Barriers and opportunities for circularity in plastics

Circularity in practice: materials

Photo by James Wakibia

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Executive Summary

The current, predominantly linear approach to the plastics economy results in inefficient resource use, unnecessary waste and unprecedented pollution. This gives rise to the need to transition to a circular plastics economy, in which materials are retained in the economy for as long as possible to minimise waste and pollution. However, the specific approach to delivering operational plastics circularity is often undefined and unclear. Therefore it is necessary to identify barriers and opportunities to circularity that helps to determine where Defra's existing powers can act and where certain challenges may need to be approached differently to drive positive change.

The objectives of this study were to explore multi-disciplinary barriers and opportunities across the entire lifecycle of plastics for 9 different materials, identifying key interventions and leveraging points that could drive substantial changes in production, material use and waste management practices. The study used a two-part methodological approach: a comprehensive literature review and expert interviews, focusing on both the individual material level and systemic factors influencing circularity. The nine materials covered are:

- Biodegradable and Compostable Plastics – all settings
- Poly(vinyl) chloride, PVC – in Construction
- Poly(ethylene) terephthalate, PET – in Packaging
- High density polyethylene, HDPE – in Packaging
- High density polyethylene, HDPE – in Construction
- Low density polyethylene, LDPE – in Packaging
- Polypropylene, PP – in Textiles
- Polypropylene, PP – in Packaging
- Polyhydroxyalkanoates, PHA – all settings

For each material, an analysis of the barriers and opportunities for circularity across each stage of the plastics lifecycle is presented. This is followed by a discussion on circularity considerations from the perspective of various different disciplines or elements of the plastics value chain (consumer attitudes, economics, technology and infrastructure, policy and regulation, and the waste hierarchy), from which priority intervention for increasing the circularity of the material are identified. The different levers of change for the suite of interventions for the materials are identified before gaps in evidence are indicated.

None of the materials assessed are circular at present, and in most instances, the current consumer attitudes and behaviour, economics, technology and infrastructure or policy and regulation do not present the right enabling environment for these materials to be circular. Across all materials, 5 consistent themes emerged as critical considerations for plastics circularity. First, that all materials hold the potential to move up the waste hierarchy, transitioning from lower-level strategies such as recycling and disposal to higher-level circular practices like reduction, reuse and repair. Second, that in the literature, and by many industry positions, recycling is often misconstrued as reuse, inhibiting progress to the more circular approach of reuse. Third, to enhance circularity, a systemic shift beyond recycling is required, emphasising the importance of reuse, redesign, and the reduction of initial material use. Fourth, that managing the safety, reusability and recyclability of plastics necessitates a precautionary approach to additives and plasticizers, where producers must demonstrate their products meet stringent safety and sustainability standards. Lastly, achieving plastic circularity necessitates diverse, context-specific interventions rather than a one-size-fits-all approach, integrating multiple strategies across the plastic lifecycle to address the complexity and scale of the challenges effectively.

In identifying the opportunities and barriers to circularity, a number of limitations are evident. This research was restricted to open access literature, and given the time constraints, the literature review conducted may not be fully exhaustive. Furthermore, limiting research to English-language sources potentially overlooks valuable insights, case studies, and approaches adopted in non-English speaking regions. Additionally, the interviews with materials experts took place without equally parallel inputs from environmental and human health specialists, meaning there may be a degree of directionality bias in favour of potential interventions that do not fully capture the full suite of options.

Overall there is limited accessible data and statistics in the UK in terms of production, use, and waste generation per material or general type which impedes the ability to draw precise conclusions about the national landscape of plastic use and waste. There is also a lack of studies and data on reuse, repair, and remanufacture of plastics, most of the literature available focuses on recycling. There is much conflation between reuse and recycling in the literature, with these terms often being used interchangeably in many papers. Lastly, there is variability in waste management trends and policies across different UK administrations which presents a challenge in developing uniform recommendations that are applicable across the UK.

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Acronyms

BCP	Biodegradable and compostable plastic
Defra	Department for the Environment, Food and Rural Affairs
EMF	Ellen MacArthur Foundation
GPPC	Global Plastics Policy Centre
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
M&E	Monitoring and evaluation
NGOs	Non-governmental Organisations
PET	Polyethylene terephthalate
PTT	Pots, Tubs & Trays
PHA	Polyhydroxyalkanoate
PP	Polypropylene
PVC	Polyvinyl chloride
UNEP	United Nations Environment Programme
UoP	University of Portsmouth
WEF	World Economic Forum
WP	Work Package

1. Introduction

1.1 Context

The current, predominantly linear approach to the plastics economy results in inefficient resource use, unnecessary waste and unprecedented pollution (Sehnem et al., 2019). This approach creates multiple social, economic, and environmental problems that characterise the global plastic pollution crisis (Johansen et al., 2022). Estimates suggest that current national and private sector policies will only slow the increase in plastic pollution by 7% per year against business as usual by 2040 (Lau 2020). Therefore, alternative approaches to organising the plastics economy are needed. Multiple reports set out the case for a transition to a circular plastics economy, in which materials are retained in the economy for as long as possible to minimise waste and pollution (EMF 2017, OECD 2022, UNEP 2023). Several countries, including the Netherlands, France and Italy in Europe, have adopted circular economy policies (King and Locock 2022) guided by similar thinking at the EU level as part of the EU Green Deal. The transition to plastic circularity within planetary boundaries is a key topic in the negotiations for an international legally binding instrument to end plastic pollution (the 'Global Plastics Treaty') (Bachmann et al., 2023). However, the specific approach to delivering operational plastics circularity is often undefined and unclear.

The life cycle of plastics (Figure 1) is complex, transboundary and intersects with varying other value chains and international agendas including climate, biodiversity and human health (Nielsen et al., 2020). Therefore it is necessary to identify barriers and opportunities to circularity that helps to determine where Defra's existing powers can act and where certain challenges may need to be approached differently to drive positive change. The entire lifecycle of plastic should be in scope for action, with consideration going to environmental, social and economic impacts across the system. It is vital to consider potential trade-offs as well as assessing the timeline for action. This allows space for technological development and innovation whilst ensuring we remain on the path to circularity. As such, nine plastic materials have been assessed for their potential for circularity, aiming to identify what steps can be taken to make the material circular. The nine materials assessed are:

- Biodegradable and Compostable Plastics – all settings
- Poly(vinyl) chloride, PVC – in Construction
- Poly(ethylene) terephthalate, PET – in Packaging
- High density polyethylene, HDPE – in Packaging
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- Low density polyethylene, LDPE – in Packaging
- Polypropylene, PP – in Textiles
- Polypropylene, PP – in Packaging
- Polyhydroxyalkanoates, PHA – all settings

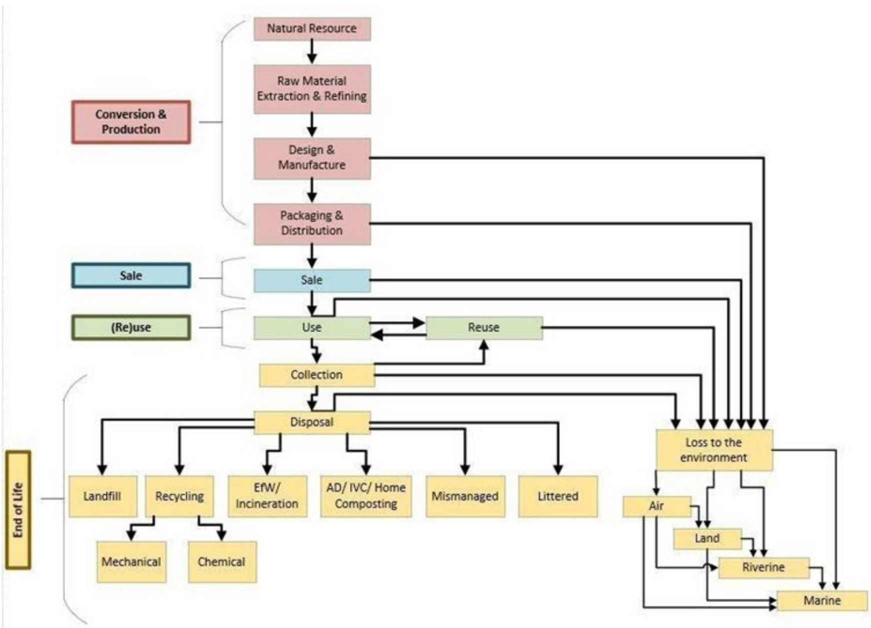

Figure 1. Flow diagram to represent each of the stages in the life cycle of plastic. Source: Defra

1.2 Objectives

The objectives of this study are as follows:

- To use a multi-disciplinary approach to identify barriers and opportunities for circularity in plastics
- To employ systems thinking across the entire lifecycle of plastics to capture potential conflicts, trade-offs and hidden opportunities relating to interventions
- To assess plastic materials (and associated products) in terms of natural and materials science, industrial processes, design, behavioural and social research and economics
- To identify where levers for change to promote circularity of plastics exist in the context of the United Kingdom vs internationally
- To identify where levers for change to promote circularity of plastics exist in the context of government, regulators, business and industry, academia and society
- To identify, where necessary, the key limiting factor(s) that are preventing circularity for specific materials (and their associated products) and/ or generally for plastics

This report is structured in four main parts following this introduction. Section 2 sets out the methods used to conduct this research, including the definitions and principles for circularity adopted. Section 3 presents the findings specific to each material type, including the key interventions needed to make the material circular. Section 4 identifies the cross-cutting findings and interventions that intersect multiple materials. Finally, Section 5 presents the limitations of this study and indicates the priority research areas needed to fill existing gaps in information and data.

2. Methods

The review to identify barriers, opportunities and key interventions for the circularity of the nine materials was undertaken in two parts - a literature review and a series of interviews with materials experts.

Literature review

A desk-based review was conducted for each material by searching the academic and practitioner literature using Boolean searches across multiple databases to ensure full coverage. In particular, materials from organisations that manufacture, reuse, recycle or deal with disposal of the materials under investigation were also identified and reviewed. The following set of search engines were used:

- Google
- Google Scholar
- Scopus
- Science Direct

Only high-quality evidence sources were used such as peer-reviewed academic articles, official reports by organisations and/or their websites, or policy briefs. Any other sources such as unofficial websites, student theses, blogs, or non-peer reviewed articles were excluded.

For each material the following themes were explored:

1. What the barriers and opportunities are across the individual stages of the material's life cycle (full suite of questions investigated in Annex 1).
2. How consumer attitudes and behaviour, economics and economic incentives, technology (including design and industrial processes) and infrastructure, and policy and regulation impact the potential for circularity.
3. The feasibility to maintain the material higher up the waste hierarchy and the material's potential for circularity (with a focus on reuse).
4. Where the levers for change exist in the key interventions identified to overcome the barriers and harness opportunities. Levers included geographic and sectoral levers.
5. Where evidence gaps make it difficult to draw conclusions about circularity.

The literature sources and findings for each material's life cycle stages were documented in a database (Annex 1).

Interviews

Remote structured interviews were conducted with materials experts on their experiences of the barriers and opportunities to the circularity of the material in question. General questions asked in the interviews can be found in Annex 2. Further questions were asked based on specific evidence gaps from the literature review. Interviewees remain anonymous to protect confidentiality. The breakdown of interviewees was:

- 8 materials experts from industry, academia and NGOs (1 for each material, with no expert available for PP in textiles)
- 2 waste management companies
- 1 chemical recycling company
- 2 organisations specialising in circularity of plastics with a focus on reuse.

Circularity definitions and principles adopted

The practical meaning of circularity and the principles that guide circular approaches are rarely defined, making the role of circularity in reducing plastic pollution challenging to implement (King and Locock 2022). The component of work that was conducted in synergy with this study sought to define the circularity of plastics and set out a suite of principles to inform decision making related to the circularity of plastics (Link or reference to WP1 report). The core elements of a definition and the accompanying set of principles that were identified (Table 1) have been adopted in this study to inform the approach taken.

Table 1. Core definition elements and principles to guide decision making on circularity

Core elements that define plastics circularity	Principles to guide decision making on circularity
● Decouples economic activity from resource use or extraction ● Covers the full life cycle of plastics ● Follows the waste hierarchy ● Maintains the value of materials by keeping them in use as long as possible ● Removes or reduces waste ● Balances environmental integrity and social sustainability with economic value	Any activity in line with plastics circularity must: ● Protect, restore or regenerate nature ● Ensure inclusive outcomes, quality job creation, fair and safe working conditions and that human rights are upheld ● Minimise pollution, including emissions and chemical leakages from plastics production, processing and disposal. ● Transition away from the production of virgin materials, in line with the waste hierarchy ● Uphold dynamic safeguarding

3 Material specific circularity opportunities and barriers

This section presents the findings related to the barriers, opportunities and enablers to the circularity of the nine different material types, focusing on the life cycle stages, future developments, and policy and technological requirements for circularity. A summary of cross-cutting findings is presented for the barriers, opportunities and levers for change that apply to multiple materials. The full database of literature review findings can be found in Annex 1 which collates all of the information gathered to inform the presentation of findings in this section.

3.1 Biodegradable and compostable plastics

i. Life cycle stages and circularity

Biodegradable plastics are materials that can decompose into water, carbon dioxide (if oxygen is present or methane in anaerobic conditions), biomass, and in some cases, other natural substances, under the action of naturally occurring microorganisms such as bacteria, fungi, and algae. The degradation process of these plastics is influenced by various environmental conditions including temperature, humidity, and the presence of microorganisms, with the rate of breakdown varying significantly based on the specific conditions and the composition of the plastic. Compostable plastics are specifically designed to break down into carbon dioxide, water, inorganic compounds, and biomass under controlled conditions at a rate consistent with other known compostable materials. The key distinction of compostable plastics lies in their ability to decompose within a specific timeframe under composting conditions, which typically involve higher temperatures, controlled humidity, and the presence of aerobic microorganisms. These conditions are often found in industrial composting facilities rather than in the natural environment.

The terms 'biodegradable' and 'compostable' are often used interchangeably, yet they denote inherently different categories of materials, each with unique properties and degradation processes. For ease of reporting, the term biodegradable and compostable plastics (BCP) is used in this report when referring to both if the conditions that apply to them are the same, and differentiate between biodegradable and compostable plastics when there is a specific point made referring to one of them only.

Across the life cycle of biodegradable and compostable plastics, the primary barriers exist in the conversion and production, sale, reuse, collection, disposal and loss to the environment stages. The main opportunities for circularity lie in the conversion and production, reuse, recycling, and loss to the environment stages (Figure 2). A summary of the barriers and opportunities are presented in Table 2.

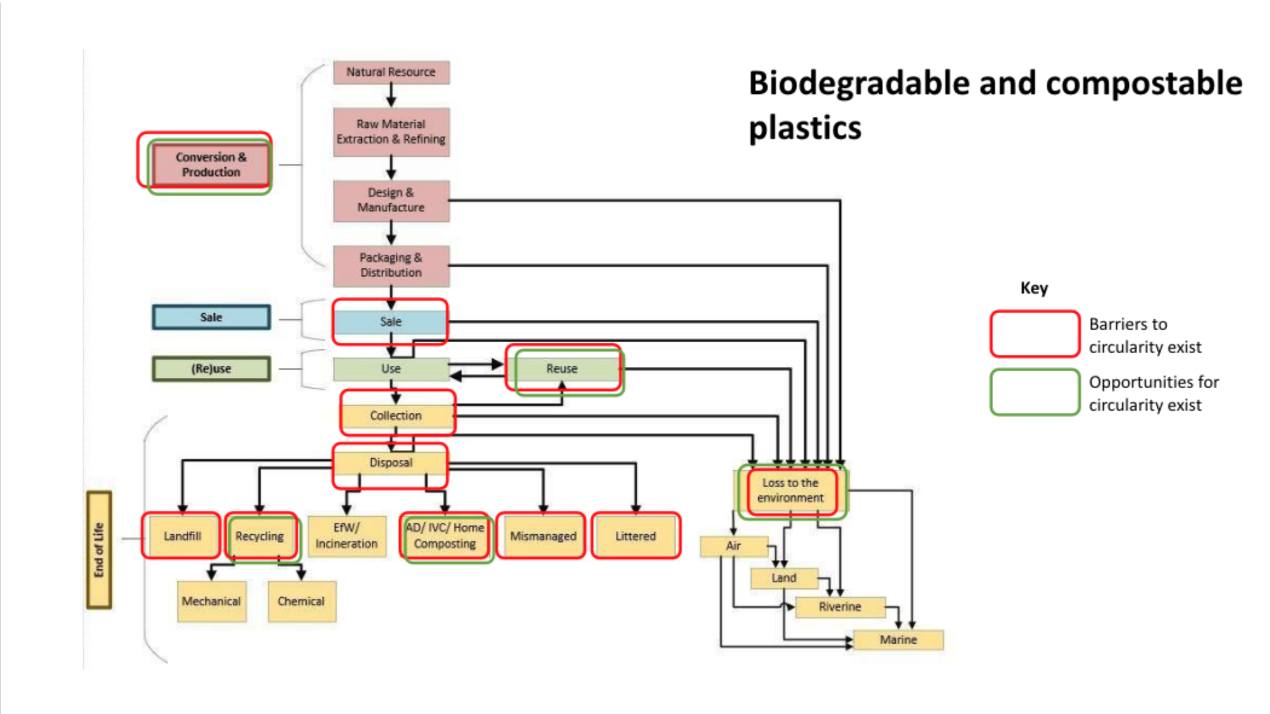

Figure 2. Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of biodegradable and compostable plastics exist.

Table 2. Overview of identified barriers and opportunities for the circularity of biodegradable and compostable plastics by life cycle stage.

