polymers evaluated for the BioPOST project.

Different types of commercial additives were used to improve the mechanical properties of the biodegradable polymer composites and blends. Table 2.2 presents the details of the additives.

2.1.2 Production of polyhydroxyalkanoates

In order to optimise the bioprocess for the production of PHA and PHB, 250 mL flask fermentation experiments were carried out with bacterial strains *Pseudomonas putida* (KT2440) and *Burkholderia sacchari* with a 50 mL working volume, using glucose and sodium octanoate, respectively, as their carbon source. The cells were then harvested and lyophilised and solvent extracted for gas chromatography analysis to determine the percentage PHA. Based on the preliminary experimental data, PHA-producing bacterial strains *P. putida* (KT2440) and *B. sacchari* were grown in a 5 L Sartorius Biostat fermenter with a 3 L working volume using octanoic acid and glucose as a carbon source. Fermentations were fed-batch and carried out at 30°C, pH 7, over a period of 29–30 hours. The cells were then harvested and lyophilised and solvent extracted for gas chromatography analysis to obtain percentage PHA.

Table 2.1. List of polymers used in the BioPOST project

Polymer	Trade name	Supplier
PLA	Ingeo 4043D	NatureWorks
PCL	CAPA 6500	Perstorp
PHA	Nodax	Danimer Scientific
PHB	Biomer P226	Biomer
PBS	BioPBS FZ91PB	PTT MCC Biochem
Cellulose acetate esters	ACI 002	NaturePlast
PHO		UCD
oaPHA		UCD
HWCO PHA		UCD

HWCO, hydrolysed waste cooking oil; oaPHA, oleic acid polyhydroxyalkanoate; PHO, polyhydroxyoctanoate; UCD, University College Dublin.

Table 2.2. Additives used for making the composites

Chemical name	Trade name	Supplier
Mg LDH	Hydrotalcite	Prolabin&Tefarm
Zn LDH	Hydrotalcite	Prolabin&Tefarm
$CaCO_3$	Omya Smartfill 55-OM	Omya
Microcrystalline cellulose	Avicel Ph-101	Sigma-Aldrich
Lignin		Merck

$CaCO_3$, calcium carbonate; LDH, layered double hydroxide; Mg, magnesium; Zn, zinc.

Table 2.3 presents the percentage PHA, along with results such as cell dry weight (CDW) and monomer composition, and Figure 2.1 shows the timeline of the CDW (g/L) and the percentage PHA (% CDW) for the 5 L fermentation with *P. putida* (KT2440).

Optimisation of PHA and PHB production in the 5 L fermentations continued, with the addition of oleic acid and hydrolysed waste cooking oil as substrates with *P. putida* (KT2440). The cells produced from these fermentations were harvested and lyophilised for gas chromatography analysis to determine the percentage PHA/PHB (Loan *et al*., 2022). Fermentations were fed-batch and carried out at 30°C, pH 7, over a period of 28–30 hours. Once the cells were analysed and polymer accumulation was deemed sufficient, they were solvent extracted, evaporated, dried and underwent material property analysis. They were ultimately used in polymer blends along with commercial biodegradable polymers for packaging prototypes. Table 2.4 presents the strain, substrates, medium and amount of polymer produced during the 5 L fermentation experiments.

PHA produced using bacterial strains was harvested and lyophilised, and solvent extracted using acetone. The extracted sample was purified by repeated precipitation and dried in a fume hood at 21°C, followed by final drying in a 50°C incubator. Figure 2.2 shows the cells harvested (freeze-dried), solvent extracted (drying at 21°C) and sample post 50°C drying.

The dried samples were characterised for their thermal, chemical and molecular properties. Table 2.5 presents the properties of PHA samples produced using various carbon sources.

Based on the initial characterisation of various PHA samples, PHA polymer produced with octanoic acid as a carbon source was found to be more suitable for blending with commercial biodegradable polymers. The fermentations were scaled up using a 20 L fermenter with *P. putida* (KT2440) and octanoic acid as a carbon source, and 5 kg of PHA polymer was produced. Figure 2.3 shows the fermentation timelines of biomass accumulation (CDW g/L) and PHA accumulation (% CDW) via gas chromatography analysis for a 20 L fermentation.

Table 2.3. Results summary – 5 L fermentations for *P. putida* (KT2440)

Experiment date	Strain	Substrate	Medium	CDW (g/L)	PHA (% CDW)	PHA (g/L)	Monomer composition (No. carbons)
22/10/2020	KT2440	Octanoic acid	MSM	76.2	73.1	55.7	C6, C8, C10
29/10/2020	KT2440	Octanoic acid	MSM	71.9	65.6	47.2	C6, C8, C10
19/11/2020	KT2440	Octanoic acid	MSM	64.7	57.6	37.3	C6, C8, C10
25/11/2020	KT2440	Octanoic acid	MSM	64.9	52.7	34.2	C6, C8, C10

MSM, mineral salt medium.

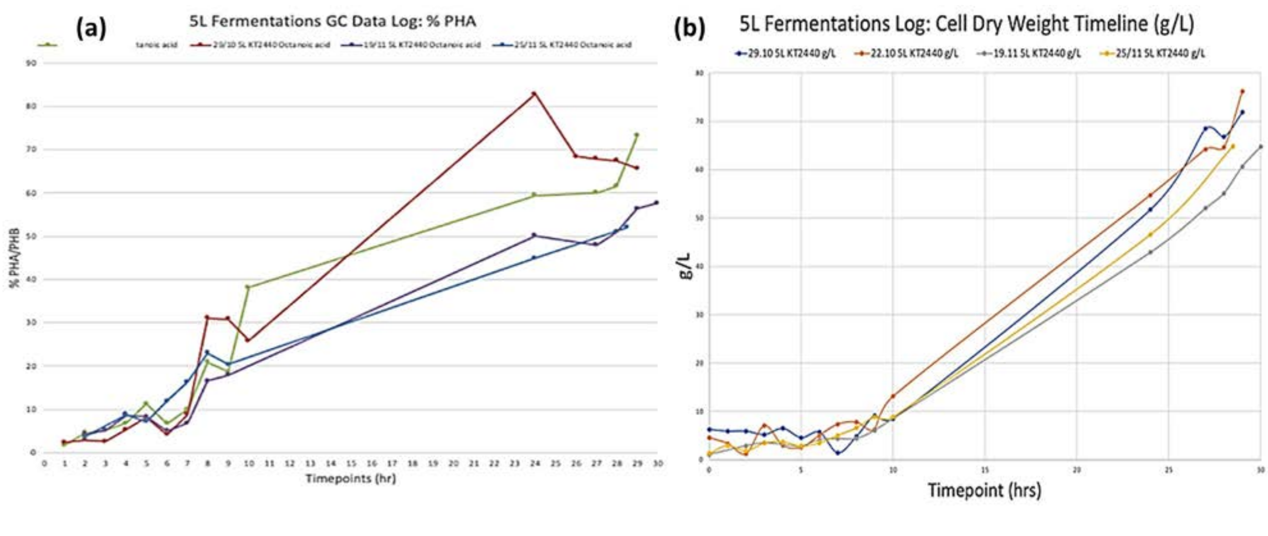

Figure 2.1. 5 L *P. putida* (KT2440) fermentations – (a) percentage PHA and (b) CDW timeline.

Table 2.4. Results summary – 5 L fermentations of *B. sacchari* on glucose and *P. putida* (KT2440) on oleic acid and hydrolysed waste cooking oil

Experiment date	Fermenter size/working volume	Strain	Substrate	Medium	CDW (g/L)	PHA (% CDW)	PHA (g/L)
04/02/2021	5/3 L	*B. sacchari*	700 g/L glucose	MSM + yeast extract	46.0	22.9	10.5
11/02/2021	5/3 L	*B. sacchari*	700 g/L glucose	MSM + yeast extract	52.0	19.3	10.0
18/02/2021	5/3 L	*B. sacchari*	700 g/L glucose	MSM + yeast extract	47.0	18.2	8.6
03/03/2021	5/3 L	*B. sacchari*	700 g/L glucose	MSM + yeast extract	55.4	19.0	10.5
25/03/2021	5/3 L	*P. putida* KT2440	Oleic acid	MSM	85.0	25.0	21.3
08/04/2021	5/3 L	*P. putida* KT2440	Oleic acid	MSM	97.6	34.0	33.2
29/04/2021	5/3 L	*P. putida* KT2440	Oleic acid	MSM	81.0	34.0	27.5
06/05/2021	5/3 L	*P. putida* KT2440	Oleic acid	MSM	87.9	26.0	22.9
13/05/2021	5/3 L	*P. putida* KT2440	HWCO	MSM	95.9	26.0	24.9
20/05/2021	5/3 L	*P. putida* KT2440	HWCO	MSM	91.1	23.4	21.3

HWCO, hydrolysed waste cooking oil; MSM, mineral salt medium.