Life cycle stage	Barriers	Opportunities
Natural resource	● The production of BCP produces more agricultural pollutants due to the use of pesticides and chemical fertilisers during the cultivation of crops and the chemical processing necessary to convert biomaterials into BCP (Ali et al., 2023) ● The use of arable land that would otherwise be used for agricultural purposes to produce plastics rather than food, resulting in potentially higher food prices (Ali et al., 2023; van den Oever et al., 2017) ● The material itself can limit circularity. Different BCP require different conditions to ensure full biodegradation. (Nanda et al., 2022) Furthermore, not all bio-based plastics are biodegradable. (Nanda et al., 2022)	● The use of alternative biomass such as algae and wastes for BCP can help to reduce the arable land pressure, lessen the issue of competition for food production, the use of agricultural pollutants, and the overall carbon footprints. (Ferreira-Filipe et al., 2021) ● The commercial exploitation of microalgae for BCP production (Nanda, & Bharadvaja, 2022) on a large scale, in a cost-effective manner without generating much waste in pre-treatment. Microalgae also have the potential to remediate the wastewater they grow in and recycle the CO_2 bubbled into the growth medium in the form of higher biomass productivity. ● The use of chitin and chitosan (alternate biomass) from industrial seafood waste to produce bioplastics (Ferreira-Filipe et al., 2021).
Raw material extraction & Refining	-	-
Design & Manufacture	● High costs of production vis-a-vis fossil-fuel based polymers (Ali et al., 2023; Ciriminna, & Pagliaro, 2020; Seyyedi et al., 2023; Song et al., 2009) ● Production is associated with energy requirements (with most being dependent on fossil fuel resources), leading to a lack of clarity regarding their wider environmental benefits when considering carbon emissions (Ali et al., 2023; Ferreira-Filipe et al., 2021). ● The addition of components such as additives or/and fillers to ensure biodegradability or/and functionality can negatively impact the existing waste management for plastics and the environment, because some can have limited functionality in an uncontrolled environment such as waste infrastructures, and others can introduce ecotoxicological issues. (Ferreira-Filipe et al., 2021) ● The production of BCP is associated with a higher contribution to the depletion of the ozone layer compared to the production of conventional plastics from fossil fuels (Ali et al., 2023) ● There are no clearly defined technical standards for assessing biodegradability (Ferreira-Filipe et al., 2021; Westlake et al., 2023) ● Properties of BCP are not always able to match those of fossil fuel based plastics (Boccalon & Gorrasi, 2022; Ferreira-Filipe et al., 2021)	● The addition of natural stabilisers and fillers such as polyphenols and chitosans to BCP can improve their functionality while minimising the risk of ecotoxicity (Bonnenfant et al., 2022; Muneer et al., 2021) ● The use of renewable energy sources (e.g. solar, hydro, wind) can help to mitigate GHG emissions and ecotoxicological impacts associated with BCP. (Ferreira-Filipe et al., 2021) ● The use of natural materials and fibres can help improve some properties of the (bio)degradable plastics and reduce the production cost (De Gisi et al. and references therein., 2022).

Packaging & Distribution		
Sale	● The lack of knowledge, a system of certification, and clear instructions for handling of BCP has resulted in inappropriate disposal, littering behaviour, and contamination in the waste management systems for conventional plastics as pointed out by De Gisi et al. (2022). (Ciriminna, & Pagliaro, 2020; Cucina et al., 2021; Ferrreira-Filipe et al., 2021; Nanda et al., 2022) ● Green washing practices and a lack of transparency associated with BCP can negatively affect the sales of BCP products. (Cucina et al., 2021; Ferreira-Filipe et al., 2021; Nanda, & Bharadvaja, 2022; Nandakumar et al., 2021)	-
Reuse	● Compostable plastics usually have a short life span, those that are designed to be durable are usually not compostable and will require different waste systems at end of life. (Song et al., 2009; Springle et al., 2022). ● Reuse of some PLA products is achievable, however composting is not generally considered as one of the best end of life options due to no energy recovery and low compost quality. (Rezvani Ghomi et al., 2021) ● PLA often ends up in landfills due to a lack of appropriate infrastructure for PLA recycling and the high cost of separation and the poor quality of the recycled PLA. (Rezvani Ghomi et al., 2021)	● Composting can be used for both bio-based wastes and BCP plastics to produce useful soil amendment products. Composting BCP can produce valuable compost along with water and CO_2, which does not contribute to an increase in greenhouse gases since it was already part of the biological carbon cycle. (Song et al., 2009) ● Bio-based products that can be composted by industrial composters, can be utilised for the production of biofuel through fermentation (biogas, hydrogen, ethanol, and biodiesel as final products). Wojnowska-Baryła et al., 2020)
Collection	● There are no established large-scale sorting facilities for BCP due to their limited production. As a result, BCP usually end up in landfills. (Nanda et al., 2022; Rezvani Ghomi et al., 2021) ● Most of the recycling technology is quite recent and has not been implemented on a large industrial scale yet. (Morici et al., 2022) ● There are no established standards for sorting procedures and disposal of BCP. (Nandakumar et al., 2021) ● The high cost of transportation and collection due to the large volume of plastic products is a barrier to recycling. (Morici et al., 2022) ● The waste stream of BCP such as PLA and/or PLA-based composites is limited, and as such they are not collected separately from other polymer waste streams, which in turn negatively impacts the recycling process of BCP and the BCP-based composites. (Morici et al., 2022)	● Plastics manufacturers could provide financial assistance to localities for equipment that can reduce plastics into a smaller form that would be more economical to transport. (Morici et al., 2022)

Disposal	● Challenges in recycling of post-consumer BCP include: heterogeneity, low market volumes, diverse sources and high potential for plastics waste contamination (RameshKumar et al., 2020), and the lack of infrastructure (Rezvani Ghomi et al., 2021). ● Other challenges include: technical difficulties of recycling (separation, contamination from other waste streams, etc.), low qualities of recyclates, costs of recycling (Hassanian-Moghaddam et al., 2023) in addition to the lack of continuous and reliable supply of BCP polymer waste in large quantities (Song et al., 2009). ● The waste infrastructure for BCP requires additional land space, a controlled environment and regular monitoring to ensure optimal conditions for biodegradability, facilitated microbial proliferation, investments etc. (Nanda et al., 2022) ● BCP have the same appearance as conventional plastics from fossil fuels, which can cause confusion in terms of their disposal (van den Oever et al., 2017; Springle et al., 2022) ● Composting produces methane and other GHG emissions that are several times more harmful than CO_2 (Ali et al., 2023)	● Composting can be used for both bio-based wastes and biodegradable plastics to produce useful soil amendment products. Composting bioplastics can produce valuable compost along with water and CO2, which does not contribute to an increase in greenhouse gases since it was already part of the biological carbon cycle. (Song et al., 2009) ● Products that can be composted by industrial composters, can be utilised for the production of biofuel through fermentation (biogas, hydrogen, ethanol, and biodiesel as final products). Wojnowska-Baryła et al., 2020)
Loss to the environment	● The full decomposition of BCP requires special conditions typically not found in the natural environment (Nanda et al., 2022) leading to a problem with the remaining plastics in the environment, i.e., microplastics. ● Incomplete degradation of BCP in the mass of organic waste may also cause pollution of the compost produced from this waste leading to soil contamination. (Cucina et al., 2021; Markowicz, & Szymańska-Pulikowska, 2019; Nazareth et al., 2022; Pascoe Ortiz, 2023; Song et al., 2009)	● The use of waste or waste water can be used for PHA production to improve circularity by maintaining the value of waste products (Amulya et al., 2015) ● ●

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

BCP are, of the 9 materials evaluated, those that generate the most misinformation, confusion and greenwashing for consumers. Consumers extend beyond just the general public; consumers also include policy makers and businesses as well. An increasing number of BCP are joining the UK plastics market, with the current UK BCP market size at nearly £330 million which is expected to increase to nearly £1 billion by 2032 (EMR, 2023). However, there is a lot of misinformation around what BCP are, and how to handle them, with consumers often being the victims of greenwashing. The key consumer attitude and behaviour considerations for the circularity of BCP include:

The distinction between the terms "biodegradable" and "compostable" is not always clear, they are often used interchangeably in various contexts. The confusion surrounding these terms usually stems from a general lack of public education on the subject (Kawashima et al., 2019; Nanda et al., 2022), which results in unintended consequences on the waste management systems (Cucina et al., 2021). Consumers can be lulled by these terms and dispose of biodegradable and compostable plastics incorrectly, assuming that these materials can be discarded in the environment or left into regular waste bins without causing harm. For example, dog waste bags are increasingly marketed as compostable, with high volumes of purchase by dog owners (Walker, 2023). This first poses an issue where many dog owners wrongly assume these bags can be composted at home or will break down naturally in any environment, leading to inappropriate disposal. Second, while the bag itself might be compostable under certain conditions, the content (dog waste) is not suitable for composting due to potential health risks associated with pathogens in pet waste. This distinction is often not made clear, misleading consumers into thinking the entire waste package (bag plus contents) is environmentally benign when disposed of (Walker, 2023).

The general public is susceptible to greenwashing, jeopardising potential sustainability initiatives by the government or stakeholders. Studies have shown that consumers are more likely to purchase products from brands that use materials that are 100% bio-based compared to brands that do not (Reinders et al., 2017). However, the lack of transparency from key players in the industry can lead to a lack of customer trust in environmental claims made by manufacturers (De Jong et al., 2017) which in turn can hinder the promotion of genuine BCP products or the implementation of BCP policies.

Due to the misinformation about the biodegradability of BCP, consumers are less likely to reuse products of these materials. If individuals believe that BCP will naturally and harmlessly decompose in any setting, they may be less motivated to reuse these products. The belief in the benign nature of BCP might lead to increased consumption and disposal rates, under the assumption that these actions have a negligible environmental impact due to the misconception of biodegradability (UNEP, 2015).

There is no consistent system for certification and labelling of BCP, confusing consumers (Cucina et al., 2021; Nanda et al., 2022). Labels and logos do not clearly indicate to the consumer (and retailer) when a plastic is bio-based, biodegradable or compostable, and how to dispose of the plastic after use. Furthermore, BCP products usually have a similar appearance to conventional fossil-based plastic products and the same can be said about biodegradable and non-biodegradable products making it even more difficult for consumers to distinguish them (van den Oever et al., 2017).

There are limited, and unclear guidelines for the handling and disposal of BCP post-consumer. Despite the growing popularity of BCP (specifically compostable bio-based packages) for their perceived sustainability, the absence of straightforward, universally understood disposal instructions contributes to lower rates of correct disposal compared to traditional, petroleum-derived packaging (Taufik et al., 2020). The misidentification of BCP results in their being placed in recycling bins meant for traditional plastics, contaminating mechanical recycling streams (Titone et al., 2023).

There are already challenges in existing waste collection in terms of consumer compliance and understanding, which presents further difficulties for the different collection streams that bioplastics require. Existing systems already grapple with numerous issues, such as contamination from incorrect recycling practices, known as "wish cycling," where consumers optimistically place non-recyclable items in recycling bins, hoping they can be recycled (Kramer and Yoeli, 2023). Interviewees who were experts in the design of BCP and their waste management highlight that a separate stream for the collection of household and business BCP waste is going to be necessary to upscale their use. However, given the existing challenges with household waste collection, this is likely to inhibit waste collection of BCP to some degree.

Based on the above the following key interventions for consumer attitudes and behaviour should be considered:

- **Improved, consistent labelling standards.** Beyond standards on labelling for content and composition (See Section 3ii.e. on Policy and Regulation), labels should also clearly indicate whether a product is suitable for industrial composting facilities or if it can be composted at home, and under what conditions.
- **Education and awareness raising activities for consumers and retailers on the realities of biodegradable and compostable materials.** This could include addressing myths about biodegradable or compostable plastics (see Goel et al., 2021 for myths and myth busting, and Nandakumar et al., 2021). Consumers include policy makers and businesses.
- **Clear guidelines for consumers on how to handle and dispose of biodegradable and compostable plastics.** This would need to be coupled with the earlier identified robust standards for the composition and labelling of these materials to ensure that consumers can dispose of items in the correct manner according to the type of material.
- **Incentivising the return of BCP to the correct reuse, recycling or waste management streams.** By implementing deposit schemes or similar incentives that have specific provisions for BCP, consumers are encouraged to return used BCP products for proper reuse, recycling or degradation. This approach not only increases the likelihood of BCP being processed in the most efficient manner, but also reduces contamination in recycling streams.

b. Economics

Despite the growing BCP industry, biobased or biodegradable plastics still only contribute to 1% of the 368 million tonnes of plastic produced worldwide, where a major contributor is the economic barriers to their proliferation (Filho et al., 2022; Rajvanshi et al., 2023). Plastic packaging that is compostable and/or biodegradable was included in the UK Plastic Packaging Tax introduced on 1 April 2022. Economic considerations for circularity include:

The cost of production of BCP is high. The cost of resources required for the bulk production of BCP such as carbon and nitrogen is a limiting factor for industrial applications (Ali et al., 2023). In addition, stringent testing of BCP materials are required to evaluate their performances in terms of barrier properties, physical properties, optical properties and mechanical properties such as tensile strength. Another key factor is the choice of raw materials or feedstocks and advancements in the technology required for the manufacturing of such BCP materials, which can also have a significant impact on the overall production cost. For example, despite being technically closest to petroleum-based plastics, PLA is unable to keep up with their prices due to the high cost of the multiple number of steps required for the production including material extraction, glucose extraction, fermentation, and polymerization. Other biobased plastics, such as PHA are nearly four times the price of conventional plastics (Rajvanshi et al., 2023; see Section 3.2 on PHA). Furthermore, the majority of testing standards for biodegradability are operated by commercial laboratories which are prohibitively expensive for product manufacturers.

There is an uneven playing field between bio-based BCP and fossil fuel based plastics. Bio-based BCP are often expected to catch-up against and sometimes surpass conventional petrochemical plastics - a sector characterised by more than fifty years of research, development, and a commanding presence in the market - without providing the same level of research and funding (Ferreira-Filipe et al., 2021). Most fossil fuel-based plastics benefit more from subsidies and lower tariffs through subsidising the cost of extraction of oil and gas, than plastic substitutes. In comparison, bio-based BCP have to account for the full price of extraction in production. Thus, current tariffs are making fossil-based plastics cheaper (UNCTAD, 2023)

The recycling of BCP tends to be less economically attractive than for conventional plastics. This is due to their limited production and more specifically lack of continuous and reliable supply of BCP polymer waste in large quantities (Song et al., 2009).

The development of the production and waste management of BCP requires further land usage. Some BCP production requires the use of arable land that would otherwise be used for agricultural purposes to produce food, resulting in potentially higher food prices (Ali et al., 2023; van den Oever et al., 2017). Increasing the amount of BCP plastic would require several infrastructural developments, including additional land space, a controlled environment and regular monitoring to ensure optimal conditions for biodegradability, facilitated microbial proliferation, and investments (Nanda et al., 2022). However, with new opportunities such as the commercial exploitation of microalgae or the use of chitin and chitosan from industrial seafood waste (Nanda, & Bharadvaja, 2022; Ferreira-Filipe et al., 2021) for bioplastic production some of these barriers can be overcome.

As an end of life solution, composting is viable given the growing demand for composted material. Composting is a £400 million market in the UK (OIM, 2023). When end-of-life is reached for compostable plastics, their decomposition into compost is a more circular approach than landfill, incineration or energy-to-waste.

Based on the above the following key interventions for economics should be considered:

- **Incentivising the development of sustainable BCP to balance out the market.** This could include grants for innovative BCP projects, tax incentives for companies that produce or use sustainable BCP with viable end-of-life solutions, or subsidies that lower the cost of bio-based raw materials.
- **Removing incentives or subsidies on fossil fuels that favour virgin plastics to balance the market.** The strategic withdrawal of financial support mechanisms that lower the cost of producing traditional virgin plastic materials from petroleum sources. This can include phasing out tax breaks, direct subsidies, and other forms of governmental financial assistance that are currently benefiting the petrochemical sector. By doing so, the cost of virgin plastics would more accurately reflect their true environmental and societal costs, making bio-based BCP more competitive in the marketplace.
- **Removing trade barriers to biodegradable and compostable plastics.** Reducing tariffs, quotas, and other trade restrictions on the import or export of biodegradable and compostable plastics can encourage their use in the right settings.
- **Introducing a mandatory minimum set of LCA indicators on which actionable policy can be based to define substitutes which should be produced.** In collaboration with environmental and industry experts, legislators would need to identify and mandate a core set of LCA indicators that accurately reflect the environmental impacts of proposed BCP and products. The indicators would need clearly defined benchmarks or threshold values, defining the acceptable limits for environmental and social impacts.

c. Technology and infrastructure

BCP usually end up in landfills as there are no established large-scale sorting facilities for BCP in the UK due to their limited production (Nanda et al., 2022; Rezvani Ghomi et al., 2021)**.** Despite the growing interest in BCP, their waste stream remains limited (Morici et al., 2022), and consequently BCP such as PLA and/or PLA-based composites are not collected separately from other polymer waste streams (Di Bartolo et al., 2021), which negatively influences the recycling status of BCP. Life cycle assessments show that the current system, with no dedicated UK-wide collection and processing facilities for compostable plastics, is not environmentally favourable (UCL, 2020).

The biodegradability and compostability of BCP are highly dependent on environmental conditions such as temperature, pH and humidity. The full decomposition of BCP often requires controlled conditions, which are typically not found in the environment or most waste infrastructures (Nanda et al., 2022).

The waste management of BCP is incompatible with the system used for conventional plastics and can negatively impact current and upcoming practices in the recycling of conventional plastics. When disposed of incorrectly, BCP can be a source of contamination that could disturb the current recycling of plastics and hence inhibit the closure of plastic cycles (Alaerts et al, 2018). During a typical conventional recycling process, the quality of the recycled plastics can be significantly impacted by the presence of natural materials and or fibres sometimes added to bio-based plastics (Alaerts et al, 2018). For example, PLA is known to be incompatible with PET recycling and should not be discarded along with PET waste streams (Goel et al., 2021) unless the materials can be sorted and separated after collection.