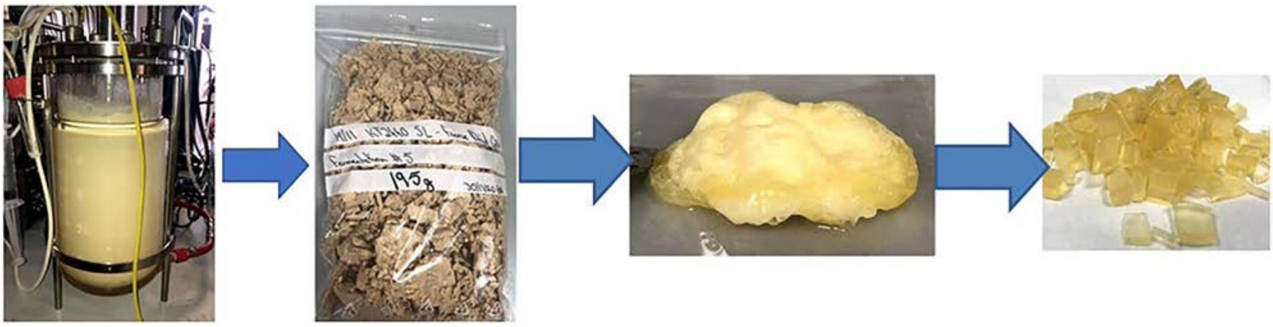

Figure 2.2. Freeze-dried cells, solvent extracted PHA mid-drying at 21°C, and PHA sample post 50°C drying.

Table 2.5. Comparative thermal characteristics of different PHA polymers

PHA type supplied by UCD	Physical property	Glass transition temperature (°C)	Melting temperature (°C)	Crystallisation temperature (°C)	Onset degradation temperature (°C)
PHO	Solid, bit sticky at RT	–37.0	50.0		283.0
Oleic acid PHA	Sticky liquid at RT	–49.0	48.0		180.3
PHB	Soft solid at RT	–40.0	54.0	73.0	272.5
HWCO PHA	Sticky liquid at RT	–48.0	35.0		175.0

HWCO, hydrolysed waste cooking oil; PHO, polyhydroxyoctanoate; RT, room temperature; UCD, University College Dublin.

2.2 Methods

2.2.1 *Production of biodegradable polymer composites*

Polymer composites were prepared via conventional melt processing using a laboratory-scale Brabender mixer to develop optimised formulations for prototype packaging films. All the polymers were dried under a vacuum at 40–80°C overnight (depending on the polymer type) before processing in the Brabender. The polymer samples (40 g) were processed with a rotor speed of 50 rpm for 10 min. The melt-processed samples were compressed and moulded into rectangular specimens with a thickness of 0.1 mm under specified pressure conditions for further characterisation. Based on the preliminary characterisation, selected composites were produced using a pilot-scale twin-screw extruder.

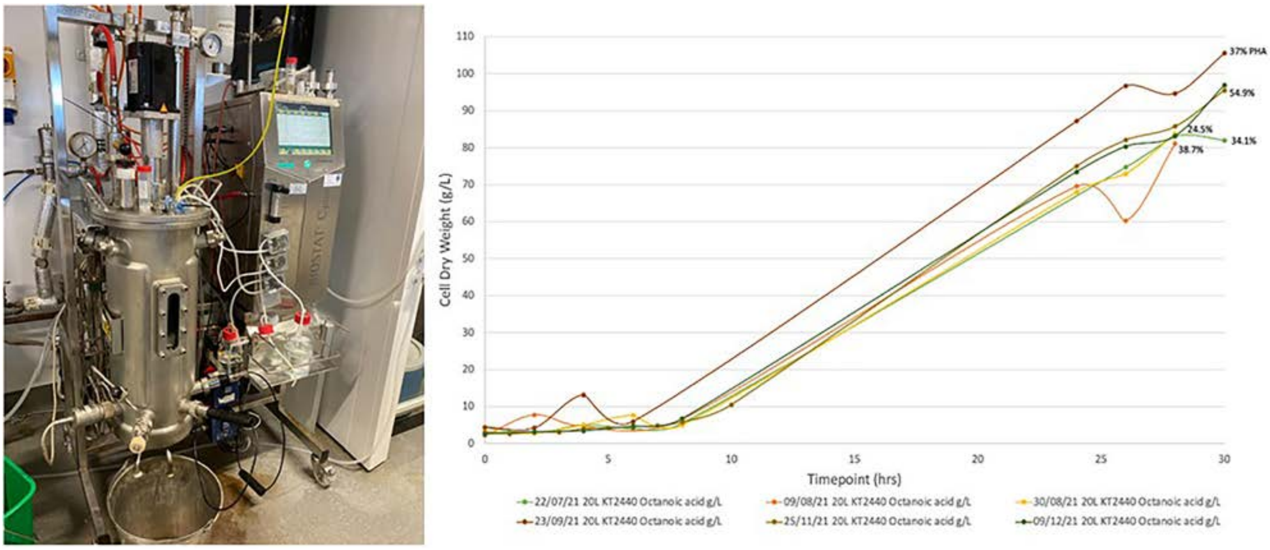

Figure 2.3. Biomass accumulation (g/L) and PHA purity (percentage PHA/CDW) over 20 L fermentations with *P. putida* (KT2440) on octanoic acid.

Figure 2.4 shows the Barbender mixer, pilot-scale twin-screw extruder and compression press used for the preparation of the composites.

2.3 Analytical Methods

Tensile measurements were carried out using a Zwick twin-column tensile tester with a 2.5 kN load cell. The tensile tests were carried out at room temperature and at a cross-head speed of 50 mm/min. Young's modulus, ultimate tensile strength, breaking strength, elongation at break and toughness values were calculated by integrating the stress–strain data obtained from the samples. The glass transition temperature and melting temperature of polymers and biodegradable plastics were analysed using a PerkinElmer Pyris Diamond calorimeter calibrated to indium standards. The samples were sealed in aluminium pans and heated from −70°C to +200°C at a rate of 10°C/min.

A PerkinElmer TGA 4000 thermogravimetric analyser was used to carry out the thermal stability of the samples in the range of temperature (25–700°C), at a scanning rate of 10°C/min, keeping up an inert atmosphere of nitrogen (at 30 mL/min flow rate). The Fourier transform infrared spectroscopy (FTIR) spectra of the prepared composites were recorded on a Nicolet FTIR spectrophotometer (Impact-410,

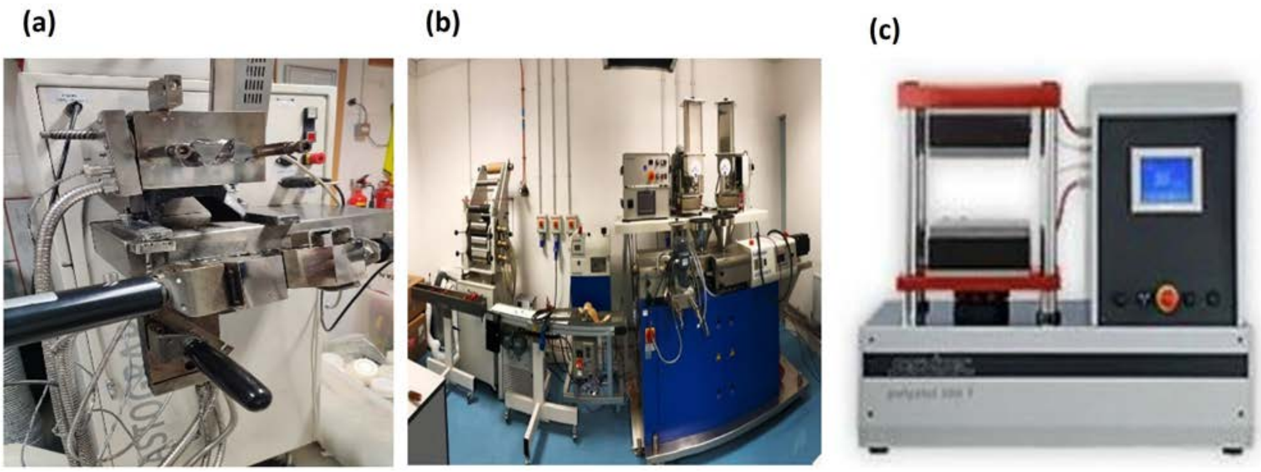

Figure 2.4. Processing of polymer composites using (a) a laboratory-scale Brabender, (b) a twin-screw extruder and (c) a compression press used for characterisation.