Propositions for introducing additional waste streams for biodegradable and compostable plastics may complicate the existing (and already strained) waste management system. As indicated in Section 3.1.ii.a on consumer attitudes and behaviour, consumers already struggle to ensure that the correct household waste is distributed between general, recycling and food waste bins correctly (Kramer and Yoeli, 2023; Oluwadipe et al., 2021). BCP should be designed in a way that they can be processed within existing waste management collection frameworks, such as being compatible with either reuse, recycling or composting systems, to avoid the need for entirely new waste collection streams. Interviewees indicated that the current waste management system *post-collection* is what will need to be adapted to process biodegradable and compostable plastics to avoid putting further burden on consumers.

Based on the above the following key interventions for technology and infrastructure should be considered:

- **Invest in, or incentivise innovation to generate materials that can be composted in the general conditions.** Funding should be directed towards research and development projects aimed at creating new biodegradable materials or improving existing ones to ensure they degrade efficiently at lower temperatures to be compatible with home composting systems, or the natural environment given that there will be a lag time for all waste to be sufficiently managed without any products entering the environment (including aquatic and marine environments), particularly for products that necessitate single use and cannot be reused.

d. Policy and regulation

Given the nascency of biodegradable and compostable plastics, the legislative landscape in the UK corresponding to these materials is relatively limited. Stakeholders interviewed highlighted that the UK is lagging behind the rest of Europe and the United States of America when it comes to regulating the production, design, testing, and management of these materials. At present, the following strategies or regulations relate to biodegradable and compostable plastics in the UK:

- Our Waste, Our Resources: A Strategy for England, published in December 2018, which sets out how the government will minimise waste by moving towards a more circular economy. The primary activity within this strategy relating to biodegradable and compostable plastics is to launch a call for evidence on the development of standards for bio-based and biodegradable plastics, which was completed in 2021(Defra, 2021).
- Series of standards that exist such as BS EN 13432 which is European Standard adopted by the UK, specifying requirements for packaging recoverable through composting and biodegradation. It provides a certification process for compostable plastics, ensuring that products labelled as such meet strict criteria for biodegradability, compostability, and minimal environmental impact.
- The single-use carrier bag charge aims to reduce the use of single-use carrier bags and encourage more sustainable alternatives, including reusable, biodegradable, or compostable options. While not a direct regulation on the biodegradable or compostable plastics themselves, it has implications for the use of plastic bags made from these materials.

The following policy and regulatory considerations for the circularity of BCP have been identified:

Within existing regulations for plastics, there is little to no distinction between biodegradable or compostable plastics and conventional fossil-fuel based plastics. For example, the Plastic Packaging Tax makes no distinction between BCP and conventional plastics. The Packaging and Packaging Waste Regulations also do not make the distinction. Given the inherent differences in these materials and their associated waste management requirements and impacts, making BCP subject to the same legislation as fossil-fuel based plastics risks contention and creating barriers to further development in the bioplastics industry.

The differentiation between the terms 'compostable' and 'biodegradable', and their associated functional properties is highly necessary for ensuring clarity and consistency in managing these materials, yet current policies fall short of mandating clear compliance with these definitions, relying instead on guidance alone. This issue underscores the need for processes and manufacturing standards that leave no loopholes for interpretation, ensuring that all stakeholders have a consistent understanding of the materials' environmental impacts and management requirements (Westlake et al., 2023). Enforcing strict compliance would streamline waste processing, reduce contamination, and support the transition to a circular economy by making it easier for consumers and waste management facilities to correctly dispose of these materials. By clarifying these definitions in policy, the government can foster greater innovation in material development, ensuring that new products are designed from the outset to meet these stringent criteria.

Regulatory frameworks are critically required to prioritise and enforce the reuse, recycling, and, when necessary, composting of these innovative materials. Significant investment is needed to seamlessly incorporate the reuse and recycling of BCPinto the existing waste management infrastructure. A primary challenge here is the complexity of sorting BCP, especially when their physical properties closely mimic those of traditional plastics. Addressing this sorting challenge through regulation would help to overcome this barrier.

The development of biologically based BCP should ensure that local sourcing practices for raw materials are employed to have the maximum benefit, particularly in reducing the carbon footprint associated with their production and distribution. For example, the transportation of bagasse (sugarcane residue) and other raw materials from global locations to manufacturing sites contributes significantly to carbon emissions, potentially offsetting the environmental advantages offered by the compostable nature of the final products. Therefore, when creating bio-based BCP, prioritising local sourcing and production of these materials can substantially lessen the overall environmental impact.

The lack of coherent established standards for biodegradability raises a number of environmental issues associated with toxicity and microplastics. Products that can be composted are generally plant based, and biodegradable plastics such as PLA can be alcohol based from biological and microbial fermentation processes. To pose a measurable environmental advantage, BCP must have good biodegradability profiles. However, there is a general lack of clarity concerning biodegradability since the definition may allow microplastic-forming materials to be termed as biodegradable in some instances. There are some standards that have a degree of limits for BCP to be sold as a certified biodegradable such as EN 13432 and EN 14995, but there are also allowances for these standards to include a degree of non-BCP, with some gaps for toxicity. For example, the British Standards Institution standard for biodegradable plastic (2020), PAS 9017, identifies that, predominantly for polyolefins, the plastic must pass tests proving decomposition in the open air on land within 2 years, leaving behind nothing but a non-toxic wax substance and strictly no microplastics or nanoplastics. However, the standard does not check for decomposition in landfill, freshwater, or the sea, leaving a huge gap in the standards. Moreover, when considering nutrients and toxicity in agriculture for compostables, the current standards, such as PAS100, which focus on the growth impacts of compostable materials, typically limit their testing to a narrow scope of applications, often only on tomatoes. This narrow focus overlooks the potential for diverse interactions between different biodegradable materials and a wide array of food plants.

Based on the above the following key interventions for policy and regulation should be considered:

- **Improve the existing standards for biodegradable and compostable plastics to include tightened criteria for microplastics, toxicity, degradation conditions, and labelling; including on imported materials and products.** The application of these standards should be mandated and enforced, and also fully apply to imported materials of this nature.
- **Standards should be linked to a certification scheme rather than just being a stand-alone entity.** This would provide further assurance to both industry and the public that products have been tested and independently verified to comply with an existing standard.
- **Support through research financing, or collaborative innovation efforts, the development and promotion of accessible and affordable rapid testing methods for biodegradable and compostable materials.** This would make it simpler for manufacturers to understand and meet the required degradation parameters.
- **Incentivise or mandate the sourcing of local raw materials for the production of bio-based materials.** This would help to reduce carbon footprint and support local economies, enhancing the sustainability of biodegradable and compostable products.
- **LCA criteria should be adopted and be applied as required by law for the development of new materials** as identified in Section 3.ii.b.

e. Waste hierarchy

The current system for BCP is placed predominantly at the recovery (waste to energy) and waste management (disposal) stages of the waste hierarchy (Figure 3). When considered as resources on their own in terms of circularity, BCP are not yet fully circular, especially compostables, which are designed to be downcycled into compost. If the compost was used specifically for the production of the raw materials upon which the biodegradable and compostable plastics were based, this would begin to close the loop for this material, but a full LCA would be needed to determine the true benefits of this approach. Plant-based BCP can offer environmental benefits over petroleum-derived plastics, but there is no additional benefit to be gained from the fact that they are compostable if they are not ultimately composted (Velvzhi et al. 2020).

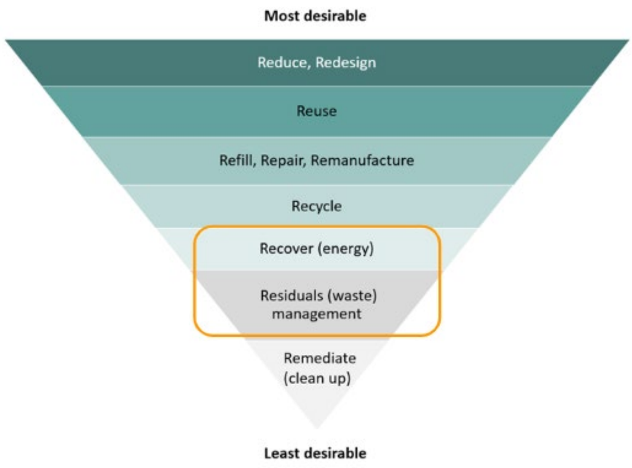

Figure 3. Current position of biodegradable and compostable plastics on the waste hierarchy.

In terms of moving biodegradables and compostables up the waste hierarchy to reuse, there are a number of barriers, the primary one involving their most important feature: biodegradability. With regards to the physical and chemical properties of compostable plastics, there is a trade-off between durability and compostability. Bio-based BCP that are developed to be durable are usually not compostable outside of industrial composting facilities (Song et al., 2009). Conventional polymers remain the preferred options among the possible materials for a long-life product. Therefore, to facilitate the transition towards reusable BCP products, would be required and their properties would need to match the properties of conventional polymers. BCPcould still play a role in this transition for items which could not be replaced with reusable or recyclable options (Springle et al., 2022).

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for biodegradable and compostable plastics (Table 3).

Overall potential for circularity:

Currently, findings from the literature indicate that this material is not yet circular but does contribute to a circular economy for plastics. To be considered fully circular, BCP would need to meet a number of certain criteria that differs from the existing system. First, BCP would need to be obtained from renewable or recycled resources and their production would need to be reliant on the use of renewable energy, which is true for all types of plastic production (Ali et al., 2023; Rosenboom et al., 2022; Westlake et al., 2023). The literature indicates that for BCP to fit into a circular material flow, waste infrastructure and systems would need to be available in terms of end of life options. In addition to a host of additional changes (e.g., consumer behaviour), having these systems in place would support biodegradable and compostable plastic products to contribute to the circular economy, and reduce detrimental impacts such as plastic leakage into the environment (Cucina et al., 2021; Nanda et al., 2022; Springle et al., 2022). Third, full biodegradability profiles would need to be evaluated, validated and shown to occur in real life conditions (Nanda et al., 2022). Fourth, BCP should be able to be reused as many times as possible before proceeding to material recovery, which is also true of all other plastic types (Lamberti et al., 2020).

Table 3. Interventions to transition to a circular system for biodegradable and compostable plastics, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Education and awareness raising activities for consumers on the realities of bioplastics.	National	Civil society, Retailers, policymakers	High
Clear guidelines for consumers on how to handle and dispose of biodegradable and compostable plastics.	National	Government, Industry	High
Incentivising the return of BCP to the correct reuse, recycling or waste management streams.	National	Civil society, Industry, Government	High
Incentivising the development of sustainable BCP to balance out the market.	National	Industry	Medium
Removing incentives or subsidies on fossil fuels that favour virgin plastics to balance the market.	National	Government	High
Removing trade barriers to biodegradable and compostable plastics.	Regional, international	Government	Medium
Introducing a mandatory minimum set of LCA indicators on which actionable policy can be based to define substitutes which should be produced.	National	Government, Academia, Industry	High
Invest in, or incentivise innovation to generate materials that can be composted in the general conditions.	National	Government, Academia, Industry	High
Set a target for the introduction of a country-wide system to process biodegradable and compostable plastics after collection along with a roadmap for delivery.	National	Government, Industry	High
Improve the existing standards for biodegradable and compostable plastics to include tightened criteria for microplastics, toxicity, degradation conditions, and labelling; including on imported materials and products.	National, international	Government, Academia, Industry	High
Standards should be linked to a certification scheme rather than just being a stand-alone entity.	National, international	Government, Industry	High
Support through research financing, or collaborative innovation efforts, the development and promotion of accessible and affordable rapid testing methods for biodegradable and compostable materials.	National	Government, Academia, Industry	Medium

iv. Gaps in evidence

A number of gaps in evidence exist in determining the circularity for biodegradable and compostable plastics, including:

- The length of supplier contracts across the whole life cycle and how these impact circularity.

- How this material or product is packed for onward transport and associated impacts on the products' design or choice of material, the impacts on the volume that can be purchased, and whether the packaging for transport leads to excess stock or waste.
- The feasibility for the reuse of biodegradable and compostable materials.

3.2 PHA in all settings

i. Life cycle stages and circularity

Polyhydroxyalkanoates (PHAs) are naturally occurring biodegradable organic polymers, and are the most popular type of BCP (Rajvanshi et al., 2023). PHAs are energy storing compounds produced when microbes grow in nutrient limited environments with excessive carbon, meaning that PHAs also act as a carbon sink (Rajvanshi et al., 2023). The production of roughly 1kg of PHA saves 30 MJ of fossil energy and 2 kg of CO2 emissions when compared to the production of Petroleum-based plastics (PBP) (Wang et al., 2023).

PHAs are produced naturally by microbes through bacterial fermentation in response to ecological stress, and can be found in diverse environments such as sediments from coastal water bodies, the marine environment, rhizospheric soil, and sludge (Rajvanshi etal., 2023). The most reliable and cost effective way to produce PHAs is through the fermentation of sugars and fatty acids, which can be extracted from food crops such as corn starch, sugarcane and vegetable oil by microbes (Zytner et al., 2023). A variety of microbes can be used in production, including microalgae and mixed microbial cultures (Rajvanshi etal., 2023). PHAs can also be produced through enzymatic catalysis and synthesis within genetically modified plants, although this is less efficient (Zytner et al., 2023).

Commercially, PHAs have been used in bulk commodity plastics, medicine, fishing lines, agriculture and aquaculture (Ladhari et al., 2023). PHAs have also been used for single-use items, such as plastic bags, and food service items such as plates, cups and cutlery (Dominish et al., 2023). A growing "PHA industry", consisting of over 25 companies and over 30 brands, signifies the advancement of PHAs as a conventional plastic product commercially and industrially (Mukherjee and Koller, 2022; Zytner et al., 2023). PHAs have garnered investment and commercial interest due to their ability to safely biodegrade across a range of environmental factors, such as temperature, availability of water, and oxygen, and the presence of decomposing microbes such as fungi, bacteria, and algae via mineralization to methane, water, carbon dioxide, biomass, and inorganic compounds (Folino et al., 2020). By 2027, production is expected to reach 570 kt/year which is indicative of their rapid growth and traction (Pesante and Frison, 2023).

PHAs can include additives to improve design and manufacturing limitations, such as poor processability, brittleness, hydrophilicity, poor moisture and gas barrier properties, low compatibility, and poor electrical, thermal, and physical properties. Generally, plasticizers can be added to bio-based plastic materials however their addition brings environmental safety issues and can affect biodegradability (Rajvanshi etal., 2023). The resultant chemical composition of the PHA can cause baseline toxicity, oxidative stress, anti androgenicity, and estrogenicity (Zimmermann et al., 2020 Rajvanshi et al., 2023). Such chemical modifications can impact biodegradability and raise environmental safety issues, the extent to which is not clearly defined (Rajvanshi et al., 2023).

PHAs are known for safely degrading in a variety of environments, with degradation beginning when the bio-based biodegradable comes into contact with microflora present in composting facilities, in soil, or in water (Mukherjee and Koller, 2023). Biodegradation results reported in the literature can vary significantly depending on environmental factors (such as microbial activity of the environment, exposed surface area, moisture, temperature, pH, and molecular weight) and the type of PHA involved (Rudnik, 2013). For example, in marine environments, it can take between 1.5 and 3.5 years for a PHA water bottle to degrade (Dilkes-Hoffman et al., 2019) compared to degradation between 20 and 45 days in freshwater with sufficient humidity, oxygen, and a sufficient number of microbes (Moshood et al., 2022). This is in contrast to non-biodegradable plastics, which can have a degradation time of between 100 and 1000 years (Moshood et al., 2022).

Despite relatively fast degradation times, PHAs and biodegradable plastics in general are still considered pollutants when lost to the environment due to impacts on wildlife and physical contamination (Mukherjee and Koller 2023; Dominish, Berry and Legg, 2023). Degradation will take differing lengths of time dependent on environmental factors, which will mean that environmental impacts will persist throughout degradation. Coupled with a lack of information regarding collection, disposal and public perceptions that biodegradable plastics degrade in any conditions, this could cause significant impacts on natural environments as noted in Section 3.1 (Fletcher et al., 2024; Mhaddolkar et al., 2024).

Across the life cycle of PHA, the primary barriers exist in the design and manufacture stages, which is also where the main opportunities for circularity lie (Figure 4). Several barriers and opportunities for circularity can be identified from the lifecycle of PHAs, detailed in Table 4. Given that PHAs are a type of biodegradable plastic there are several overlaps to Section 3.1, but specific considerations for PHAs are highlighted here.

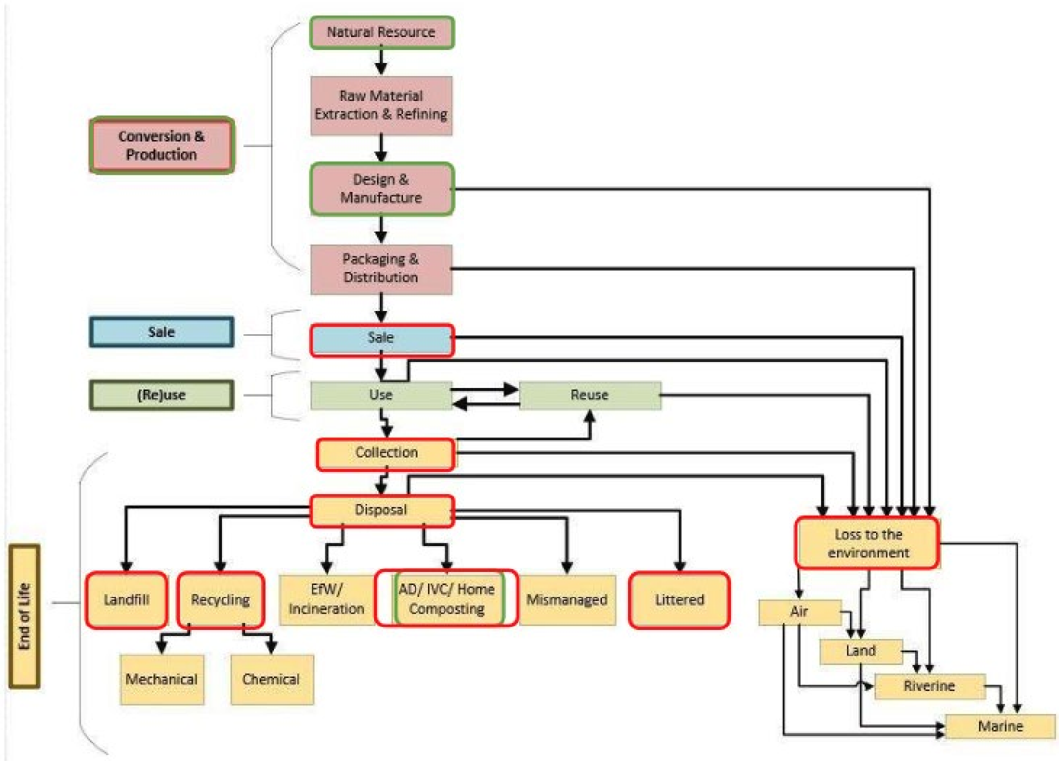

Figure 4. Barriers and opportunities to circularity for PHA by life cycle stage

Table 4. Overview of identified barriers and opportunities in the life cycle of PHA

Life cycle stage	Barriers	Opportunities
Natural resource	● PHAs are roughly four times the price of conventional plastics due to the high cost of carbon substrates, purification steps required in PHA production, high energy requirements needed during cultivation of raw materials, sterilisation in pure culture fermentation and downstream processing (Arcos-Hernandez et al., 2013; del Oso et al., 2021). Substrate costs can account for up to 50% of the total cost of production (Rajvanshi et al., 2023). ● PHAs have similar barriers as listed for biodegradable plastics in Section 3.1, including agricultural pollutants, need for biomass leading to land clearing, and crop competition influencing food security (Dominish et al., 2023) .	● Diversifying the feedstocks (or primary product) required for the growth of bacteria required for PHA production would enable greater circularity (Zhou etal., 2023). ● Widely available and inexpensive feedstocks should be sought, such as waste stream material. This will reduce the need for virgin materials and minimise total waste, which could enable a closed-loop system in a circular economy (Zhou etal., 2023). However, in the UK waste reduction targets would work against this. For example, converting organic waste streams into volatile fatty acids would significantly reduce the cost and could improve the environmental performance of PHA production (Atasoy et al., 2018; del Oso et al., 2023). Additionally, using different waste streams from industry, agriculture, and daily life for PHA production, such as sugar cane molasses, pulp and paper mill, and multiple types of wastewater (Zhou et al., 2023). Food waste can also be used in PHA production, and can simultaneously decrease production costs and decrease food waste (Zytner et al., 2023)
Raw material extraction & Refining	-	-
Design & Manufacture	● High production cost limits the scale-up of PHA production. Factors such as culture conditions including physical parameters (pH, temperature, carbon/ nitrogen/ phosphorus ratios), type of substrate, optimization strategies, selected microbial community, etc impacting overall PHA production and yield, further affecting the market value of the end product (Sabapathy et al., 2020; Tsang et al., 2019). The high cost of enzymes limits the mass production of such bio-based polymers (Arcos-Hernandez et al., 2013). ● Natural polyphenols and plasticizers are occasionally added to bio-based plastic materials to improve material and physical limitations however their addition brings environmental safety issues and can affect biodegradability, .The implications of plasticizers on biodegradability are not clear (Bonnenfant et al., 2022; Rajvanshi et al., 2023). Addition of plasticizers can also cause baseline toxicity, oxidative stress, anti androgenicity, and estrogenicity (Zimmermann et al., 2020).	● High substrate costs can be mitigated by substitution with cheap carbon sources from waste streams, limiting the need for virgin materials and reducing waste, which may increase the economic competitiveness of PHA commercialization. (Wang et al., 2023) ● Using low-cost carbon sources for fermentation, such as microalgae. Microalgae has diverse habitats, including waste water, and does not compete with traditional agriculture for resources (Bin Abu Sofian et al., 2023; Możejko-Ciesielska et al., 2023; Zytner et al., 2023).. ● Using methods such as biorefinery can reduce the cost of production and will also make it possible to obtain multiple products combined in PHA production, making production more widely efficient (del Oso et al., 2023). ● The by-products of PHA production can be used for animal feed, pet food and dietary supplements among other uses (Pesante and Frison, 2023)

Packaging & Distribution	-	-
Sale	● Additives (such as natural polyphenols and plasticizers) could impact biodegradability of PHAs, which presents challenges for sale and marketing, although this has not been studied (Expert interview)	
Reuse	-	● Reused as primary raw materials, although evidence for this is limited (Expert interview)
Collection	● Proper disposal and sorting practices are often not well known or established (Nandakumar et al., 2021) ● Acceptance of biodegradable plastics at composting facilities is limited, so biodegradable plastics end up in landfill (Dominish et al., 2023) ● Same as Section 3.1	
Disposal	● PHAs produce methane when anaerobically degraded, which occurs in oxygen limited environments such as landfill (Dominish et al., 2023)	
Loss to the	● Barriers are the same as identified in Section 3.1	● Opportunities are the same as identified in Section 3.1

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

PHAs, as a type of bio-based plastic, have the same broader consumer attitudes and behaviour implications as biodegradable and compostable plastics, detailed in Section 3.1. Specific consumer concerns regarding PHAs were not identified in the literature.

b. Economics

Within the broader context of BCP, several general challenges are relevant to PHA production. These include the need for appropriate and specific waste management infrastructure, purchasing cost of BCP, and an uneven playing field between conventional plastics and BCP. These challenges are outlined in more detail in Section 3.1. Despite the attractiveness of PHAs as a degradable alternative to non-bio plastic and its growth as an industry, several specific economic factors present barriers to circularity. PHAs are roughly four times the price of conventional plastics, with the market price of PHA polymers being approximately €5 per kg, which is almost 6 times higher compared to petroleum-based plastics (€0.8–1.5 per kg). Industrial production is limited by two factors: the cost of material, and cost of production (van den Oever et al., 2017).

PHA production is expensive compared to conventional plastic production due to the cost of materials. PHAs are produced through microbial fermentation of feedstock (such as sugars and fatty acids). The feedstock can account for up to 50% of the total production cost, representing a significant barrier to production (Zytner et al., 2023). Wang et al., (2023) attribute high production costs to the use of pure sugar substrates in production, and Arcos-Hernandez et al., (2013) attributes high production costs to carbon substrates. To combat this, abundant and low or zero-cost carbon sources, such as agricultural residues, forest residues, agro-food processing waste, and dedicated energy crops can be used (Zytner et al., 2023).

PHA production is expensive compared to conventional plastic production due to inefficiency and complexity of process. Different methods of PHA production exist, but no standard analysis of efficiency (cost or labour) exists. PHA production can be disaggregated into phases, all of which have considerations for efficiency and cost. For example, there are significant economic and process efficiency implications for biomass pre-treatment technologies, which can lead to higher or lower fermentation yields (Zytner et al., 2023). The high cost of reactors and energy required during biomass pretreatment could contribute significantly to overall process sustainability. Extracting and estimating PHA content in microorganisms requires multiple purification steps with organic solvents, in processes described as “challenging, tedious and expensive” (Behera et al., 2022). Additional complexities in production which contribute to a general higher cost of PHAs include sterilisation, inadequate microbial growth, and inefficient carbon-to-PHA conversion (Rajvanshi et al., 2023).

Based on the above the following key interventions for economics should be considered:

- **Invest in re-usable low or zero-cost carbon sources.** Reusing carbon from waste streams, such as agricultural residues, forest residues, and agro-food processing waste, will improve circularity. However, as noted above, UK waste targets will work against this.
- **Invest in research to improve efficiency of PHA production.** This will decrease the amount of energy and resources required for production of PHAs.

c. Technology and infrastructure

In general, specific information about waste management infrastructure in the UK for PHAs is limited, with information focusing on broader BCP. As outlined in Section 3.1, BCP waste is not sorted separately from other plastic waste streams, leading to presence in landfill (in which anaerobic PHA degradation releases methane), contamination of conventional plastic recycling and reduced degradation.

PHA degradation depends on environmental conditions, which limits composting. While PHAs are marketed and understood to biodegrade across a broad range of environmental factors, a study of home composting undertaken in the UK in 2022 indicated that BCP did not degrade in home composting facilities (Purkiss et al., 2022). Purkiss et al., (2022) did not specifically include analysis of PHA, but included it as part of a broader category of biodegradables . From this study, it was determined that home composting was an inadequate method of waste processing, thus necessitating investment in controlled and industrial waste processing for BCP.

Innovative and more circular forms of PHA production are still at low technological readiness levels (del Oso et al., 2023). As outlined above, PHAs can be generated from waste streams but this requires wholescale investment in ensuring that waste streams are optimised and can provide a constant source of feedstock for PHA production. Thus, investment in technology and infrastructure to accommodate this is required to ensure consistent resource availability in line with targets to reduce waste generally.

Based on the above the following key interventions for technology and infrastructure should be considered:

- **Invest into waste sorting infrastructure to isolate PHAs.** This will prevent contamination of conventional plastic recycling and prevent PHA presence in landfill, which will release methane upon anaerobic degradation.
- **Prioritise further research or public awareness regarding home composting of BCP.** Consumers can be confused about the differences between biodegradable plastic and compostable plastic leading to incorrect disposal, for example, domestic composting of biodegradable plastic (Fletcher et al., 2024; Mhaddolkar et al., 2024; Taufik et al., 2019),

d. Policy and regulation

The broader context of BCP regulation is still emerging, as outlined in Section 3.1, and PHAs fall under the remit of larger BCP policy and regulation. A regulatory framework for PHAs should include consideration of production, use, disposal and reuse (Samadhiya et al., 2022; Rajvanshi et al., 2023). However, two specific PHA considerations are highlighted here.

The use of plasticizers in PHA products should be regulated. Plasticizers are included in PHA products to accommodate for manufacturing and design limitations against conventional plastic products. For example, plasticizers reduce brittleness and poor processability (Rajvanshi etal., 2023; Zimmermann et al., 2020, and as outlined in Section 3.2). The use of plasticizers should be regulated to ensure that there are no unexpected environmental impacts upon degradation, and that PHA products are limited in toxicity. Additionally, further research into more ecologically sensitive plasticizers should be encouraged.

Policy and regulation should prioritise reuse where possible as an end of life pathway for PHA based BCP, or alternatively, industrially regulated recycling. While the unique selling point and attractiveness of PHA products often emphasise their ability to degrade naturally in a wide variety of environments, the products are still environmental contaminants that represent a range of hazards while they degrade. As noted in Section 3.1, coupled with public perception, this could lead to increased incidences of littering (Ansink, Wijk and Zuidmeer 2022), although there is no direct evidence of this. Additionally, the limitations of home based composting of PHAs and broader BCP (Purkiss et al., 2022) necessitate tighter regulation and signposting. Therefore, policy and regulation should prioritise reuse over domestic composting. As noted in Section 3.1, however, there is a lack of regulation and policy in place to facilitate the investment needed for industrial composting in many cases.

Based on the above the following key interventions for policy and regulation should be considered:

- **Regulate what plasticizers can be used and to what extent.** Currently, no regulation or policy or standards govern what plasticiers can be added which presents risks for biodegradability and toxicity of PHA based products.
- **Policy should prioritise designing products for reuse first, and then incentivize the use of BCP for difficult to reuse or recycle items.** For example, takeaway containers can be designed for reuse in closed systems, but could be BCP based in open systems where reuse is not possible, such as takeaway containers.

e. Waste hierarchy

PHAs are currently placed at the 'waste management' level of the waste hierarchy (Figure 5). The majority of PHAs are disposed of in landfill , however this still raises several concerns regarding circularity and sustainability. As discussed in Section 3.1, while the impacts of biodegradable products are less harmful than that of pure plastic in the right composting environment, PHAs cannot be considered fully circular unless the product is used to degrade into compost to create more feedstock for future plastic production. Additionally, PHAs are unsuitable for home composting and often require industrially controlled composting conditions for the product to fully break down.

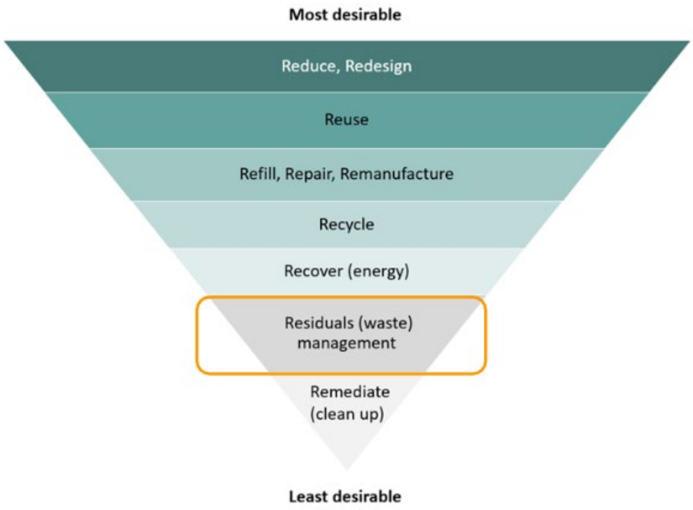

Figure 5. Current position of PHAs on the waste hierarchy.

PHAs are a good substitute for unavoidable single use items that are often food contaminated before disposal, however care needs to be taken to ensure proper disposal and avoid anaerobic degradation, which produces methane. This includes items such as takeaway food containers which will be contaminated with food waste and therefore difficult to recycle. However, given the strict decomposition environments needed, it must be questioned if PHA should be used as a wide substitute for items that can be designed to be reused. An additional consideration is the unknown added toxicity of plasticizers which are often used to accommodate design and manufacturing limitations. In short, PHAs should be used for items that are required to be single use, and alternative materials (preferably non-plastic) should be used for items that can be designed to be reused. Therefore, moving PHAs up the waste hierarchy would primarily entail redesigning for reusable products.

Based on the above the following key interventions for the overall circularity should be considered:

- **Introduce guidance regarding what products can be made compostable in-line with a reuse agenda.** This would involve incentivising design for reuse in product design the first instance, before using BCP or PHA in product design.

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for PHAs (Table 5). Many of the interventions from Section 3.1 are also applicable to PHAs. Table 5 outlines the PHA specific interventions required for circularity.

Overall potential for circularity

PHAs and BCP have a natural fit towards circularity given their ability to degrade naturally into compost or primary raw materials, although this is still an emerging area of research and infrastructure is insufficient. Despite this natural propensity, caution needs to be exercised. To be considered fully circular, PHAs would need to satisfy a range of circular principles. Firstly, PHA would need to be exclusively produced from renewable carbon or reused waste materials. The process of producing PHA would need to be streamlined for economic and environmental efficiency. Significant investment into waste infrastructure (including collection, recovery and recycling) would be required to prevent contamination of the natural environment or contamination of recycled plastic. Investing in such infrastructure would allow for PHAs to be recaptured and recycled.

Table 5. Interventions to transition to a circular system for PHA, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Invest in re-usable low or zero-cost carbon sources from waste streams, such as agricultural residues, forest residues, agro-food processing waste, and dedicated energy crops can be used	International	Industry	High
Invest in research to improve efficiency of PHA production, decreasing the amount of energy and resources required	International	Industry	High
Investment into waste sorting infrastructure to isolate PHAs. This will prevent contamination of conventional plastic recycling and prevent PHA presence in landfill, which will release methane upon degradation.	National	Government	High
Invest in further research or public awareness regarding home composting of BCP	National	Government	Low
Regulate what plasticizers can be used and to what extent.	National	Government	High
Policy should prioritise reuse when creating end of life regulation for PHA bio-based plastic.	National	Government	High
Introduce guidance regarding what products can be made compostable in-line with a reuse agenda.	National	Government	High

vi. Gaps in evidence and assumptions

Generally, literature tends to focus on the broader social and infrastructural landscape of BCP, and the technical manufacturing of PHAs. Thus, the following gaps exist:

- The impacts of plasticizers on the ability of PHA to degrade in natural environments is poorly understood
- What end products PHAs can be turned into remains poorly understood. For example, there is some potential for PHAs to be recycled into animal feed, but this has limited evidence available.
- Whether length of supplier contracts impact circularity across design and manufacture, packaging and distribution, collection and disposal
- How PHA is packed for onward transport, and whether this impacts its design or choice of material
- How PHA is packed for onward transport, and whether this affects the lot size/ amount that can be purchased
- Whether the packaging and distribution affects design choice.

3.3 PVC in Construction

i. Life cycle stages and circularity

One third of overall waste in the UK comes from the construction industry. This represents 120 million tonnes of waste every year. About 44% of UK construction waste ends in landfill (Davis et al., 2021). Data from Defra revealed that the UK construction industry has increased its plastic waste output by 45.72% in the last two years (Defra, 2023).

Polyvinyl chloride (PVC) is a thermoplastic material made by the polymerization of vinyl chloride (VC) derived from petroleum and sodium chloride. The PVC manufacturing process involves several steps including the production of VC through the chlorination of ethylene, polymerization of VC to form PVC resin, and processing of PVC resin into various products. The high economical significance of PVC is primarily due to its low production costs and its favourable mechanical properties, the most significant of which being high chemical resistance, thermal stability and durability due to resilience to water and weather conditions. Its versatility allows for a wide range of applications across various industries, including construction, automotive, healthcare, and packaging. Approximately 70% of PVC in the EU is utilised in the construction industry and generally comprises long-lasting and low-maintenance products (Lewandowski & Skórczewska, 2022). Typical uses for PVC in construction include flooring materials, roofing materials, wall coverings, exterior siding, sheets, pipes, window frames, and wire and cable sheathings, fastening elements, and coatings (Thornton, 2000).