Madison, WI, USA). The cross-section scanning electron microscopy morphology of the composites was imaged with the help of a field emission scanning electron microscope (Zeiss Ultra Scanning Electron Microscope). Samples for cross-sectional imaging were prepared by fracturing the films under liquid nitrogen. The films were coated with gold palladium sputtering to impart conductivity and visualise the blended segments better. For scanning electron microscopy analysis, an accelerating voltage between 3 kV and 5 kV was fixed with a secondary electron detector to capture images.

3 Processing and Scaling Up of Biodegradable Polymer Composites

3.1 Production of Biodegradable Polymer Composites and Blends

Polymer composites were prepared via melt processing using a laboratory-scale Brabender mixer. The melt-processed samples were compression moulded to rectangular specimens with 150–200 µm thicknesses using a Servitec Polystat 200 T compression press for further analysis and characterisation. The compressed samples are characterised by thermal and mechanical properties.

Figure 3.1 shows the samples obtained from melt processing and the compression-moulded sheets for various polymers. Table 3.1 shows the thermal analysis data for various polymers extracted from differential scanning calorimetry (DSC) analysis. From DSC analysis, PLA, PCL and PHB polymers show melting points at high temperatures in the range of 150–167°C. PCL and polyhydroxyoctanoate (PHO) having low glass transition temperatures could be

Samples	Pellet drying	Melt processing condition	Images	Compression moulding conditions	Images
Ingeo 4043D	70°C, under vacuum, 4 hours	180°C, 50rpm, 9 min		180°C, 10 bar- 2 mins; 100 bar-30 sec; 200 bar-30 sec	
Luminy L130	70°C, under vacuum, 4 hours	180°C, 50rpm, 10 min		180°C, 10 bar- 2 mins; 100 bar-30 sec; 200 bar-30 sec	
CAPA 6500	45°C, under vacuum, 4 hours	110°C, 50rpm, 5 min		110°C, 10 bar- 2 mins; 100 bar-30 sec; 200 bar-30 sec	
BIO PBS FZ71PB	70°C, under vacuum, 4 hours	185°C, 50rpm, 9 min		150°C, 10 bar- 2 mins; 100 bar-30 sec; 200 bar-30 sec	
Nodax™	55°C, under vacuum, 2 hours	180°C, 50rpm, 5 min		180°C, 10 bar- 2 mins; 100 bar-30 sec; 200 bar-30 sec	
Biomer P226	60°C, under vacuum, 2 hours	180°C, 50rpm, 6 min		180°C, 10 bar- 2 mins; 100 bar-30 sec; 200 bar-30 sec	

Figure 3.1. Digital images of samples of melt-mixed and compression-moulded sheets of various polymers.

Table 3.1. Thermal properties of commercial biodegradable polymers extracted from DSC analysis

Polymer	Glass transition temperature (°C)	Crystallisation temperature (°C)	Melting point (°C)	Melting enthalpy (ΔHf) (J/g)
PLA	60.6	125.3	150.3	23.7
PCL	–58.4	32.2	57.5	51.9
Nodax PHA	61.0	101.0	167.0	19.8
PHB	31.8	109.7	51.2, 168.9	69.8
BioPBS	57.8	85.3	49.5, 113.3	56.6
PHO	–36.7		50.0	20.6

Two melting point values are given for PHB and BioPBS due to unknown additives in the commercial polymers.

advantageous for packaging materials stored at low temperatures.

Table 3.2 presents the mechanical properties of the individual biodegradable polymers. PLA and PHB are brittle in nature; however, PLA is stronger than all other polymers, as indicated by its higher ultimate tensile strength. Furthermore, both PHA and PHB have shown similar mechanical properties. PCL is a highly flexible material that is very tough compared with other polymers.

Over 80 composites/blends were developed based on commercial biodegradable polymers, additives and proprietary polymers produced by University College Dublin during the course of the project. All the composites were characterised for their thermal, chemical and mechanical properties to develop the most suitable composites for film applications. The polymers and polymer blends were selected based on their mechanical properties and processed using a pilot-scale twin-screw extruder to produce the prototype films. Prototype films were also produced using various bio-based pigments (Figure 3.2).

Polymer blends and composites prepared with various combinations were evaluated for their mechanical and thermal properties (Table 3.3).

The PBS-PCL-PHO blend shows reduced ultimate tensile strength, whereas elongation at break has significantly improved. However, the PBS-PCL blend did not show any change in the elongation break when compared with virgin PBS. This may indicate that PBS is slightly more compatible with PHO than with PCL. The addition of PHO to the PBS-PCL blend resulted in significant improvement in the elongation, and the resultant tensile toughness also increased. PLA is a brittle polymer with high mechanical strength. Blending PHO and PHB with the PLA matrix improved the elongation. In fact, it is much more advantageous to add PHB along with PHO to increase the elongation properties. These blends show selectively improved mechanical properties, especially elongation properties, which is one of the requirements for making packaging films. Further studies are required to optimise the blend compositions to produce the blends with specific mechanical, thermal and barrier properties needed to develop packaging films.

3.2 Scaling of Biodegradable Polymer Composites at Industrial Facilities

To assess the scalability and processability of biodegradable polymer composites and blends,

Table 3.2. Mechanical properties of commercial biodegradable polymers

Sample code	UTS (MPa)	Young's modulus (GPa)	Elongation at break (%)	Toughness (kJ/m³)
PLA	71.60	1.60	6.40	20.60
PCL	15.40	0.18	650.00	62.85
Nodax PHA	26.20	0.59	12.80	20.20
PHB	21.30	0.45	13.40	18.70
BioPBS	31.60	0.24	203.10	47.20
PHO	9.88	0.13	361.40	21.90

UTS, ultimate tensile strength.

Figure 3.2. Films developed using different bio-based pigments.

Table 3.3. Mechanical data of samples extracted from tensile stress–strain graph

Polymer/polymer blend	UTS (MPa)	Young's modulus (GPa)	Elongation at break (%)	Toughness (kJ/m^3)
PBS-PHO	34.05±5.09	0.36±0.02	297.80±80.66	58.71
PBS-PCL	31.59±0.26	0.33±0.05	202.70±35.48	51.34
PBS-PCL-PHO	36.44±2.88	0.31±0.03	390.30±34.66	91.78
PLA-PHO	44.64±1.17	1.24±0.09	16.31±4.73	23.74
PLA-PHB-PHO	34.46±1.93	1.04±0.13	16.76±6.04	24.98

HBP, hyperbranched polymer; UTS, ultimate tensile strength.

selected blend formulations, namely PBS, PLA, PBS-PCL-PHO, PLA-PHB-PHO, PLA-PCL-lignin and PLA-PCL-microcrystalline cellulose blends, were produced at 20–50 kg scale in an industrial environment using a commercial twin-screw extruder (Figure 3.3) at Innovative Polymer Compounds (IPC). The blends have shown similar mechanical properties.

From the processing at IPC, it was evident that those polymer blend formulations optimised at the laboratory scale can also be produced in larger amounts and are scalable, and that the novel blends that were developed can be manufactured in an industrial environment.

3.3 Production of Packaging Films on a Pilot Scale

Packaging films based on biodegradable polymers are sustainable alternatives that can help to address the problems associated with conventional plastic packaging. Biodegradable packaging can undergo decomposition into non-toxic products in controlled environments. The blends that were scaled at IPC were processed into prototype films using a pilot-scale twin-screw extruder at AIMPLAS in Valencia, Spain (Figure 3.4). Most were suitable for producing films with a thickness of 100–125 µm. However, there were some difficulties in producing films from those blends based on PCL and PHO.

Figure 3.3. Scaling up utilising twin-screw extruders for biocomposites at IPC.

3.4 Sorting of Biodegradable Polymer Composites

Efficient identification and sorting of biodegradable plastic products from mixed plastic waste is required to foster the mechanisms conducive to sustainable end-of-life management, such as mechanical recycling, chemical recycling and composting, that promote the circular economy. To understand the detection of biodegradable polymer composites and blends developed in the BioPOST project using commercial sorting systems, polymer film samples

Figure 3.4. Packaging films produced on a pilot scale.

Figure 3.5. Sorting of biodegradable plastics at TOMRA.

produced from different biodegradable polymers, composites and blends were sent to TOMRA in Germany. TOMRA is a world-leading equipment supplier of industrial plastic waste segregation machines that are used in many materials recovery facilities. The AUTOSORT multifunctional sorting system, consisting of sophisticated near-infrared and visible light spectrometer-based sensors with high optical resolution, was used to detect the BioPOST composites (Figure 3.5).