Despite its extensive production and wide applications, PVC has been referred to as a “contested” versatile material because of the environmental and human health concerns throughout its lifecycle that have been raised by scientific research and regulatory bodies (Turner & Filella, 2021). The high versatility of PVC is in the most part due to the use of additives such as plasticizers which vary in amount in different PVC products determining flexibility and durability. Generally, flexible PVC may contain up to 70% of plasticizers while rigid PVC contains less than 10% of plasticizers (Peng et al. 2020). The use of such additives as plasticizers in PVC production have raised environmental protection and society health issues because phthalate plasticizers often used in PVC have been found in soils, sea water and sediments, in living organisms and even in human breast milk (Czogała et al., 2021). Moreover, PVC is a high-energy-demanding material and its production relies on the use of ethylene obtained from the petrochemical industry, presenting challenges of extraction and reduction of natural resources such as fossil fuels and increased carbon emissions (Rosenboom et al. 2022).

Across the life cycle of PVC in construction there are multiple barriers to circularity that exist in the: natural resource, design and manufacture, reuse, collection, disposal and loss to the environment stages. The main opportunities for circularity lie in the natural resource, design and manufacture and recycling (Figure 6). A summary of the barriers and opportunities are presented in Table 6.

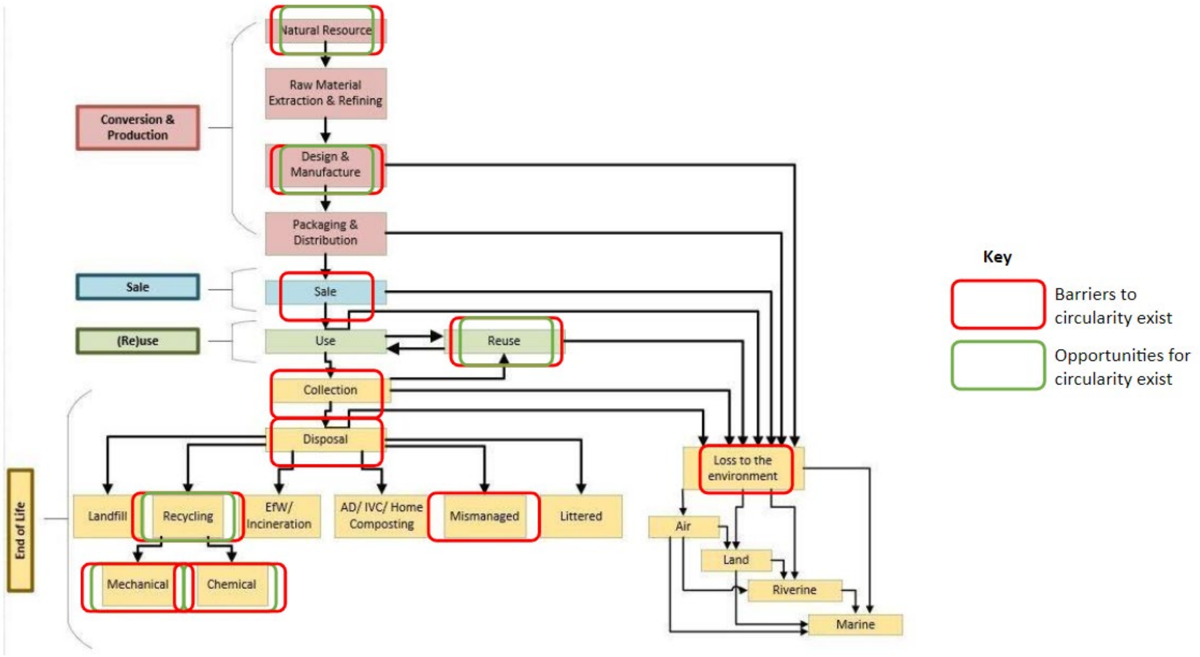

Figure 6. Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of PVC in construction exist.

Table 6. Overview of identified barriers and opportunities for the circularity of PVC in construction by life cycle stage.

Life cycle stage	Barriers	Opportunities
Natural resource	● PVC production relies on ethylene obtained from the petrochemical industry and contributes to the pressure of global fossil fuel extraction (Rosenboom et al. 2022). ● The production of PVC as a high-energy-demanding material presents environmental challenges related to energy consumption and carbon emissions (Correa et al., 2019). ● PVC is non-biodegradable and can persist in the environment as pollution (Lewandowski & Skórczewska, 2022). ● The use of hazardous heat stabilisers, now prohibited, such as cadmium and lead can negatively impact existing waste management systems and the environment because of waste degradation and release of these components into the environment introducing ecotoxicological issues (Czogała et al. 2021; Turner & Filella, 2021). ● The production of the PVC polymer involves the release of feedstocks such as ethylene dichloride (EDC) and vinyl chloride (VC) which pose human and environmental health risks (Thornton, 2002).	● Considered a cost-effective natural resource as PVC is derived from readily available and relatively inexpensive raw materials, primarily chlorine obtained from salt and ethylene from natural gas or petroleum (Lewandowski & Skórczewska, 2022). ● The durability of PVC under natural conditions could constitute a valuable raw material for recycling as long-lasting PVC in construction related products are generally not significantly degraded post-consumer (Lewandowski & Skórczewska, 2022).
Raw material extraction & Refining	-	-
Design & Manufacture	● The manufacturing process of PVC is associated with high energy requirements, mostly dependent on fossil fuel resources, leading to challenges when considering carbon emissions and environmental impact (Correa et al., 2019). ● The high versatility of PVC is dependent on the incorporation of various additives, including heat stabilisers, fillers, pigments, gliders and as well as a significant amount of plasticizers (Thornton, 2002) which if released into the environment present additional health and environmental concerns such as toxicity (Petrović & Hamer, 2018). ● The mercury-based method of chlorine production releases mercury into the environment contributing to the associative health and environmental risks (Thornton 2002). ● The versatility of PVC allows for a high diversity of PVC products with varying PVC content available on the market and may create problems for recycling (Lewandowski & Skórczewska, 2022). ● Extended lifetime poses challenges for recycling as older products may contain prohibited substances or lack identification of their production date (Lewandowski & Skórczewska, 2022). This makes efficient sorting and separation difficult in the face of evolving technologies and substance restrictions (Baitz et al. 2004).	● The use of eco-friendly alternatives including epoxidized vegetable oils, such as epoxidized soybean oil and epoxidized linseed oil, offer similar or improved mechanical properties providing environmentally friendly alternatives for conventional petroleum-based plasticizers and stabilisers sourced from renewable resources (Marceneiro et al. 2022). ● Initial assessment of utilising raw materials such as rock salt (sodium chloride) in PVC synthesis results in only 43% of the polymer mass coming from petrochemical raw materials, offering an ecological advantage (Lewandowski & Skórczewska, 2022). ● New technologies for the production of vinyl chloride from natural gas hold prospects for further reducing the carbon footprint of PVC (Lewandowski & Skórczewska, 2022).

Packaging & Distribution	-	-
Sale	● Lack of correct information and clear instructions for handling of PVC in construction has influenced consumer usage and subsequent disposal practices (Lewandowski & Skórczewska, 2022) resulting in inappropriate waste disposal and continued use of landfills and incineration as the most common form of disposal. ● Misconceptions of PVC recyclability can negatively affect the sales of PVC (Lewandowski & Skórczewska, 2022).	
Reuse	● PVC is highly durable with certain products with long lifetimes creating problems of pollution due to accumulation in the environment. For example, PVC utilised for underground piping presents a challenge to reuse as this material is often lost to the system due to an inability or lack of a cost-effect method of retrieval (expert interview, 2024). ● The average lifetime of PVC in construction varies. For example, PVC floor tiles or roofing materials have a moderate lifetime averaging 9 to 10 years, (Thornton, 2000) while PVC pipes, window frames, and cables (comprising about half of all PVC applications) have a lifetime of 30 years or more, with PVC pipes having an almost proven lifetime of more than 50 years (Baitz et al. 2004). ● The majority of PVC in construction ends up in landfills or incinerated due to a lack of appropriate infrastructure for PVC recycling and the high cost of separation and the poor quality of the recycled PVC (Ciacci et al. 2017).	● PVC materials in construction have high reuse potential due to their high durability and chemical stability (Baitz et al. 2004). ● Their extended life-cycle and low maintenance potential generally results in less frequent replacements in the construction industry (Baitz et al. 2004). ● Potential of eco-friendly alternatives for such components as plasticizers allowing PVC products in construction to be more easily refurbished and reused (Marceneiro et al. 2022).
Collection	● There are no established standards for sorting procedures and disposal of PVC in construction across the industry (expert interview, 2024). ● The high cost of transportation and collection due to the large volume of plastic products is a barrier to recycling (Morici et al., 2022). ● Regulatory issues associated with prohibited additives present a barrier to the recycling of these materials (Lewandowski & Skórczewska, 2022). ● The necessary high-quality standards in recycled materials needed for PVC processing further complicates the collection and sorting stages in the recycling process of PVC waste (Ciacci et al. 2017). ● Costly and advanced post-consumer recycling technology is required to separate the diverse PVC materials or simultaneous processing techniques to produce new materials with desired properties (Lewandowski & Skórczewska, 2022).	● Various sedimentation and gravimetric methods due to density difference in between plastics enable the easy mechanical separation of PVC from other plastic waste such as PET, PP and PE in the stream (Lewandowski & Skórczewska, 2022). ● Governmental support could provide regulatory and financial incentives for industry through collection and sorting equipment toward effective recycling of PVC, thereby supporting recycling over manufacturing new PVC.
Disposal	● Disposal methods such as incineration potentially release hazardous hydrogen chloride and generate dioxins and furans, which are persistent organic pollutants that bioaccumulate in the food chain and have adverse effects on human and environmental health (Lu et al. 2023). ● The incorrect thermal treatment of PVC may result in significant damage to	● Only a small amount of additional additives are necessary for recycling post-consumer PVC into new PVC products as the material re-activates upon reheating due to its high initial processing (expert interview, 2024). ● The use of microorganisms and invertebrates to assist in PVC biodegradation (Yao et al. 2022). PVC has been found to depolymerize and biodegrade in the

	installations due to the corrosive properties of the resulting gaseous products (Lewandowski & Skórczewska, 2022). ● Challenges in recycling of post-consumer PVC include: heterogeneity, low quality waste streams, diverse sources and high potential for plastics waste contamination (Ciacci et al., 2017), and the lack of advanced infrastructure and technology (Lewandowski & Skórczewska, 2022). ● High chlorine content and the presence of various other additives presents a barrier to chemical recycling of PVC in construction due to health and environmental issues associated with the release and bioaccumulation of these substances (Lu et al. 2023). ● Further barriers to effective recycling of old PVC products in construction (+30 years) is the lack of dated products and the presence of now prohibited process additives, such as lead-based thermal stabilisers and certain plasticizers (Lewandowski & Skórczewska, 2022).	gut of the mealworm *Tenebrio molitor* larvae (Peng et al. 2020), but it should be noted that this was tested on PVC lacking plasticizers and other additives. ● The continued development of dechlorination in the chemical recycling of PVC waste (Lu et al. 2023). ● New technique enables products with a high content of PVC to be separated into syngas and hydrogen chloride which subsequently can be reused in PVC production (Leadbitter, 2002). ● Feedstock recycling methods, such as processing PVC into valuable raw materials for the chemical industry, represent a slightly more advanced approach towards circularity in PVC manufacturing (Lewandowski & Skórczewska, 2022).
Loss to the environment	● The degradation of PVC requires chemical and thermal conditions not found in the natural environment leading to the problem of the accumulation of the remaining plastics in the environment (Lu et al. 2023). ● The long-term physical and chemical breakdown of PVC, especially during combustion, leads to environmental emissions of toxic organochlorine substances and additives (Turner & Filella, 2021). ● The formation of hazardous byproducts at various stages of the PVC lifecycle such as Organochlorine as well as Dioxin and related compounds raise concerns due to their persistence, bioaccumulation and toxicity in the environment (Thornton, 2000). ● The release of toxic substances due to the use of plasticizers (mainly phthalates), metal stabilisers (lead) as well as mercury-based processes for chlorine production with numerous impacts on human health and environmental contamination (Thornton, 2002). For example, flexible vinyl products release phthalates resulting in poor air-quality and foster the growth of moulds harmful to human health. The release of phthalates is associated with adverse human health risks, particularly toxic effects to reproduction and fertility.	● The use of bio-based fillers in PVC compounding such as calcite from treated eggshells to replace inorganic additives such as calcium carbonate ($CaCO_3$) to decrease the emission of dioxins resulting from PVC thermal degradation (Marceneiro et al. 2022). ● Utilising recycling PVC materials can reduce energy consumption when compared to energy input required for processing virgin materials thereby reducing CO_2 emissions (Ciacci et al. 2017; Lewandowski & Skórczewska, 2022).

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

Consumers in this context includes particularly the purchasers within the construction industry, businesses, home owners, contractors and builders.

The reuse of PVC is currently non-existent due to changing consumer tastes, trends and preferences. Few people in the UK opt for second hand building materials mostly because of the connotation that it has already been used and the perceived wear-and-tear damage to the product. Generally the perception that new is better and more durable dominates when it comes to building materials. However, this is not always the case when considering long-lasting and highly durable PVC construction materials (Expert interview, 2024). For example, windows with PVC frames are continuously discarded due to damage to the non-PVC compartments such as the glass while the PVC aspects of the product are still usable. Experts in PVC in the construction industry comment on this trend and the high potential for refurbishment and reuse of these products with the right market infrastructure and consumer willingness to reuse PVC products. Moreover, consumer preferences follow trends based on overall product perception including its environmental potential and impact on human health. PVC has been labelled the least environmental plastic and 'The Poison Plastic' by Greenpeace, furthering the notion of PVC as a waste product to be hidden and discarded rather than be kept in circulation and reused (Greenpeace, 2003).

The lack of a collection system for plastic materials in construction means that consumers may not think recyclability of PVC products is possible. There is no large scale collection system for plastic in the construction industry and this may well influence how consumers perceive PVC. There is a prevailing view of PVC as waste to be discarded and disposed of which ultimately results in their placement in landfills or incineration along with other plastics (Lewandowski & Skórczewska, 2022). This lack of plastic collection systems restricts consumer choice and belief that there are ways to utilise PVC post-consumer and limits the recycling industry.

Misconception that PVC is difficult to recycle may limit options for reuse and recycling of PVC and compromise consumer ability to dispose of plastic waste correctly. The literature indicates that consumer attitudes and behaviour towards PVC negatively affect its collection and recycling rates (Lewandowski & Skórczewska, 2022). PVC is mistakenly considered difficult to recycle due to its complex composition and its low thermal stability. This misconception, prevalent in public opinion and among those interested in polymer materials, may impact consumer and businesses choices and result in incorrect disposal behaviour. This in turn can impact the quality of material collected for recycling due to contamination from other waste products, residues within the stream and other similar density polymers, resulting in a potential barrier to circularity (Hahladakis & Iacovidou, 2018). In addition, the perception in the construction industry that products that contain legacy additives, now prohibited, are unrecyclable and harmful to human health impacts the disposal of these older PVC products. Ultimately these products will end up in landfills or incinerators, contributing to environmental pollution and resource depletion (Teuten et al. 2009, Wang et al. 2021).

Recycled PVC is often perceived as not as durable as virgin PVC. The durability of PVC is one of the defining qualities of the material promoting its continued use in the construction industry. However, there is a low acceptance of re-processed or recycled PVC material within the construction industry as shown by Oyedele et al. (2014). Consumers often view recycled material as a weaker substance with a short lifespan and a higher probability of damage and/or corrosion. It has been found that the top hindrance of the use of recycled products in construction is the lack of preference shown by designers in their specifications in the most part due to limited information and designer unfamiliarity with the product for use in the construction industry (Oyedele et al. 2014). Therefore, education is the main challenge to be overcome towards consumer acceptance of the use of recycled PVC products in the construction industry.

The waste classification system in the construction and demolition waste sector often creates confusion among the key actors involved in construction sites leading to misdescription of waste which causes issues at receiving sites. For more details see HDPE in construction in Section 3.4.ii.a.

There is sometimes misrepresentation of waste as a form of tax evasion in the management and classification of construction and demolition waste. Another issue is the misdescription of construction waste linked to tax evasion. Companies are expected to pay a standard rate for disposing of hazardous waste of £94.15 per tonne versus £3.00 per tonne for inert waste (Environment Agency, 2021). Consumers are willing to misrepresent the contents of their waste and thereby avoid paying the tax associated with plastics as hazardous waste and compromising the quality of the resultant plastic waste streams (Hahladakis, & Iacovidou, 2019). PVC is particularly problematic in this regard due to its high ability to contaminate other plastic waste as its inclusion with other types of plastic makes recovery for reuse and/or recycling impossible in the resultant waste stream (Expert interview, 2024; Jones, 2024).

Based on the barriers and opportunities for PVC in construction, the following key interventions have been identified:

- **Clear labelling of recycled and recyclable building materials.** Manufacturers as well as government bodies would need to communicate with designers, contractors, and suppliers/recycling companies about available construction products that can be reused or recycled, as well as be transparent on the toxicity of materials.
- **Educating construction teams and businesses on the recyclability of materials used.** This could include how to handle products, how to install for easier recovery, and how to efficiently manage waste on construction sites to ensure recoverable materials are directed to the correct waste streams.
- **Clarity and management of waste classification.** This would include stakeholder education on the accurate reporting of waste according to the waste classification, as well as improving the waste classifications to ensure that PVC with toxic additives are indeed considered hazardous.

b. Economics

The high economic significance of PVC is the outcome not only of its low production costs but is primarily determined by its good properties, the most important of which are high chemical resistance, durability and versatility as well as resistance to water and weather conditions (Lewandowski & Skórczewska, 2022) making it a valuable material in the construction industry. Since the 1930s, the production volume of PVC has consistently increased with 10% of the global plastic production of 368 million tonnes attributed to PVC (Czogała et al. 2021).

There is currently no large-scale market for second-hand building products. In general, PVC-related building products that are still usable for the same function as manufactured are discarded before their full potential can be realised. This is partly due to the difficulties and high costs of the additional infrastructure required for the at-scale recovery and separation of mixed material products and PVC recovery (Lu et al. 2023), but there is high potential for reuse or reuse with minor repairs in this sector (Expert interview, 2024).