The initial evaluation indicated that the composites and blends developed in the project are detectable by conventional plastic sorting equipment. However, sorting efficiency depends on different factors, such as prototype layout, sorting task, sorting settings and input materials' quality specifications. Based on the preliminary experiments at TOMRA, the sorting of BioPOST films from mixed plastic waste was carried out at AIMPLAS using a pilot-scale PICVISA optical sorting machine (https://picvisa.com/optical-sorting/). Dynamic sorting was performed by mixing 1 kg of BioPOST film samples with 4 kg of mixed plastic waste collected from municipal solid waste and using the standard machine settings for sorting biodegradable plastics. In all five sorting runs performed using different BioPOST samples, the sorting efficiency ranged from 60% to 90%, depending on the type of polymer and polymer blend. The sorting efficiency of PLA and PLA-based blends was close to 90%. However, the sorting efficiency of blends based on PBS, PCL and PHO was lower. Several factors could affect sorting efficiency, such as shape, thickness, size and colour of the materials, which need to be evaluated to understand the sorting efficiency using real-time plastic products.

4 End-of-life Management

Biodegradable polymers offer a broader spectrum of end-of-life options than fossil fuel-based polymers, as the former enables waste prevention through reuse, recycling (mechanical, chemical, upcycling) and recovery (composting, anaerobic digestion) and are designed for disposal (degradation in soil and water) and disposal processes (landfill and incineration) (Figure 4.1). According to the waste hierarchy principle, the sustainability of the options can be ranked as recycling > recovery > designed for disposal > disposal.

4.1 Mechanical Recycling of Biodegradable Plastics

Mechanical recycling involves the physical processing of waste materials to reclaim valuable resources for reuse (Maris *et al*., 2018). In the case of biodegradable composites, mechanical recycling typically begins with collecting and sorting discarded items, such as packaging materials, agricultural waste or bioplastic products. Once collected, the materials undergo a series of mechanical processes to break them down into smaller components that can then be reprocessed into new products (Rujnić-Sokele and Pilipović, 2017). Mechanical recycling offers several advantages for biodegradable composites. It helps to divert waste from landfills or incineration, reducing environmental pollution and conserving valuable resources (Schyns and Shaver, 2021). Moreover, mechanical recycling can be more energy efficient than other recycling methods, such as chemical or thermal processes (Kumar *et al*., 2023). Additionally, mechanical recycling enables the preservation of the inherent biodegradability of the materials, ensuring that the recycled products retain their eco-friendly characteristics.

The BioPOST samples PLA, PLA-PCL, PLA-PHB-PHO and PBS-PCL-PHO recovered from the sorting process were used to mimic the mechanical recycling process in the laboratory. The film samples were cut into flakes smaller than 5 mm and washed with a 1 wt% sodium hydroxide solution, followed by a 0.3 wt% TERGITOL soap solution at 80°C. The recovered flakes were rinsed with fresh water and dried at room temperature followed by vacuum drying at 80°C. The dried samples were processed using a Brabender mixer to evaluate the thermal, chemical and mechanical properties of mechanically recycled samples.

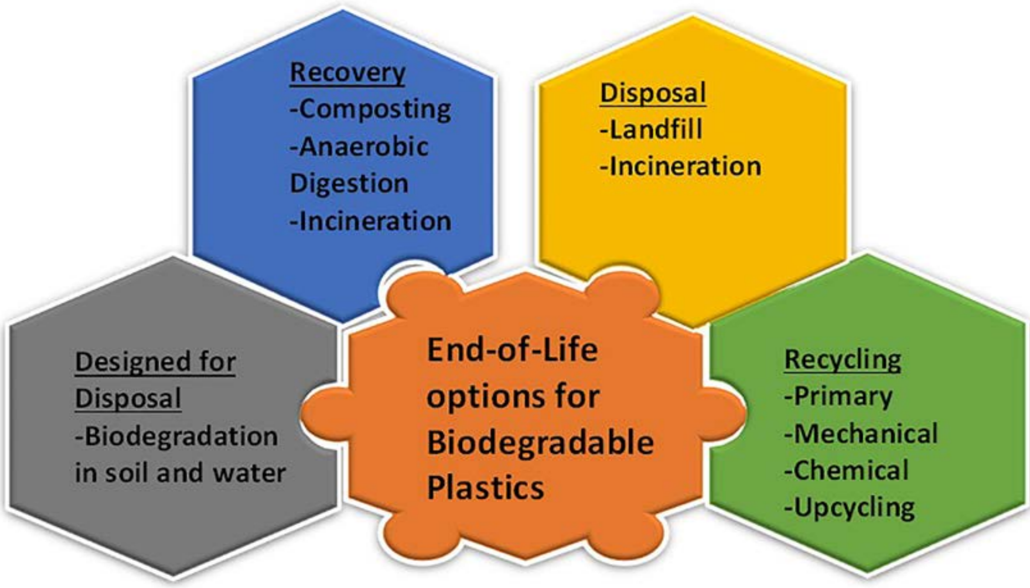

Figure 4.1. End-of-life options for biodegradable plastics.

As shown in Table 4.1, thermal analysis (DSC and thermogravimetric analysis) of composites made from mechanically recycled polymers showed moderately decreased thermal stability in terms of their glass transition temperature, melting point, crystallisation temperature and onset temperature. FTIR analysis indicated no change in a polymer's chemical structure after reprocessing of mechanically recycled polymers.

The mechanical properties are important for assessing the reusability of recycled biodegradable polymer materials. Table 4.2 shows the mechanical properties of the mechanically recycled BioPOST samples.

These results suggest that mechanical recycling significantly affects the mechanical properties of biodegradable composites. The mechanical properties decreased from 30% to 50% depending upon the type of polymer and blend composition. The decrease in the mechanical properties is mainly due to mechanical shearing and thermal hydrolysis during the recycling process (Kumar *et al.*, 2023).

In order to retain the mechanical properties of the mechanically recycled composites, we evaluated the addition of virgin polymers, which is a standard approach for producing recycled-grade polymers. Depending on the composition of the blend, 10% of the virgin polymer was added to recycled BioPOST samples and reprocessed on a laboratory-scale Brabender mixer to evaluate the mechanical properties. Table 4.3 shows the mechanical properties of the reprocessed composites. In the case of PLA and PLA-PHB-PHO blends, the mechanical properties were regained with the addition of 10% virgin polymer.

4.2 Industrial Composting and Anaerobic Digestion of Biodegradable Plastics

Cré, the Composting and Anaerobic Digestion Association of Ireland, performed industrial composting of selected BioPOST samples at an industrial composting site in Ireland. The Cré testing protocol is a modification of the laboratory-based disintegration test

Table 4.1. Thermal degradation parameters of the composites

Sample	T_g (°C)	T_{m1} (°C)	T_{m2} (°C)	T_{cc} (°C)	T_{onset} (°C)
PLA	65	151		122	324
PLA (W)	65	148		113	323
PLA-PHB-PHO	53	143	151	109	308
PLA-PHB-PHO (W)	53	150	153	110	300
PBS-PCL-PHO	58	55	114	94	341
PBS-PCL-PHO (W)	58	57	115	95	351
PLA-PCL	59	58	151	105	334
PLA-PCL (W)	59	56	151	105	315

The mechanically recycled samples were coded as PLA (W), PLA-PHB-PHO (W), PBS-PCL-PHO (W) and PLA-PCL (W). T_{cc}, cold crystallisation temperature; T_g, glass transition temperature; T_{m1}, first melting temperature; T_{m2}, second melting temperature; T_{onset}, onset of degradation temperature; W, washed sample.

Table 4.2. Mechanical properties of mechanically recycled composites

Polymer/polymer blend	UTS (MPa)	Young's modulus (GPa)	Elongation at break (%)	Toughness (kJ/m^3)
PLA	54.14±12.71	0.96±0.36	9.90±1.31	2529.66
PLA (W)	41.88±11.57	1.69±0.32	4.98±0.01	760.74
PLA-PHB-PHO	38.89±7.81	1.25±0.14	16.27±0.70	3766.77
PLA-PHB-PHO (W)	27.93±1.32	0.85±0.096	15.00±1.78	2616.95
PBS-PCL-PHO	24.20±2.41	0.39±0.20	71.23±19.00	12,842.65
PBS-PCL-PHO (W)	21.55±1.95	0.20±0.08	53.03±3.80	3432.10
PLA-PCL	43.93±14.32	0.54±0.030	75.10±1.17	9565.11
PLA-PCL (W)	38.72±3.42	1.04±0.060	33.81±1.19	10,528.84

UTS, ultimate tensile strength; W, washed sample.

Table 4.3. Mechanical properties of mechanically recycled composites with the addition of virgin polymer

Polymer/polymer blend	UTS (MPa)	Young's modulus (GPa)	Elongation at break (%)	Toughness (kJ/m³)
PLA (W)	41.88 ± 11.57	1.69 ± 0.32	4.98 ± 0.01	760.74
PLA(W) + 10%PLA	86.78 ± 5.52	1.75 ± 0.25	9.62 ± 2.03	2826.24
PLA-PHB-PHO (W)	27.93 ± 1.32	0.85 ± 0.09	15.00 ± 1.78	2616.95
PLA-PHB-PHO (W) + 10%PLA	52.81 ± 1.55	1.43 ± 0.10	15.05 ± 0.49	3766.78
PBS-PCL-PHO (W)	21.55 ± 1.95	0.20 ± 0.08	53.04 ± 3.80	3432.11
PBS-PCL-PHO (W) + 10%PBS	33.57 ± 2.15	0.44 ± 0.02	15.38 ± 3.94	5700.38
PLA-PCL(W)	38.72 ± 3.42	1.04 ± 0.06	33.81 ± 1.19	10,528.84
PLA-PCL(W) + 10% PLA	34.87 ± 2.32	1.05 ± 0.07	5.10 ± 0.69	614.78

UTS, ultimate tensile strength; W, washed sample.

under the EU standard EN 13432 that is conducted as a field trial in an industrial composting plant. The Cré test provides clarity regarding the performance of a product within the Irish composting context. In addition, the stand-alone testing enables producers of packaging to better understand how their materials/products might perform in an Irish composting facility. A Cré test is deemed to be successful if less than 10% (by weight) of the original film is present in the over 2 mm fraction. The BioPOST team at Trinity College Dublin produced rectangular films of 7 × 7 cm, with a thickness ranging from 100 µm to 300 µm, using various BioPOST samples for industrial composting. The samples were also produced with red biodegradable pigments to make them more visible in the compost during the composting process.

Cré evaluated the industrial compostability (in duplicate) of 60 different BioPOST film samples made from various polymers, polymer composites and polymer blends produced from different biodegradable polymers. Polymer composites produced with commercial biodegradable polymers, such as PLA, PHB, PCL and PHO, are compostable under Irish industrial composting conditions. However, polymer composites and blends produced using commercial PBS samples were not fully compostable under standard industrial composting conditions due to the short time frame. A substantial amount of PBS polymer/polymer composite samples were retrieved from the compost after the composting (Figure 4.2). However, given a longer composting time frame PBS will undergo complete biodegradation under industrial composting conditions (Narancic *et al*., 2018).

The fragmentation of PBS biodegradable plastics into smaller pieces, generating micro- and nanoplastics, is an integral part of the biodegradation process (Li *et al*., 2023; Sintim *et al*., 2020; Yu *et al*., 2021). The fragmentation process is rapid in the case of biodegradable polymers under suitable conditions (composting) and the polymer converts to carbon dioxide, methane and water. All the BioPOST composites evaluated for industrial composting

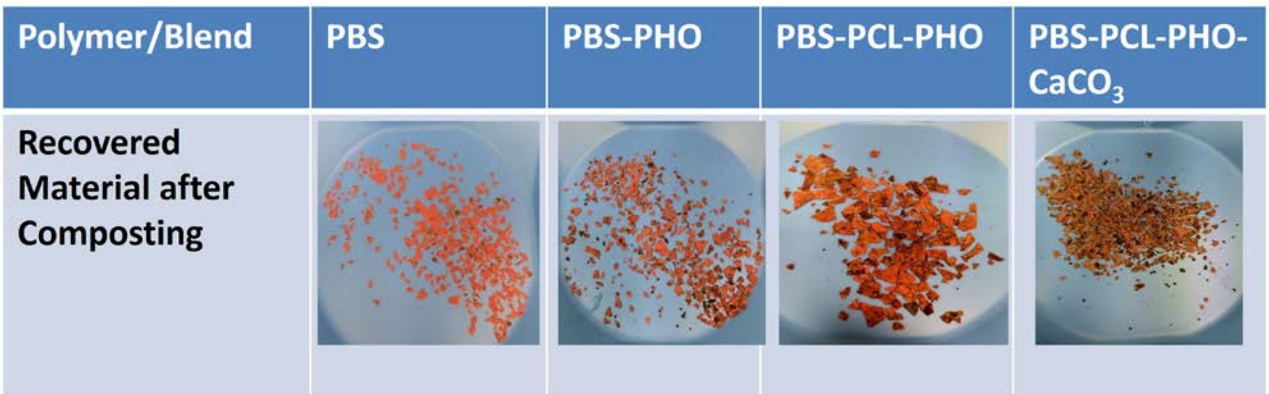

Figure 4.2. Partially degraded PBS and PBS-blend samples recovered from the compost after industrial composting.

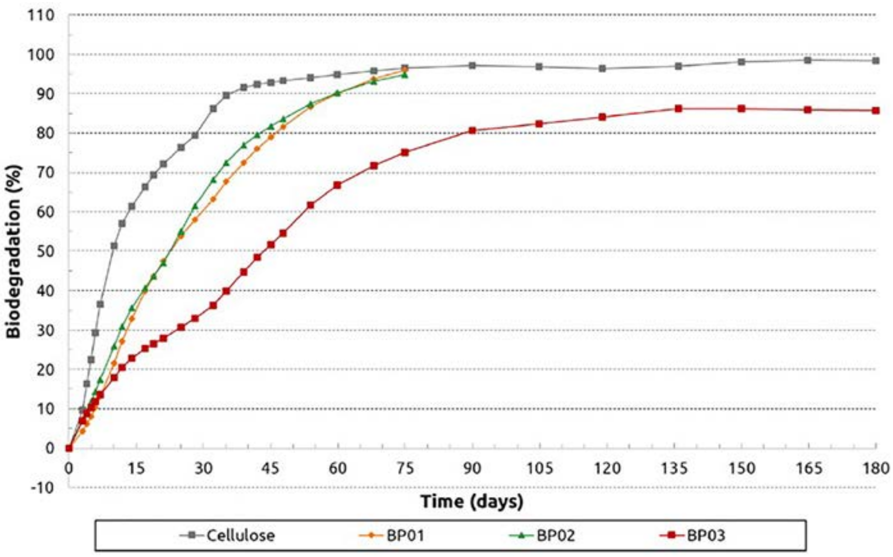

Figure 4.3. Industrial composting of BioPOST composites as per EN 13432 under controlled conditions.

showed complete degradation, except PBS-based composites. The composites and blends made with PBS were not fully compostable under Irish industrial composting due to the limited 10-week time frame. However, given an extended time period of 25 weeks, PBS is compostable under industrial composting conditions as per EN 13432 (Narancic *et al.*, 2018).

4.2.1 Biodegradation testing under controlled conditions

Biodegradation testing of the selected composites was carried out at Normec OWS, Belgium, to evaluate their biodegradability under simulated laboratory conditions. Industrial composting and anaerobic digestion of the selected composites were performed as per the EN 13432 and ASTM D5511 standards, respectively. The testing protocols and procedures are provided in Appendix 1.

Figure 4.3 shows the biodegradation profiles of three selected BioPOST composites samples: BP01, PLA-PCL; BP02, PLA-PCL-microcrystalline cellulose; and BP03, PLA-PCL-lignin.

Overall, all the composites have demonstrated a satisfactory level of biodegradation reaching 90% absolute or relative biodegradation. From the results, it was concluded that the composites BP01 and BP02 reached 90% biodegradability threshold within 75 days of testing under the given aerobic conditions. The requirement was, however, not met for the composite BP03 within 180 days, but an improved level of percentage of biodegradation was observed.

The biodegradability of samples in a solid-state anaerobic digestion system or in a sanitary landfill was evaluated by high-rate dry anaerobic batch fermentation. The incubation temperature was 37°C ± 2°C, and the duration of the test was at least 15 days under mesophilic conditions. During the course of fermentation, the release of the methane was monitored to understand the biodegradation of the composite sample PLA-PCL-lignin.

According to ASTM D5511, the test is considered valid only if the biodegradation percentage is more than 70%. The sample PLA-PCL-lignin did not show any biodegradation within 15 days under high-solids, mesophilic anaerobic conditions at low temperatures. Further testing is necessary at higher temperatures (thermophilic conditions) and longer time frames to understand the biodegradation under anaerobic digestion conditions.