The high costs of alternatives to PVC and adapting PVC production processes to allow for greater circularity can be prohibitive. The literature indicates that the use of non-plastic alternatives as well as other materials such as PE, HDPE and LDPE, as safer alternatives for many construction applications can mitigate health issues related to PVC (Petrović & Hamer, 2018). Meanwhile, PVC products in construction are often competitively priced compared to alternative materials, making them a cost-effective choice for manufacturers and consumers. The European Chemicals Agency (ECHA) report on PVC estimates that the use of polyethylene pipes are 20% more expensive than PVC while ductile iron pipes are 90% more costly (ECHA, 2023). Meanwhile, the production cost of compounds such as bio-based plasticizers from renewable sources, can be significantly higher than that of commonly used counterparts and may come with higher production costs (Czogała et al. 2021). Additionally, the use of bio-based stabilisers is hindered by their relatively high pricing and technology investment costs as well as the need for further research concerning their holistic environmental viability (Wallenwein, 2006).

The reuse and/or recycling of PVC materials via chemical and physical methods is very expensive and releases toxic chemicals and produces persistent organic pollutants. Chemical or feedstock recycling, which involves the processing of PVC into valuable raw materials for the chemical industry, requires large investments in specialised infrastructure and technology, making it potentially uneconomical (Lewandowski & Skórczewska, 2022). The reuse and recycling processes involve collection, reclamation, washing and reprocessing costs for used PVC products. These costs can be restrictive, especially during periods of lower prices for virgin PVC materials, making the economics of reuse and/or recycling less favourable (Leadbitter, 2002). Meanwhile, the large investments associated with the need to design and construct adequate industrial systems for post-consumer recycling is a potential barrier to circularity, due in most part to the high versatility of the material itself. There is a need for an initial fund injection to develop and construct technologies able to efficiently separate PVC materials with different properties and compositions and improve the quality of the waste stream and recycled material. For example, a particular challenge is the recycling of old PVC waste in construction consisting of now-prohibited and potentially hazardous process additives, such as thermal stabilisers based on lead compounds and certain plasticizers, ultimately contaminating the waste stream (Lewandowski & Skórczewska, 2022). Therefore, development of separation methods for these compounds from the raw material are necessary toward reuse and/or recycling of PVC in construction. Moreover, even when efficiently recovered and recycled, these processes lead to the release of microplastics, i.e. via the mechanical grinding of PVC. The health and impact on the environment of these persistent organic pollutants are only just beginning to be understood as problematic as toxic irritant products, and have proved to be dangerous to animal, human and ecosystem (Ojha et al., 2017).

There are hidden healthcare associated costs due to exposure to plastic chemicals throughout the lifecycle of PVC from production, use and disposal. It is difficult to estimate the medical and environmental costs due to a specific chemical with limited data available relating to PVC related chemical exposure globally and in the UK. However, a recent study from New York University shows that lifetime exposure to plastic chemicals in 2018 cost $249 billion in health care relating to preterm births, obesity, heart disease, and cancer across the United States (Trasande et al. 2024). While this study relates to all plastics, PVC production was noted as the primary player in the exposure to functional additives, in particular phthalates. Meanwhile, the PVC-specific report by ECHA makes particular note of liver cancer from worker exposure to PVC with phthalates again highlighted as of highest concern (ECHA, 2023).

Using bio-based feedstocks in PVC production while seeming to present a sustainable alternative, are generally costly and may have hidden environmental impacts. The shift towards bio-based feedstocks, while aimed at reducing environmental impact, poses several potential issues (Rosenboom et al. 2022). These barriers to circularity are summarised for biodegradable and compostable plastics in Section 3.1.i. The current production costs of bio-based materials are heavily influenced by the feedstock used, and the economic feasibility of using bio-based additives in PVC production when compared to fossil-based ones will depend on feedstock and available biotechnology (Brizga et al., 2020). Research indicates that while the move towards making PVC material from bio-based feedstocks is seen as having a sustainable impact without compromising the mechanical properties of PVC products (Marceneiro et al. 2022), the economic viability and feasibility hinge on factors like financial incentives, knowledge of market demand, and the cost-effectiveness of feedstock sources.

Based on the above the following key interventions for economics should be considered:

- **Support research and innovation on how to use bio-based, and non-toxic additives in PVC production in a way that is economically viable for the industry, accompanied by a toxic additives ban.**
- **Provide economic incentives to improve construction waste collection and separation systems for the reuse of PVC products in construction.** This could be through incentivising industry to manage a reuse or repair hub and system, for PVC materials that have been detoxified.

c. Technology and infrastructure

The manufacturing process of PVC impacts its circularity in different ways. The current industrial processes include challenges to circularity such as energy consumption (Correa et al., 2019) as well as the use of hazardous heat stabilisers (cadmium and lead) and traditional plasticizers like phthalates (Czogała et al. 2021) which have raised environmental and health concerns. PVC is a high-energy-demanding material, and its production relies on ethylene obtained from the petrochemical industry (Rosenboom et al. 2022).

There is no current infrastructure that facilitates the reuse, repair, or remanufacture of used PVC. Globally and in the UK, there are some efforts in recycling PVC in construction with the majority of PVC waste placed in landfills or incinerated (Lu et al. 2023). However, there is no push in research, industry and/or policy towards reuse with no current technology for the repair or remanufacture of PVC-related products in the construction industry. The technology and infrastructure for repair or remanufacture does not yet exist in the UK due to a number of barriers. High initial investment is required for the necessary infrastructure towards the large-scale collection, sorting as well as repairing and remanufacturing of PVC in construction. Moreover, reuse of PVC in construction is further hindered by the degradation of material and the subsequent release of toxic compounds into the environment. Recent research on the volatile organic compounds released from indoor PVC building materials (Xui et al. 2023) and the effect of chemical compounds leaching into water supply through PVC pipes (Wu et al. 2023) has found cause to be cautious. Although the impacts of these chemical compounds are still poorly understood, these issues of ecotoxicity should be of primary concern towards circularity.

The high chlorine content and use of chemicals such as functional additives in PVC production can have detrimental effects on the environment as well as serious risks to human health and can significantly affect the quality of the recovered material. Achieving the diverse range of PVC products available in the construction industry requires the use of varying amounts of additives such as stabilisers, colourants or plasticizers to obtain hard and soft variants (Czogała et al. 2021). The rigid form (<10% plasticizers w/w) is utilised in pipe construction and in doors and windows while the flexible form (70% plasticizers w/w) is generally used in plumbing in the construction industry as replacement rubber (Peng et al. 2020). Over time, these chemical compounds can be released into the environment as a result of the natural degradation of polyethylene waste through a natural light oxidation process which generates greenhouse gases (Iskander et al. 2016). Furthermore, various chemical or feedstock recycling treatments, generally suited to the rigid forms of contaminated PVC products, involve thermal degradation at extremely high temperatures and produce environmentally damaging HCl acid and chlorinated organic compounds as byproducts (Lu et al. 2023). Therefore, the development of environmentally clean techniques suitable for the removal of these chemical compounds before the material recovery process to obtain high quality recycled polymers is crucial. Currently, industry promotes Pyrolysis due to its production of valuable materials (Lu et al. 2023). However, this mechanism still produces HCl acid and is by no means circular with high energy requirements, and circulation of chemicals (Lu et al. 2023). As long as the processes for PVC production, recovery, reuse and recycling result in the release of these chemicals, and until it can be prevented from leakage, PVC in construction cannot be considered circular.

The high diversity of PVC products with mixed materials and varying amounts of PVC-content present a challenge to post-consumer material recovery. Generally from a technical perspective, there is a need to separate flexible and rigid PVC for PVC recycling while most other PVC types can be recycled together (Expert interview, 2024). In the construction industry, finished products consist of a complex mix of multiple PVC and non-PVC-related materials. In the case of windows given by experts in the PVC construction industry, the frame is reinforced with metal and PVC structuring and fronting while the pane is glass and this is held together with a mixture of other products. This complex composition is a challenge to reuse, repurposing, remanufacturing, and/or recycling due to the difficulty in separating the PVC mixed up in other waste and originating from diverse sources (Ciacci et al., 2017). The high-quality requirements of recycled PVC materials further complicate the recycling process for PVC waste, creating barriers to its successful and efficient use (Ciacci et al., 2017; Miliute-Plepiene et al. 2021). Moreover, the post-use recycling of older PVC materials in construction is often complicated due to the on-going phase-outs of phthalates, contaminating the waste stream (Miliute-Plepiene et al. 2021). The literature indicates that the separation of mixed plastics is required to improve PVC recycling while simultaneously reducing PVC contamination of other plastic streams (Miliute-Plepiene et al. 2021).

The large-scale reuse of PVC in construction is limited by the availability of waste material due to the high durability and the difficulty in recovering the material. The current infrastructure and technology for recovering PVC post-consumer is limited. The long life-spans of the material itself restricts the availability of PVC products for reuse and recycle schemes. Moreover, experts in the PVC construction industry highlight PVC pipes as the biggest challenge to recovery as these products are usually installed underground or in walls and can only be recovered via the exhumation and extraction of pipes from demolition and construction sites (Whittle & Pesudovs, 2007). However, studies do show that once recovered, plastic pipes are generally in a condition to be cleaned and reworked for reuse (Pufik, 2024; Whittle & Pesudovs, 2007).

Based on the above the following key interventions for technology and infrastructure should be considered:

- **Support research on alternatives to the use of functional additives in the production of PVC and safe removal of additives.** The development of cost-effective techniques suitable for the safe removal of additives before the recycling process to obtain high-quality recycled polymers and sustainable alternatives, which can be utilised without negatively affecting the environment.
- **Improved waste separation mechanisms at construction sites or at the sites of construction waste delivery.** This could be in the form of a public system or could incentivise or penalise the construction sector to improve waste separation. This will ultimately reduce waste stream contamination and result in the ability to reuse products, or if recycled will produce a higher quality recycled PVC.

d. Policy and regulation

Despite the environmental and health concerns associated with PVC, the legislative landscape in the UK corresponding to these materials is relatively limited. Research indicates that the UK is lagging behind the rest of Europe when it comes to regulating the material through its life cycle from production, use and disposal of PVC in construction. While there are no PVC-specific national waste management plans or strategies in the UK, efforts to address PVC waste are integrated into broader waste management plans and strategies. At present, the following strategies or regulations relate to PVC in construction are considered for the UK:

- European Union's REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) legislation, 2010, includes restrictions on phthalates such as bis- (2-ethylhexyl) phthalate (DEHP), dibutyl-phthalate (DBP), diisobutyl-phthalate (DIBP) and benzyl butyl phthalate (BBP) towards the the on-going phase-out of these chemical additives. While the UK has left the European Union (EU), the framework is still used in UK legislation.
- The VinylPlus initiative, previously Vinyl2010, is a voluntary commitment of the PVC Industry in the EU and the UK to support PVC waste-collection and recycling systems including responsible use of process additives towards minimising the impact of PVC production, use and disposal

on the environment. There is a particular focus on management strategies to address organochlorine emissions through sustainable use of additives (Miliute-Plepiene et al. 2021).

- The UK Building Regulations, while not explicitly mentioning PVC, indirectly influence the use of PVC in construction through requirements related to materials, insulation, and building components. These regulations set standards for safety, energy efficiency, and sustainability in building design and construction projects in the UK.
- The Resource and Waste Strategy for England (2020) outlines the UK government's approach to managing resources and waste more sustainably. It includes measures to increase recycling rates, reduce plastic waste, promote producer responsibility, and transition to a circular economy. While not specifically focused on PVC, it addresses PVC waste as part of broader efforts to manage plastic waste and promote recycling.
- PVC manufacturing facilities and PVC-containing products are subject to environmental regulations in the UK aimed at controlling emissions, waste management, and environmental impact. These environmental regulations address the environmental impact of PVC, particularly in terms of its production, use of additives, and disposal.
- Control of Substances Hazardous to Health (COSHH) Regulations where PVC is listed as a substance that may pose health risks in certain occupational settings. The COSHH regulations require employers to assess and control the risks associated with the use of hazardous substances, including PVC, in the workplace.
- Landfill tax, while not explicitly mentioning PVC, is a continuously increasing tax level in the UK aimed at reducing the amount of waste accumulating in landfill sites and subsequently promoting the use of alternative waste disposal methods such as reuse, recycle and composting. Plastics are considered 'active waste' currently taxed at the standard rate of £102.10 per tonne from April, 2023.

Issues of recycling long-lasting products containing legacy chemical compounds now prohibited in PVC production as a barrier to recovery, reuse and recycling. Over the last 90 years, regulations concerning the use of certain chemical compounds have changed with additives such as lead-based stabilisers and some phthalate plasticizers prohibited in PVC production (Lewandowski & Skórczewska, 2022). This is problematic for the reuse and recycling of legacy materials especially with respect to long-lasting PVC materials typical in the construction industry. While the on-going phase-out of these legacy compounds allows for continued use of a certain amount of lead legacy additives for a specific number of years, it is unclear how industry should handle and dispose of PVC products consisting of these legacy additives (Expert interview, 2024). This puts pressure on the industry to design strategies to recover clean circular material involving high investment cost toward recycling mechanisms such as chemical extraction of materials like the lead metals, or chemical plasticizers.

Limited policy concerning unknown impacts of alternative additives used in PVC production. Certain functional additives, in particular plasticizers, have been highlighted as particularly problematic for human and ecosystem health linked to neurodevelopmental, metabolic, and reproductive disorders. The E.U. and the U.S. have restricted the use of several phthalates including di(2-ethylhexyl) phthalate (DEHP) and di-n-butyl phthalate (DnBP) in plastics resulting in the subsequent use of alternative plasticizers in PVC production (Edwards et al. 2022). These replacement plasticizers are poorly understood. Moreover, while 4 200 chemicals are known to be harmful in the use of plastics, a further 10 000 have insufficient data to be designated as hazardous (Jones, 2024). This leaves a lot of room for unknown impacts on human health to the use of alternative plasticizers in PVC materials.

Lack of governmental support lays the financial burden of recovery, reuse and recycling of PVC in construction to the associated industry. Experts in the PVC in construction industry comment on their obligation to self-finance the management of PVC waste with limited regulatory support or financial incentives from municipalities to invest in alternatives such as reusing and recycling efforts for PVC in construction. Issues and the related costs of collection and sorting of PVC waste are the main barriers to the potential closed-loop system of plastic reuse and recycling without the issues of material export.

With the development of industrial strategies and governmental mechanisms, improved recovery methods are possible for more efficient reuse or recycling of PVC in construction.

Based on the above the following key interventions for policy and regulation should be considered:

- **Ban known toxic additives and plasticizers and mandate that all additives should be proven to be safe before reaching the market, rather than proving to be toxic.** This approach shifts the responsibility to manufacturers, ensuring a precautionary principle is applied, where the safety of additives must be established prior to market release, thereby potentially reducing the risk of public exposure to harmful substances.
- **Provide clear guidelines for the disposal of legacy PVC in construction that is considered toxic.** There is a clear need to communicate with the construction industry about handling and disposing of existing plastics even if contaminated.

e. Waste hierarchy

The current system for PVC in construction is placed predominantly at the recovery (waste to energy) and waste management (disposal) stages of the waste hierarchy (Figure 7). While recycling of PVC in construction is possible, only a small percentage is currently recycled in the UK due to the numerous barriers identified in the previous sections.

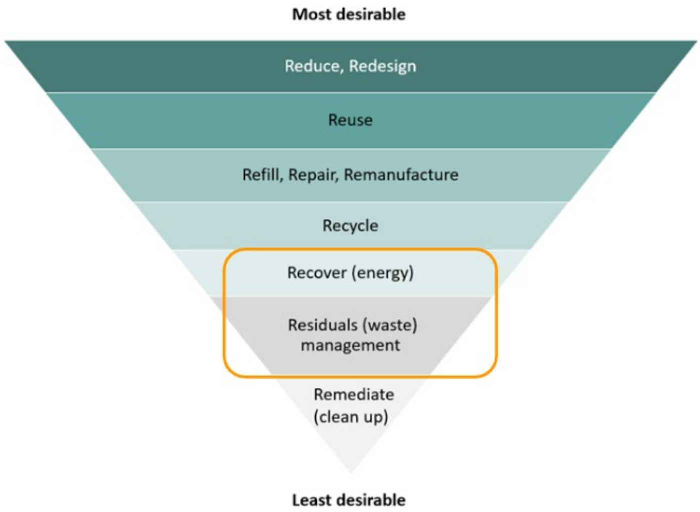

Figure 7. Current position of PVC in construction on the waste hierarchy.

In terms of moving PVC in construction up the waste hierarchy to reuse, repair and recycle, there is potential but a number of barriers need to be addressed. There is currently a heavy focus on the recycling possibilities for PVC material with intensive work underway on the development of feedstock recycling (Lewandowski & Skórczewska, 2022), while little attention is given to the potential mechanisms towards the reuse, repair and remanufacture of PVC in construction. There has been a recent push in post-consumer use of PVC in construction. Window profiles have been at the forefront of this recent increased focus due to the accessibility of the material to be deconstructed and then reused in new window frame products. Experts in the PVC for construction industry highlight the success of window profile producers who have taken control upstream of the business by investing in co-extrusion technology to improve the product quality from using recycled PVC. In the UK, more than 30% of window profiles by weight originate from recycled material (Expert interview, 2024).

Meanwhile, some aspects of the material itself limits recycling while creating possibilities towards repair and remanufacture and even reuse. The high durability and long-life (+40 years) of many PVC products keeps the products in circulation and enables reuse, while subsequently limiting the availability of waste material for the large-scale recycling of PVC. Further trade-offs between economic benefit, positive environmental impacts and potential health risks need to be thoroughly assessed to fully establish the viability of PVC reuse, repair and recycling. Issues of recovery, separation, collection and sorting need to be addressed to encourage and enable the large-scale reuse, repair and remanufacture as well as recycling efforts and move PVC in construction up the waste toward a more circular system. The cost of making these waste management processes efficient impacts the economic viability of PVC reuse, refurbishment and recycling in the construction industry. These costs can be restrictive, especially during periods of lower prices for virgin PVC materials, making the economics of refurbishing and recycling less favourable (Leadbitter, 2002). In the UK, industrial experts in PVC in construction comment on the lack of support from municipalities towards large scale recycling systems with the industry primarily self-financing the collection and sorting of construction related PVC products.