5 Life Cycle Analysis

5.1 Introduction

An LCA study was conducted to evaluate the environmental hotspots of bioplastic composite film production and the key environmental impacts of recycling bioplastic composite films via end-of-life management scenarios such as mechanical recycling and industrial composting. As shown in Figure 5.1, the mechanical recycling scenario lies within the closed-loop system of the LCA in regard to product functionality, given the final product is considered to be recycled bioplastic film. However, the composting process involves biodegrading the bioplastic waste for compost applications (Cré, 2021), and is hence considered under the open-loop recycling system.

5.2 Goal and Scope

The goal of this LCA study was to assess the key environmental impact categories and compare the resource efficiency parameters, such as fossil fuel depletion, land use and fresh water consumption, and their respective environmental impacts. The scope of this study involves a cradle-to-gate LCA model for the production of bioplastic composite film, as shown in Figure 5.2, wherein the complete inventory flows for raw material production, including feedstock processing and conversion, have been considered. The functional unit for this LCA model was set to produce 1 kg of bioplastic films.

5.3 End-of-life Scenarios

A functional unit of 1 kg post-consumer bioplastic films was considered as the basis for an end-of-life cradle-to-gate LCA model for mechanical recycling and industrial composting with defined system boundaries, as represented in Figures 5.3 and 5.4, respectively. An LCA model similar to mechanical recycling along with substitution of 10% and 20% PLA was also considered, as shown in Figure 5.5.

5.4 Life Cycle Inventory

Detailed information on the life cycle data inventory, along with additional assumptions, can be found in Table A3.1 (see Appendix 3). This study utilised a GaBi global database (based on TotalEnergies Corbion's

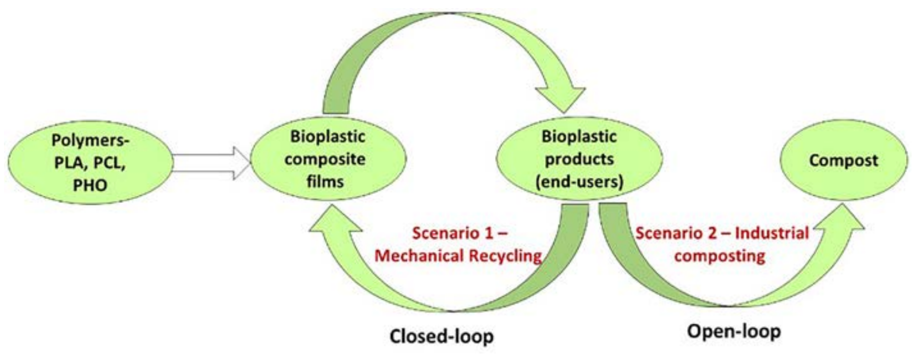

Figure 5.1. Schematic image of LCA model for the BioPOST project.

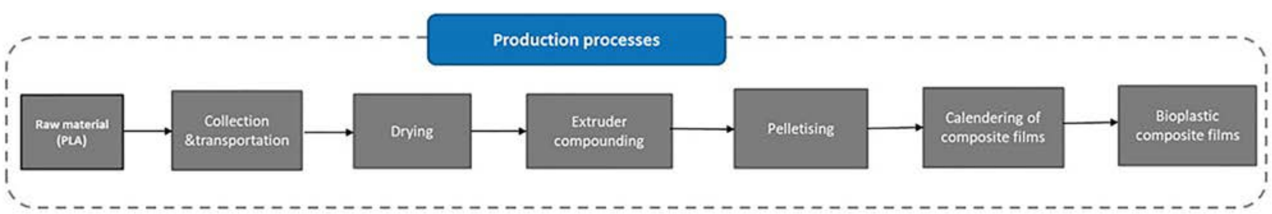

Figure 5.2. System boundary for the production of bioplastic composite films.

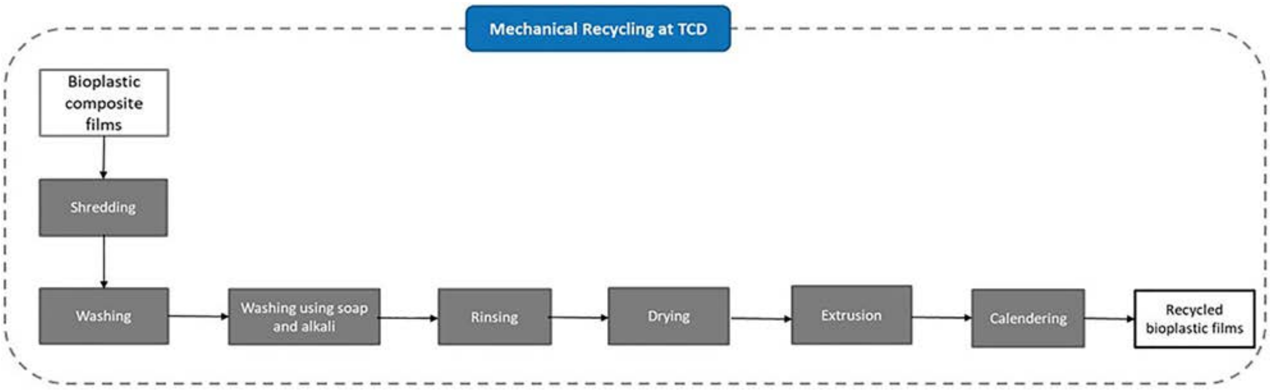

Figure 5.3. System boundary for mechanical recycling. TCD, Trinity College Dublin.

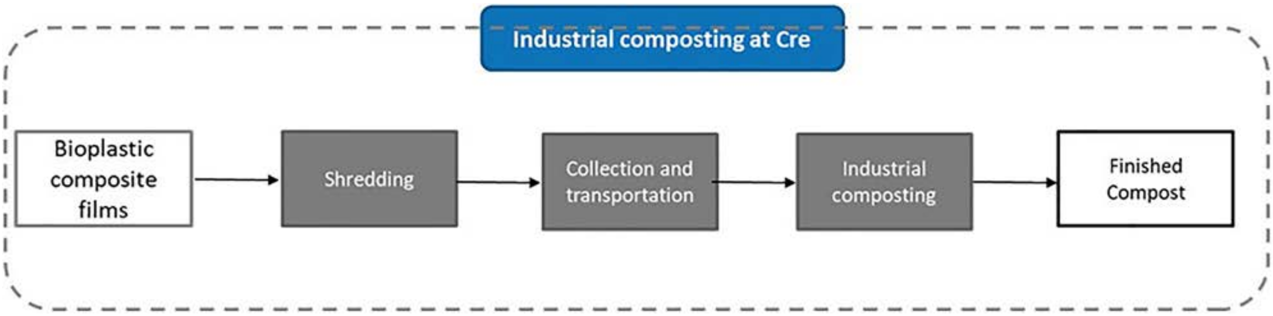

Figure 5.4. System boundary for industrial composting.

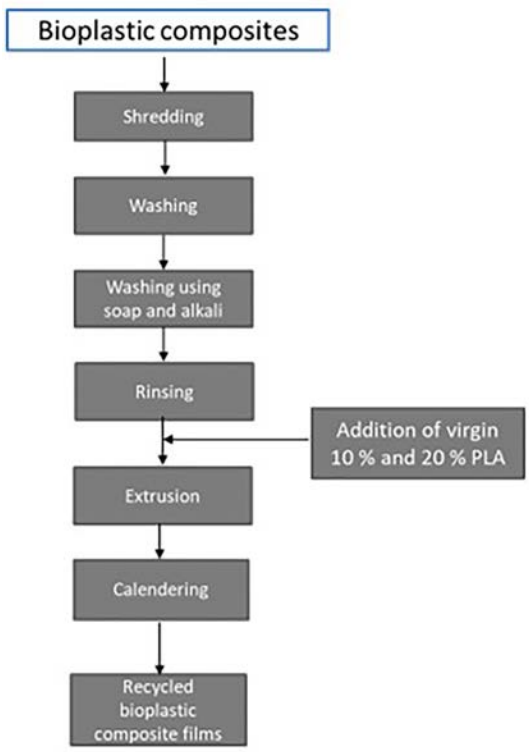

Figure 5.5. System boundary for substituting with virgin PLA.

process) for the processing of PLA and an extended database for enclosed finished composting (Sphera, UK), including its inventory flow for application and carbon crediting. Most of the inventory (input and output) flows involved were obtained from the Ecoinvent database (Germany) integrated with GaBi software; however, there are certain assumptions made, as detailed in Table A3.1 (see Appendix 3). The assumptions regarding collection, sorting and transportation distance are consistent with those used for the preparation of bioplastic composite films.

5.5 Life Cycle Impact Assessment

The impact categories and life cycle impact assessment methods used in this study align with the recommended European life cycle impact assessment methods, as published by the International Reference Life Cycle Data System (European Commission, 2010). Key environmental impact categories of both production and recycling scenarios for bioplastic composites are compared in accordance with the Tool for the Reduction and Assessment of Chemicals and Other Environmental

Impacts version 2, as represented in Figure 5.6. It can be observed that the impact categories that dominate mechanical recycling are global warming and acidification; however, its overall environmental profile is better for the industrial composting process. This comparative study suggests that the industrial composting process accounts for lower impacts in terms of global warming when considering the life cycle of biogenic carbon through compost application, which contributes to soil sequestration and renewability via crop/feedstock cultivation.

It is clear that the production of virgin bioplastic composites involves all the impacts associated with the synthesis of raw materials (in this case, biopolymer PLA). The global warming potential for this material is found to be higher than other environmental factors; LCA studies on mechanical recycling of bioplastic composites show a nearly 43.3% reduction in global warming impacts and a 122% reduction in ecotoxicity impacts when compared with production of virgin bioplastic composite films. Comparing the end-of-life scenarios, industrial composting is found to be associated with fewer environmental impacts.

It is noteworthy that the effect of substituting 10–20% of virgin bioplastic (PLA) to compensate for the mechanical properties of the final product, i.e. recycled bioplastic composites, has shown quite similar values (Figure 5.7) for all the key environmental impact categories, except ecotoxicity, confirming that the substitution method complements the mechanical properties without compromising on environmental performance.

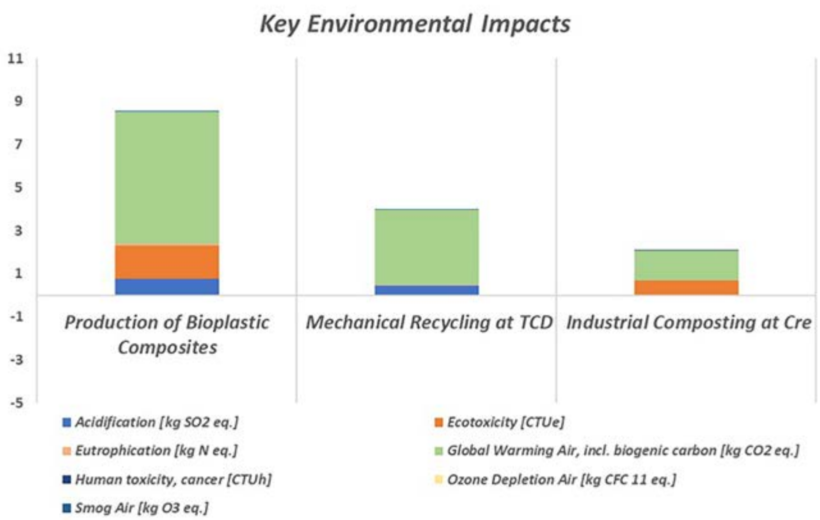

Figure 5.6. Key environmental impacts of production and end-of-life processes for bioplastic composite films. TCD, Trinity College Dublin.

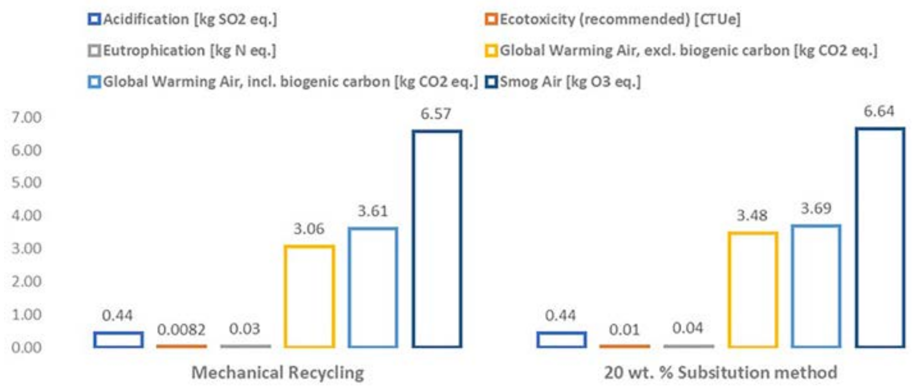

Figure 5.7. Comparative assessment of mechanical recycling with substitution method.

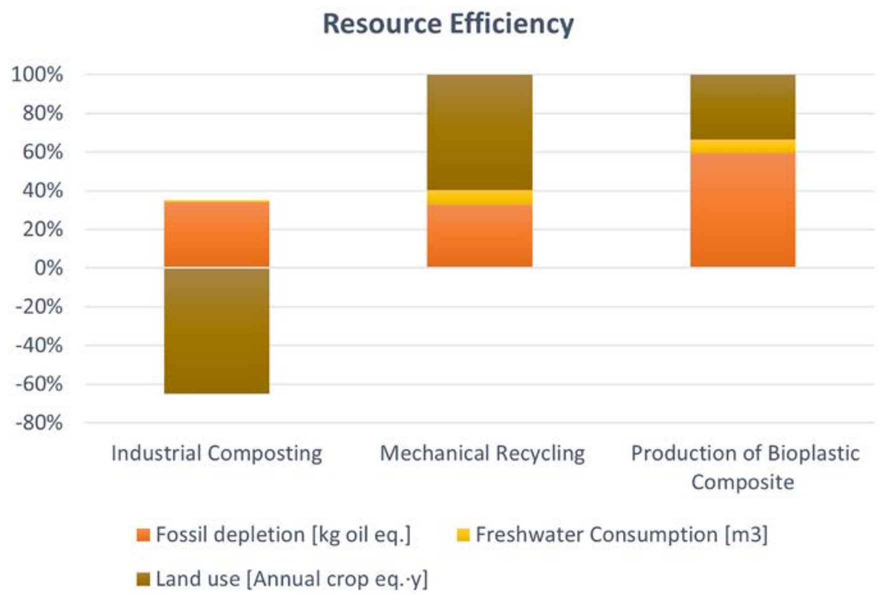

Figure 5.8. Comparative assessment of resource usage.

The key performance indicators of resource efficiency parameters of production, recycling and composting of bioplastic composite films are represented in terms of land use and fresh water depletion. There is a series of processes, such as shredding, washing and drying, that are similarly used in both the mechanical recycling and the production processes. Hence, the use of process water is equivalent in both cases. This explains how the effect of recycling processes can lead to nearly similar resource impacts, as can be seen from Figure 5.8. However, it is interesting to note that the industrial composting process compensates for land use (as indicated by negative values) by assuming that the finished compost has benefits in terms of improving soil quality and carbon sequestration and replacing fertiliser usage (White, 2012).

6 Conclusions and Recommendations

6.1 Conclusions

Biodegradable plastics are a promising substitute for conventional plastics to help curb plastic pollution. Currently, only a few commercial biodegradable polymers are available, and those polymers have different material and biodegradability properties. However, the rate of replacement of conventional plastics with biodegradable plastics is slow, primarily due to (1) the high cost of biodegradable polymers, (2) the scale of availability, (3) the performance of the biodegradable plastic products, (4) the long-term impact on the environment and (5) the lack of infrastructure and policies associated with biodegradable plastic products and their end-of-life management.

In the BioPOST project, we demonstrated the potential feasibility of a circular economy for biodegradable plastic products, from the production of biodegradable plastics through to their segregation, recycling and end-of-life management, on a pilot scale to stimulate its development. In this project, we have developed biodegradable polymer composites and blends with superior mechanical properties from individual commercial biodegradable polymers. Currently available PLA and PHB polymers are brittle and have low elongation properties, thus limiting the production of thinner films. The BioPOST project has developed blends with superior elongation properties based on PLA, PBS, PHB and PHO polymers, and has produced prototype packaging films. We also demonstrated that these blends are scalable and can be produced and processed into film products. These blends offer new types of biodegradable polymers, potentially lowering the cost of biodegradable polymers with superior properties and reducing plastic pollution.

Segregation and recycling are prerequisites for all biodegradable plastic products entering the market and fitting into the circular economy concept. We have demonstrated, on a semi-pilot scale, that the prototype packaging films produced in the project using various polymers, composites and blends can be separated from mixed plastic waste using existing sorting technologies. This indicates the feasibility of automatic detection and sorting for biodegradable plastic products with existing waste segregation infrastructure. However, more trials are required with real-time products to improve the segregation efficiency of biodegradable plastics in commercial environments. Also, further work is necessary on the aspects of increasing sample size and developing approximation both for materials and sorting machines to enable the retrofitting of operational materials recovery facilities to make them suitable for segregating biodegradable plastic products.