Interviews indicate that there is a market for PVC refurbish and reuse in construction, particularly if toxicity issues are addressed. Experts in the PVC industry for construction highlight the possibility offered by long-lasting products containing PVC for repair and reuse rather than replacement. In the UK, most PVC applications are highly durable and long-term with a lifespan of up to 40 years or more. An example given by industrial experts in PVC is the case of windows, where the replacement of the thermal lining or glass or aesthetics is often necessary before its PVC compartments. The PVC does not need to be replaced. Therefore, a focus on repair rather than replacement is needed for PVC in the construction industry. However, logically issues associated with the collection, transport, and cleaning of used PVC such as pipes (Whittle, & Pesudovs, 2007) may be a challenge to circularity in the construction industry. These recovery related costs are generally the responsibility of the industry without assistance from the government (Expert interview, 2024). Effective strategies involving government actions and policies, such as banning plastic landfilling, establishing reuse and recovery targets, and supporting initiatives for technological advancements are necessary towards a more circular use of PVC. Benefits of reusing reclaimed PVC include reduced material costs and a reduced potential for release of hazardous chemical by-products during PVC production and disposal as well as reduced carbon footprint. However, the feasibility of reusing PVC in such applications as pipes needs to be carefully evaluated before use due to the potential risks associated with the potential toxic chemical leakage and presence of wear, corrosion and other defects that can compromise the strength and reliability of such structures and to ensure their compliance with health and building codes.

There are no further interventions identified beyond those listed in the previous sections to improve the overall circularity of PVC in construction. The primary concern with PVC should be managing toxicity.

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for PVC in construction (Table 7).

Overall potential for circularity

There are mixed opinions on whether PVC in construction has a place in the circular economy with some research stating that it does while some vehemently denying this while listing its health and environmental impacts. According to some sources, PVC certainly meets the requirements for materials involved in the circular economy (Lewandowski & Skórczewska, 2022) while according to others, PVC is the antithesis of a green building material (Thornton, 2000) and the least environmental plastic (Greenpeace, 2003). Due to these views, the consideration of other materials for specific applications is an on-going thread in PVC-related research in the construction industry with the use of non-plastic alternatives as well as other materials such as PE, HDPE and LDPE, considered safer alternatives for many construction applications and can mitigate health issues related to PVC (Petrović & Hamer, 2018). However, due to the high economic significance of PVC as a result of its durability, low production costs and highly favourable properties, PVC is well-established in the construction industry and its phase out in construction seems unlikely. Therefore, it is important to support efforts in adapting the design and industrial processes of PVC production to make PVC less toxic and more environmentally sustainable.

For the circular use of PVC in construction, certain health and environmental issues in the production, reprocessing and disposal of PVC need to be addressed and mitigated. These issues include the formation of hazardous byproducts at various stages of the PVC lifecycle, the release of toxic substances due to the use of plasticizers (mainly phthalates), metal stabilisers (lead) as well as mercury-based processes for chlorine production, and emission of toxic organochlorine substances and additives during the long-term breakdown of the PVC material. The redesign of PVC towards circularity necessitates a break away from the detrimental health and environmental pollution of the chemical released as a product of PVC. Developments in material science have a part to play in shifting to more circular practices that improve the reuse and recyclability of PVC and finding alternatives to hazardous additives and petrochemicals. Researchers are exploring the development of novel plasticizers and plasticizing systems that have minimal environmental impact and do not compromise the final product's properties (Czogała et al., 2021). Additionally, the adoption of bio-based plastics, which have a lower carbon footprint and potential compatibility with existing recycling streams, is being considered as a more sustainable alternative. However, transitioning to more circular products may involve addressing complex issues and potential trade-offs in the manufacturing process (Rosenboom et al., 2022). These innovations in technology advancements and redesign are relatively novel and require further development and tight regulation (Lu et al. 2023), involving the assessment of new products entering the market to ensure their compatibility with reusing, remanufacturing and recycling processes (Leadbitter, 2002).

The above efforts, while going in the right direction, are still a long way from being considered circular. However, there is the potential for PVC reuse, refurbishment and remanufacture in the construction industry. Firstly, to prolong PVC circulation in the system during its lifecycle, efforts in the waste management to recover, separate, collect and sort PVC materials should be angled towards reuse, repair and remanufacture of PVC in construction. The PVC contamination of other plastic waste streams is a growing problem due to the fact that if any PVC enters another plastic waste stream it will contaminate the entire batch. It is therefore crucial to support and facilitate the segregation of PVC from mixed waste streams as well as sorting the flexible and rigid forms of PVC as soon as possible in waste management schemes, on construction or demolition sites and/or at the site of material production. This requires investment in specialised technology and infrastructure which could be supported by government incentives and/or fund injections into reuse initiatives. In addition, efforts should continue to ascertain the overall toxicity of reusing and/or recycling these products.

Table 7. Interventions to transition to a circular system for PVC in construction, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Clear labelling of recycled and recyclable building materials.	National	Industry	High
Educating construction teams and businesses on the reusability and recyclability of materials used.	National, Sub-national	Industry, Civil society	Medium
Clarity and management of waste classification.	National	Government, Industry	High
Support research and innovation on how to use bio-based, and non-toxic additives in PVC production in a way that is economically viable for the industry, accompanied by a toxic additives ban.	National, International	Government, Industry, Academia	High
Provide economic incentives to improve construction waste collection and separation systems for the reuse of PVC products in construction.	National	Government, Industry	Medium
Support research on safe removal of additives.	National, International	Government, Industry, Academia	High
Improved waste separation mechanisms at construction sites or at the sites of construction waste delivery.	National, Sub-national	Government, Industry	Medium
Ban known toxic additives and plasticizers and mandate that all additives should be proven to be safe before reaching the market, rather than proving to be toxic.	National, International	Government, Industry	High
Provide clear guidelines for the disposal of legacy PVC in construction that is considered toxic.	National, Sub-national	Government	High

iv. Gaps in evidence and assumptions

A number of gaps in evidence exist in determining the circularity for PVC in construction, including:

- The length of supplier contracts across the whole life cycle and how these impact circularity.
- How this material or product is packed for onward transport and associated impacts on the products' design or choice of material, the impacts on the volume that can be purchased, and whether the packaging for transport leads to excess stock or waste.
- The optimization of extraction and refining methods used to extract maximum value from the materials and the related trade-offs for extracting maximum value
- The design and manufacture of this material using alternative materials, changing product design to allow for or to promote refurbishment and reuse, the potential lack of availability of (alternative) materials a barrier to circularity
- The way this material is marketed or sold affects how much is used and in turn wasted.

3.4 HDPE in construction

i. Life cycle stages and circularity

In 2021, medium density polyethylene (PEMD) and high density polyethylene accounted for approximately 14.4% of the European plastics production (Plastics Europe, 2022). High-density polyethylene (HDPE) is one of the most used and demanded for construction especially for non-pressure and pressure pipes (Juan et al., 2020). HDPE is the third most applied plastic type in construction preceded by PE and PET (Abeysinghe et al., 2021). HDPE is also used for tubing, ducting and guttering in the construction sector (The Alliance for Sustainable Building Products (ASBP), 2021).

HDPE or polyethylene high-density (PEHD) can also be referred to as "alkathene" or "polythene" when used for HDPE pipes (Husainy et al., 2017). It is a thermoplastic polymer produced from ethylene, which is often produced by steam cracking in the petrochemical industry (Mufarrij et al., 2023).

Across the life cycle of HDPE in construction, the primary barriers exist in the use of natural resources, reuse, collection, disposal and loss to the environment stages. The main opportunities for circularity lie in the use of natural resources, reuse, recycling, and loss to the environment stages (Figure 8). A summary of the barriers and opportunities are presented in Table 8.

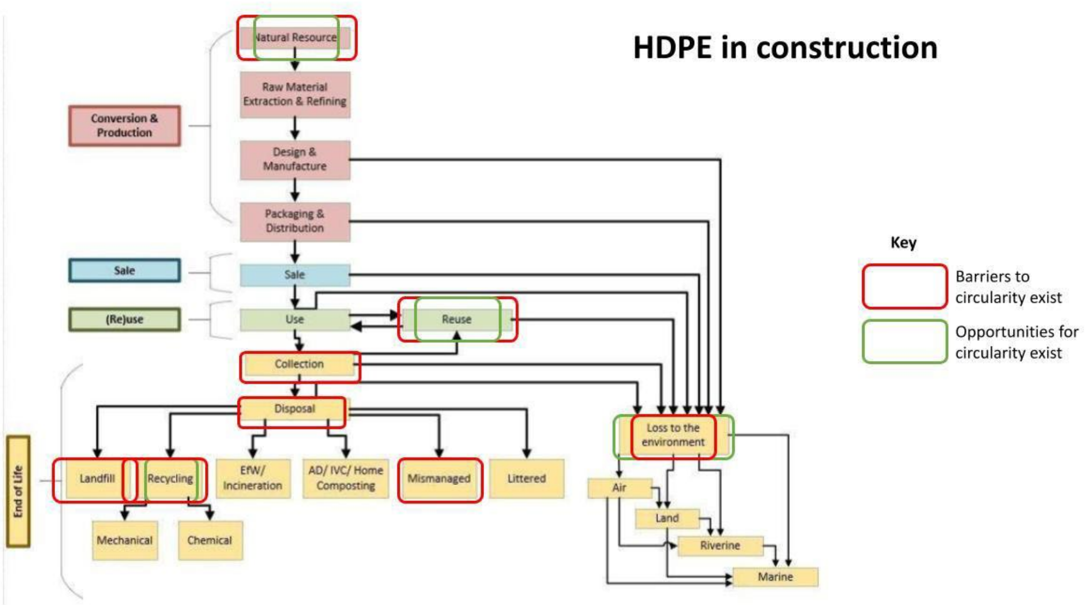

Figure 8. Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of HDPE in construction exist.

Table 8. Overview of identified barriers and opportunities for the circularity of HDPE in construction by life cycle stage.

Life cycle stage	Barriers	Opportunities
Natural resource	● A study has shown that the use of a bio-based HDPE resin for pipes has the highest material production cost although it offers the best solution for addressing climate change in long-lived thermoplastic assets compared to alternative resins such as pristine HDPE, pristine/PCR HDPE, and nanoclay-pristine/PCR HDPE composite. (Nguyen et al., 2020) ● Bio-based HDPE can also have other disadvantages linked to the manufacturing process in terms of carbon emissions. (Nguyen et al., 2020)	● Bio-based HDPE or “green-polyethylene” could help reduce the issues associated with the depletion of fossil resources (Morcillo et al., 2021). Bio-based HDPE can be produced by polymerization of ethylene obtained from catalytic dehydration of bioethanol (Morcillo et al., 2021). Bio- based HDPE has been shown to have the same physical properties as its petrochemical counterpart (HDPE), which possesses good mechanical resistance, high ductility, and improved waterproof capabilities (Quiles-Carrilloet al., 2019; Torres-Giner et al., 2017). ● There is a market for bio-based HDPE. Figures show that bio-based polyethylenes accounted for nearly 10% of the global bio-based plastic production in 2018 (Vasile et al., 2017).
Raw material extraction & Refining	-	-
Design & Manufacture	● The use of components such as plasticizers and/or additives in polyethylene can have a detrimental impact on the environment (Yao et al., 2022). Over time, polyethylene waste undergoes a natural light oxidation process, which releases the additives and plasticizers from the polymer into the environment and generates greenhouse gases (Iskander et al., 2016).	● The design and analysis of innovative environmentally friendly pathways to produce low-density polyethylene and high-density polyethylene, as the main feedstock of petrochemical industries, based on CO_2 capture and utilisation. (Mufarrij et al., 2023) ● Compared to pipes made of virgin materials, blended recycled materials can make HDPE pipes more sustainable and cost-effective (Istrate et al., 2021; Nguyen et al., 2021). Two types of recycled materials are usually used in HDPE pipes: post-industrial recycled (PIR) (pre-consumer) and post-consumer recycled (PCR). (Nguyen et al., 2021) ● The development of “HDPE-like” materials could help achieve a closed-loop recycling of “high-density polyethylene-like” or “high-density polyethylene mimic” materials (Li et al., 2024).

Packaging & Distribution	-	-
Sale	-	-
Reuse	• The use of recycled HDPE in high-pressure pipes is more restricted due to the high structural and loading requirements that must be met, limiting the incorporation of recycled materials to pressure pipes. (Juan et al., 2020) • The properties of recycled HDPE are similar to those of virgin HDPE (Tesfaw et al., 2022), however these properties decrease with each reprocessing cycle limiting circularity (Oblak et al., 2015; Papo, & Corona, 2022). • HDPE can go through ten cycles of mechanical recycling before the deterioration of its mechanical properties becomes evident. Mechanical recycling worsens HDPE processability through the first 30 reprocessing cycles.. However, it needs to be emphasised that even after 100 recycling material retains 80% of its initial mechanical properties. (Oblak et al., 2015)	
Collection	• The collection and sorting of plastic waste are often inconsistent processes due to regional variations, and diverse infrastructure (Hahladakis, & Iacovidou, 2019). • Consumers as well as businesses are not always aware of the differences in the collection systems, which can create confusion and compromise the ability of people to dispose of their plastic waste in the correct recycling receptacles, which in turn compromises the quality of the resultant plastic waste streams. (Hahladakis, & Iacovidou, 2019).	-.
Disposal	• Polyethylene wastes are normally discarded as landfill or thrown in water bodies to decompose/degrade (Priyanka & Archana, 2011). • The disposal of used HDPE and LDPE plastic materials by using chemical and physical methods are very expensive and produce persistent organic pollutants known as furans and dioxins, which are reported to be toxic irritant products, and have proved to be dangerous to animal, human and ecosystem. (Ojha et al., 2017)	
Loss to the environment	• Over time. exposure to environmental factors (moisture, heat, light, or microbial action) causes polymers to be abraded into smaller pieces, eventually to microplastics, as well as cleaved into small molecules. (Law et al., 2014; Yao et al., 2022)	• The abilities of fungal organisms and bacteria to biodegrade plastic materials can be further enhanced in an industrial scale for degrading HDPE waste. (Awasthi et al., 2017; Chaudhary, & Vijayakumar, 2020; Ojha et al., 2017)

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

Consumers in this context include purchasers within the construction industry, businesses, home owners, contractors and builders. Many of the attitudes and behaviours documented in PVC in construction (Section 3.3) apply to HDPE in construction too. Those that differ are highlighted below.

The reuse of construction HDPE is currently non-existent due to changing consumer tastes, trends and preferences. See Section 3.3 on PVC for more details.

The lack of knowledge concerning the use of recycled products and their perception in the UK construction sector among consumers compromises their marketability in the industry. Often designers and contractors have no preference for recycled products in their specifications as there is a lack of documents providing information about recycled products available for use in construction (Oyedele et al., 2014).

There is a negative societal attitude towards the use of recycled materials, which determines their overall marketability. Reused or recycled products can be perceived as second class materials of low standard and short lifecycle period, which may be unable to serve their required purpose (Oyedele et al., 2014). Similar findings have been reported in the literature (da Rocha and Sattler, 2009), consumers with lower income tend to purchase recycled products as a last resort (da Rocha and Sattler, 2009). Studies have shown that while this may be accurate for several components, other products (such as bricks, tiles, windows and wood elements) can have performance standards similar and sometimes even superior to new products (da Rocha and Sattler, 2009; Oyedele et al., 2014).

The lack of established standards concerning the durability, aesthetics, and build-ability of reused, repaired or recycled products can limit their marketability. For example, the general properties of materials with higher levels of recycled content are often questioned, although studies have shown that substitutions of virgin material with recycled material in these products tend to have little or no impact on functionality (Oyedele et al., 2014; WRAP, 2019).

Environmental benefits are usually not a deciding factor in the construction sector. The selection of building materials by clients is more influenced by cost than environmental benefits. Despite being secondary products, recycled products are usually more expensive than virgin products, which is a barrier to the promotion of recycling practices among clients, and businesses (Oyedele et al., 2014). Interestingly, the opposite trend is reported for materials manufacturers and contractors, a sense of pride is associated with the manufacturing or using recycled products and the self-awareness of contributing to a more sustainable driven environment (Oyedele et al., 2014).

The misdescription of construction waste has been linked to tax avoidance. Companies are expected to pay a standard rate for disposing of hazardous waste of £94.15 per tonne versus £3.00 per tonne for inert waste (Environment Agency, 2021). However, some businesses choose to mislabel their construction and demolition waste deliberately to reduce the costs involved in the waste management of projects. Ultimately, these practices compromise the quality of the resultant plastic waste streams (Hahladakis, & Iacovidou, 2019).

Contractors, clients, and businesses are not always aware of their legal duty of care, limiting recyclability of HDPE products. The Waste duty of care code of practice stipulates that everyone from the builder generating the waste, right through to the operator of the end destination site has a legal duty of care to ensure that construction waste is disposed of in an appropriate manner (Department for Environment, Food & Rural Affairs (Defra) and Environment Agency, 2016). However, the waste classification system in the construction and demolition waste sector often creates confusion among the key actors involved in construction sites leading to misdescription of waste causing issues at receiving sites (Chartered Institution of Wastes Management (CIWM) and Environmental Services Association (ESA); 2017); Environment Agency, 2021). Sending hazardous wastes or mixed construction and demolition waste contaminated with inclusions of wood, plastic and metal to facilities such as inert landfills and deposit for recovery sites that are not engineered or equipped to process such types of waste can cause significant issues). It is the responsibility of the entity generating the waste to ensure that waste is sent to an end destination site which is permitted to accept it (Environment Agency, 2021).