The mechanical recycling process for converting plastic waste into reusable materials for similar/new products is achieved through sorting, washing, grinding and compounding. All the segregated BioPOST prototype products were suitable for mechanical recycling. However, recycled BioPOST materials showed inferior mechanical properties compared with their virgin counterparts and hence required the addition of virgin polymers to retain desirable mechanical properties. Currently, no commercial segregation facilities are available to recover biodegradable plastic products from mixed plastic waste due to the low volume of products in use (< 1%). More emphasis is required on developing the infrastructure for the proper segregation of biodegradable plastic products, aiding the goal of more recycling and reducing waste and contamination.

Biodegradable plastics undergo biodegradation in the industrial composting process and produce compost that can be used for agriculture and gardens. We have demonstrated that the individual polymers and blends based on commercial biodegradable polymers, such as PLA, PCL, PHB and PHO, are compostable under Irish industrial composting conditions. However, the composites and blends made with PBS failed disintegration testing under industrial composting due to the limited time frame (10 weeks) of industrial composting conditions. However, given more time, PBS is compostable under industrial composting within 25 weeks (Narancic *et al*., 2018).

On performing the life cycle impact assessment on the production and end-of-life management of bioplastic composite films, it was identified that global warming potential and ecotoxicity are the key environmental hotspots in their production. Environmental impacts such as global warming potential and ecotoxicity are lower for the mechanical recycling of bioplastic composite films, underpinning the circularity potential of post-consumer bioplastic waste. Resource usage has been assessed based on fossil fuel depletion, water consumption and land use; results show benefits in terms of land use for composting. Overall, composting shows lower environmental impacts than mechanical recycling when including the carbon credits for biogenic carbon as the renewable source for feedstock production and also assuming the application of finished compost to improve soil quality.

The BioPOST project demonstrated a complete ecosystem for biodegradable plastic products based on commercial polymers and blends, starting from the production of prototype products through sorting, recycling and industrial composting in a real-time environment. Furthermore, this study suggests the feasibility of segregating biodegradable plastic waste from mixed plastic waste with improvements to existing sorting infrastructure, followed by recycling through multiple end-of-life options, to harness the potential of biodegradable plastics to curb global plastic pollution.

6.2 Recommendations

The BioPOST project has demonstrated the development of sustainable, environmentally friendly plastics to address the real-world problems of current plastics. Bio-based, biodegradable and compostable plastics, collectively known as bioplastics, are emerging as alternatives to fossil-based conventional plastics in several applications, including packaging, single-use products, construction and agriculture. Globally, these bioplastics represent less than 1% of total plastic production capacity. Due to their low volume, bioplastic products are currently treated as contaminants and not separated from mixed plastic waste products. In Ireland, no dedicated infrastructure is currently available for the segregation and recovery of bioplastic products, which limits segregation and recycling options. The volume of biodegradable plastic continues to grow in single-use packaging, and hence it is essential to establish a system for labelling, standards, collection, segregation, recycling and disposal of biodegradable plastics, as per the EU’s new Packaging and Packaging Waste Regulation. Creating an infrastructure conducive to the use of bioplastic products along with consumer education will present multiple benefits for all businesses, policymakers and consumers and will help build the circular economy. The collection and segregation infrastructure is critical to promoting the circularity of bioplastics, especially the biodegradable ones, to ensure the benefits of recycling and recovery options. The end-of-life options for biodegradable plastics are much wider than those for fossil-based polymers due to fundamental differences in the materials’ chemistry. Using materials chemistry and emerging technologies, such as chemical and enzymatic recycling, biodegradable plastic can be recycled into virgin biodegradable polymers, platform chemicals and other value-added products, thereby keeping biodegradable plastics in the regenerative loop while reducing plastic waste.

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Appendix 1

Biodegradation Test under Controlled Composting Conditions

References:

- ISO 14855;
- EN 13432;
- ISO 17088 and ISO 18606;
- ASTM D6400 and ASTM D6868;
- AS 4736.

The test is an optimised simulation of an intensive aerobic composting process and determines biodegradability under dry aerobic conditions. The sample is mixed with the inoculum in a concentration of 6–8% and intensively composted in a static reactor vessel under optimum oxygen, temperature and moisture conditions. The oxygen consumption and carbon dioxide production are continuously monitored and integrated. The percentage of biodegradation is calculated as the percentage of solid carbon of the test item, which has been converted to gaseous, mineral carbon under the form of carbon dioxide. The test is typically performed at 58°C, representing industrial compostability. In general, a test item has demonstrated a satisfactory level of biodegradation when 90% absolute or relative biodegradation is reached with reference to cellulose.

High-solids Anaerobic Biodegradation at Mesophilic Temperature (37°C)

The test was performed according to the following standard:

- ASTM D5511 – Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions (2018).

A set of six equal vessels each with a total volume of 2.5 L was used. Each reactor was filled with 1 kg of inoculum and 15 g of the reference or test item (except for the control reactors). The reference item cellulose and test item were added as powder. The reactors were kept at 37°C in an incubator. The total test duration was 15 days.

During the anaerobic biodegradation of organic materials, a mixture of gases, principally methane and carbon dioxide, is the final decomposition product, while some of the organic material will be assimilated for cell growth. The volume of the biogas produced is measured and the amount of methane and carbon dioxide produced per weight unit of test item is calculated. If the carbon content of the test item is known, the percentage of biodegradation can be calculated as the percentage of solid carbon of the test item that has been converted to gaseous mineral carbon.

The test is considered valid if the percentage of biodegradation for the reference item is more than 70% after 30 days, according to ASTM D5511 (2018).

Appendix 2

Table A2.1. The BioPOST project polymers, polymer composites and blends tested for industrial compostability under Irish composting conditions

Sample no.	Polymer/polymer blend	Industrial compostability	Comment
1	PLA-Ingeo 4043D	Yes	
2	PLA-Luminy L130	Yes	
3	PCL-CAPA 6500	Yes	
4	PHB-Biomer P226	Yes	
5	PBS-BioPBS FZ1PB	No	
6	PHO-UCD	Yes	
7	PBAT-Ecoflex FBlend C1200	No	
8	Cellulose	Yes	
9	LDPE	No	
10	PLA-PHO	Yes	PLA is a major polymer
11	PLA-PHB	Yes	PLA is a major polymer
12	PLA-PHB-PHO	Yes	PLA is a major polymer
13	PLA-PBS	Yes	PLA is a major polymer
14	PLA-PHB-PHO with $CaCO_3$	Yes	PLA is a major polymer
15	PLA-PCL-PHA	Yes	PLA is a major polymer
16	PLA-nystatin	Yes	PLA is a major polymer
17	PLA-PCL	Yes	PLA is a major polymer
18	PBS-PHO	No	PBS is a major polymer
19	PBS-PCL-PHO	No	PBS is a major polymer
20	PBS-PCL-PHO with $CaCO_3$	No	PBS is a major polymer
21	PBS-lignin	No	PBS is a major polymer
22	PBAT-lignin	No	PBAT is a major polymer
23	PBAT-wood flour	No	PBAT is a major polymer

LDPE, low-density polyethylene; PBAT, polybutylene adipate terephthalate.

Appendix 3

Table A3.1. Life cycle data inventory and assumptions

Operation	Processes	Values and units
Production of bioplastic composite films	Collection and transportation	Collection time – 1573 seconds
		Average transport distance – 100 km
	Fuel energy for collection and transportation	0.048 kWh
	Process water	0.02 L
	Specific energy consumption for extrusion	0.144 kWh
	Specific energy consumption for pelletisation	0.207 kWh
	Specific energy consumption for calendering	0.735 kWh
Mechanical recycling	Specific energy for shredding	0.060 kWh
	Electricity energy for washing	0.024 kWh
	Water for washing	40.00 L
	Washing at 80°C	10.00 L
	Sodium hydroxide	50 g
	Rinsing	40.00 L
	Specific energy consumption for drying	0.043 kWh
Industrial composting	Specific energy consumption	0.011 kWh
	CO_2, biogenic	1.26 kg
	Finished compost	0.33 kg

All the processes are considered with a reference flow of 1 kg of raw material (e.g. PLA, bioplastic composite films). Mass fraction of 1 wt% loss has been considered after shredding and extrusion processes.

Abbreviations

BioPOST	Sustainable, Biodegradable, Compostable and Recyclable Plastics for Packaging and End-of-life Management
CDW	Cell dry weight
DSC	Differential scanning calorimetry
EPA	Environmental Protection Agency
FTIR	Fourier transform infrared spectroscopy
IPC	Innovative Polymer Compounds
LCA	Life cycle analysis
PBS	Polybutylene succinate
PCL	Polycaprolactone
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PHO	Polyhydroxyoctanoate
PLA	Polylactic acid

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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