Based on the barriers and opportunities for HDPE relating to consumer attitudes and behaviours, the following key interventions have been identified:

- **Support research to change the negative societal attitude towards the use of reused or recycled materials in construction.** A positive perception of recycled or used HDPE has the potential to increase its marketability.
- **Clear labelling of recycled and recyclable building materials.** Manufacturers as well as government bodies would need to communicate with designers, contractors, and suppliers/recycling companies about available construction products that can be reused or recycled.
- **Educating construction teams and businesses on the importance of sustainable practices and recyclability of materials used and how to classify waste in general.** This could include how to handle products, how to install for easier recovery, and how to efficiently manage waste on construction sites to ensure recoverable materials are directed to the correct waste streams.
- **Incentivise the use of reuse or recycled materials in sustainable design appraisal tools in construction**. Legislation can set national targets for the usage of reused or recycled material in construction, with better incentives for reuse over recycling.
- **Improve the clarity and enforcement of waste classification.** There are over 30 common construction and demolition waste codes listed in the classification and additional codes for other waste can be found in the waste classification technical guidance. Some wastes can have more than one classification, depending on their content, and they can be classified as hazardous or non-hazardous and they can contain persistent organic pollutants. Recommendations from the latest technical guidance document for the classification of waste suggest that anyone looking to fully utilise all aspects of this guidance should be competent in hazardous waste and have some knowledge of chemistry.

b. Economics

The use of bio-based HDPE for construction, and more specifically pipes, offers one of the best solutions for addressing climate change but has the highest material production cost. The substitution of virgin fossil-based HDPE with bio-based HDPE can help tackle climate change by substantially reducing the energy requirements and GHGs emitted during feedstock extraction and production associated with the use of fossil fuels (Nguyen et al., 2020). GHG emissions for the production of 1 kg of pristine HDPE resin is higher than the alternatives (pristine/post-consumer recycled (PCR) HDPE, bio-based HDPE and nanoclay-pristine/PCR HDPE composite), largely due to the energy requirements for the conversion of crude oil and natural gas to ethylene whereas the production of bio-based HDPE results in the lowest GHG emission per kilogram of polymer (Nguyen et al., 2020). Concerning costs, the highest production cost is attributed to bio-based HDPE with an average estimated value of $1.11/kg followed by pristine HDPE ($0.83/kg) and nanoclay HDPE/PCR ($0.85/kg). Bio-based HDPE appears to be promising, however several potential issues have been associated with the use of bio-based feedstocks at a large scale (see section 3.1 Biodegradable and compostable plastics section)**.**

Chemical and mechanical recycling of HDPE plastic materials is very expensive, complex, and can produce persistent organic pollutants. Mechanical recycling often produces recycled plastic of inferior grade that can only be used in low-value applications, thus not suppressing the demand for virgin feedstock (Ferreira et al., 2021). However, mechanical recycling tends to be more common, because it is often cheaper than chemical methods (Suffo et al., 2023). In addition to the high costs, chemical recycling of polyethylene is particularly challenging due to the lack of cleavable functional groups (Li et al., 2024). Chemical recycling of polyolefins is mostly limited to thermal deconstruction such as pyrolysis and gasification, which typically require a significant amount of energy, resulting in low-value products that downgrade the polymers (Meys et al., 2020). Ojha et al. (2017) adds that recycling of HDPE materials can result in the production of compounds known as furans and dioxins, which are reported to be toxic irritant products, and have proved to be dangerous to animal, human and ecosystem (Ojha et al., 2017). To solve this issue, the degradation capability of fungal organisms on HDPE could be further developed at an industrial scale for degrading plastic waste in an eco-friendly way (Ojha et al., 2017).

The use of recycled HDPE in construction materials can help reduce construction costs. Recycled HDPE is currently used for non-pressure pipes (Juan et al., 2020) and could be used to make non-pressure pipes, tiles (Periyasamy et al., 2023), concrete (Abeysinghe et al., 2021; Tamrin, & Nurdiana, 2021), and wood-based composites (Shanmugam et al., 2021). Recycled HDPE can reduce construction costs by: using recycled HDPE or blends of recycled HDPE material can reduce the amount of virgin materials required for building components resulting in lower costs of construction materials, reducing the cost generated by transportation of other construction materials, saving waste management costs that would have been required otherwise by HDPE waste, and reducing energy costs when used for building insulation (Awoyera, & Adesina, 2020; Ingabire et al., 2018; Lamba et al., 2020). However, the recycling of blended HDPE has been shown to lower the properties of the material (Dorigato 2021). In their study, Ingabire et al. (2018) investigated the feasibility of using plastic sand pavers made of recycled HDPE for the construction of roads in the city of Kigali. Their results showed that using recycled HDPE has the potential to minimise building material costs, minimise the use of land for dumping plastics and does not compromise the properties of these pavers to be used for construction (Ingabire et al., 2018).

Research indicates that there is a market for recycled HDPE and HDPE waste in construction. The quality and the properties of the plastic waste used largely determines, whether it has the potential to be used for the same application or in another sector after recycling (Nyika, & Dinka, 2022). HDPE is a relatively hard and rigid material and can usually find application in the manufacture of plastic lumber, tables, chairs, and other furniture (Nyika, & Dinka, 2022). Recycled HDPE materials are in great demand in construction (Nyika and Dinka, 2022; da Silva et al., 2021; Lamba et al., 2022), and other sectors (Lamba et al., 2022; Suffo et al., 2023). For example, the use of encasements or manhole covers in points of access such as manholes, drains, and inspection chambers, which are subjected to pedestrian and/or vehicle traffic is very common. Studies have shown that the physicochemical, rheological, and mechanical properties of urban manhole covers (made of 100% from a blended material combining two types of recycled HDPE) far exceeded the limits required for urban traffic areas and industrial zones (Suffo et al., 2023). Using manhole covers made from recycled material could help reduce the theft of manhole covers and the resulting costs spent by municipalities to replace or repair them. Statistics show that hundreds of cast iron covers were stolen across the UK in 2022 (Whitbread, 2022). Figures indicate that the theft of these products usually increase with the price of metal (Robbins et al., 2011).

Despite the growing awareness of the environmental impacts of plastics, the use of plastics for plumbing materials has steadily increased over time, primarily due to lower costs and speed of installation. Evidence brought from the insurance industry suggests that one of the most common causes for escape of water claims involves plastic pipe plumbing failures (Broad et al., 2023). Figures from the Association of British Insurers indicate that escape of water claims can cost UK insurers up to £2.5 million a day (Jahn, 2022). Broad et al. (2023) concluded that while plastics may be the most appropriate material choice for specific applications in the construction industry, other appropriate material choices could help to minimise pipe failures and reduce the usage of fossil fuel derived products, and ultimately mitigating environmental impacts. Contrasting views have also been documented in the literature, some reports actually suggest that ‘throughout the life-cycle, from cradle to grave, the environmental impact of the plastic pipe systems is lower for most applications and along the majority of criteria, compared to the alternative materials.’ (TEPPFA, 2019).

Based on the above the following key interventions for economics should be considered:

- **Support research and development, and incentivise the production of bio-based HDPE in a way that is economically viable for the industry.** Currently, it is more cost-effective to produce HDPE from fossil fuels than using bio-based feedstocks.

c. Technology and infrastructure

The development and improvement of technology to perform repairs on HDPE pipes can help reduce the demand for virgin material and facilitate the reuse of HDPE pipes. The development of trenchless technology such as cured-in-place pipe (CIPP) and polymer spray-on coatings can save costs associated with pipe excavation and replacement and have a lower environmental impact. CIPP repairs is described as a process involving the insertion of an uncured resin material within the damaged pipe. Spray in place pipe liner is another alternative where a liner material is coated on the internal side of pipe using a spraying tool. The potential issue associated with these technologies is the release of a range of inorganic and organic contaminants into stormwater, with released substances and concentrations varying in relation to differences in pipe materials and runoff physicochemical characteristics (Taneez et al., 2023).

The use of chemicals such as plasticizers and additives in polyethylene can have detrimental effects on the environment, and can significantly affect the quality of the recycled material, resulting in downcycling. Over time, these chemicals can be released into the environment (Yao et al., 2022) as a result of the natural degradation of polyethylene waste and generate greenhouse gases (Iskander et al., 2016). Moreover, additives such as stabilisers, flame retardants, and colourants used to improve the performance of polymers constitute one of the major bottlenecks in the closed-loop recycling of plastic (Ferreira et al., 2021). Therefore, the development of techniques suitable for the removal of additives before the recycling process to obtain high quality recycled polymers is crucial. Currently, the most promising methods for that purpose include solvent extraction techniques, such as solid-liquid extraction and dissolution-precipitation due to their simplicity, the high purity of the recycled plastic obtained, and the potential to yield a plastic with the same quality as the virgin material (Ferreira et al., 2021).

The properties of recycled HDPE can match those of virgin HDPE, however these properties decrease with each reprocessing cycle, limiting circularity. Tesfaw et al. (2022) highlight that the mechanical properties of recycled HDPE can match the mechanical properties of virgin HDPE and therefore, using recycled HDPE in place of virgin HDPE can be very cost effective and environmentally viable. However, there is a catch. HDPE can go through ten cycles of mechanical recycling before the deterioration of its mechanical properties becomes evident. Mechanical recycling worsens HDPE processability through the first 30 reprocessing cycles. However, it needs to be highlighted that even after 100 cycles, recycling material retains 80% of its initial mechanical properties (Oblak et al., 2015). These issues add to the complexity of closed loop recycling.

The development of "HDPE-like" materials could help achieve a closed-loop recycling of "high-density polyethylene-like" or "high-density polyethylene mimic" materials. In addition to conventional recycling and upcycling HDPE waste, an alternative strategy focuses on the design and synthesis of new polymers by introducing potentially degradable functionable groups into the HDPE backbone while keeping its properties (Li et al., 2024). The goal is to ensure that these degradable functional groups in the HDPE chains can be recycled chemically by solvolysis, resulting in short fragments, which can be further polymerized to afford materials with similar properties to their original polymers and achieve closed-loop recycling of "high-density polyethylene-like" or "high-density polyethylene mimic" materials (Li et al., 2024).

Based on the above the following key interventions for technology and infrastructure should be considered:

- **The development and improvement of technology to facilitate the reuse of HDPE pipes rather than their excavation and replacement.**
- **Support research on alternatives to the use of chemicals such as plasticizers and additives in polyethylene, and ban toxic chemicals, based on the premise that chemicals and additives should be proven to be safe.**
- **Improve the properties of recycled HDPE in a sustainable manner for upcycling.** The development of technology, which can better preserve the properties of recycled HDPE can help level the playing field between recycled HDPE and virgin material. This will also require improving techniques for the safe removal of additives before the recycling process to obtain high quality recycled polymers and sustainable alternatives, which can improve HDPE without negatively affecting the environment.
- **Invest in the development of "HDPE-like" materials to achieve a closed-loop recycling of "high-density polyethylene-like" or "high-density polyethylene mimic" materials**. The design and synthesis of new polymers with degradable functionable groups incorporated into the HDPE backbone could ensure that these degradable functional groups can be recycled chemically by solvolysis, resulting in HDPE backbone fragments, which can be further polymerized to afford materials with similar properties to their original polymers.

d. Policy and regulation

The UK has several policies and regulations that indirectly affect the use of HDPE in construction, primarily through broader waste management, recycling, and building material standards. While there may not be specific regulations solely targeting HDPE in construction, relevant policies include:

- The Construction Product Regulation ensures that construction products are fit for their intended use and comply with performance requirements, including those related to health, safety, and environmental considerations. HDPE used in construction must comply with relevant standards under this regulation.
- The UK Building Regulations cover aspects of safety, energy efficiency, and sustainability in building design and construction. While not specific to HDPE, these regulations demand that materials used in construction meet certain standards, which could influence the choice and application of HDPE in construction projects.

The government has also set out to reduce construction waste to landfill for economic and environmental reasons (WRAP, 2009), through the implementation of national initiatives including:

- A target for halving construction, demolition and excavation waste to landfill by 2012, relative to 2008, adopted in England by the Government's Strategy for Sustainable Construction 2008, building on the Waste Strategy for England 2007
- The Zero Waste Scotland Plan (2010) goal of achieving 70% recycling and recovery by weight of non-hazardous construction and demolition waste by 2020
- The Welsh Assembly Government's plan to move towards becoming a zero waste nation
- The Northern Ireland Waste Strategy 2006-2020, which includes a commitment to SMART targets for construction waste by 2010 and the recovery of 75% of all construction wastes by 2020
- The Site Waste Management Plan Regulations which became mandatory in England from April 2008; and the Strategic Forum's sector-wide Construction Commitments.

The following policy and regulatory considerations for the circularity of HDPE have been identified:

The lack of national policies and regulations can affect the circularity HDPE. Most policy limits what recycled HDPE can be used for, but there is limited policy that incentivizes the use of recycled HDPE in construction. For example, the use of recycled HDPE in high-pressure pipes is restricted due to the high structural and loading requirements that must be met, limiting its incorporation into pressure pipes (Juan et al., 2020). The lack of established standards for applying plastic waste for construction purposes is another barrier to the circularity of HDPE. (Naderi Kalali et al., 2023)

Legislation and fiscal policies are one of the key drivers of sustainability across the construction industry, but the contribution of the industry for their successful implementation is crucial. Reducing waste to landfill or incineration not only requires improvement on existing waste management regulations, policies and fiscal framework; but also the inputs from the construction industry.

Based on the above the following key interventions for policy and regulation should be considered:

- **Implement policies that facilitate the use of reused or recycled material in construction.** A policy to encourage reuse could provide economic incentives for businesses that can demonstrate that at least 30% to 50% of their products are manufactured with used and/or recycled materials. The publications of national standards concerning the reuse of material or the use of recycled HDPE could facilitate the incorporation of such materials

e. Waste hierarchy

The current system for HDPE in construction is placed predominantly at the recovery (waste to energy) and waste management (disposal) stages of the zero waste hierarchy (Figure 9). The most common waste management methods used for HDPE in construction along with most other construction waste include landfills and incineration although a small percentage of HDPE is recycled. Some of the barriers associated with this have been previously identified in the previous sections. However there are also opportunities for the reuse of HDPE products in construction and the creation of closed loop recycling systems, these opportunities are further described in the next paragraphs.

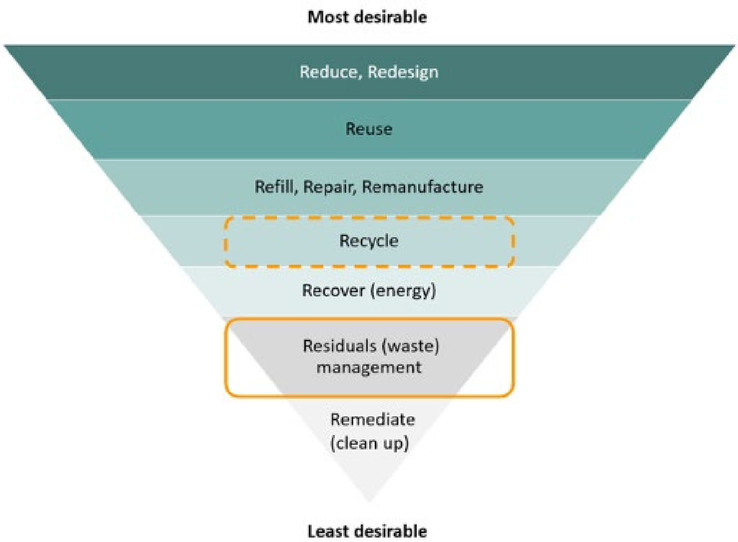

Figure 9. Current position of HDPE in construction on the waste hierarchy.

There is significant potential for the reuse of reclaimed pipes in construction. The use of reclaimed plastic pipes in construction has been reported in the literature. The main barriers to reuse include the trade-off between economic benefits, positive environmental impacts and potential risks associated with reusing pipes in construction and the challenges associated with the exhumation and extraction of pipes from demolition and construction sites (Pufik, 2024; Whittle, & Pesudovs, 2007). Some of the benefits of reusing reclaimed pipes include reduced material costs and a reduced carbon footprint. However, the feasibility of reusing such pipes should be carefully evaluated before use due to the potential risks associated with the presence of wear, corrosion and other defects that can compromise the strength and reliability of such structures and to ensure their compliance with building codes. Another issue is the logistics associated with the collection, transport, and cleaning of used pipes (Whittle, & Pesudovs, 2007), a system based on the reuse of plastic cups or even packaging would likely be easier to implement and scale up than a system involving construction materials such as pipes without the assistance of the government or major players in the industry.

Based on the above the following key interventions for the overall circularity should be considered:

- **Provide economic incentives for the reuse of HDPE products in construction.** Businesses who can demonstrate their reuse of HDPE material could be entitled to lower taxes or be able to use a specific logo, which would indicate their involvement in the reuse of used HDPE to the public.
- **Implement a national reuse system for construction material when applicable.** A national reuse system could include the collection and transportation of used HDPE material from construction sites to stations where the recovered material can be cleaned and assessed for safe reuse with no additional reprocessing. Businesses would be able to access these stations and purchase used material given a small fee to cover the maintenance of the reuse system in terms of infrastructures etc.
- **Set standards in line with building codes to facilitate the safe reuse of HDPE building material.** The publication of national guidelines on how to reuse HDPE material could encourage local businesses to reuse their own material in a more eco-friendly and safe way..

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for polypropylene in packaging (Table 9).

Overall potential for circularity:

HDPE in construction is not circular but does have potential to contribute to a circular economy for plastics. This material has the potential to become circular if certain considerations are taken into account. For specific applications, other materials considered more sustainable for certain applications can match HDPE properties, so an evaluation of the tradeoffs associated with each material need to be completed to conclude. Bio-based HDPE has been shown to have the same physical properties as its petrochemical counterpart (HDPE) (Quiles-Carrilloet al., 2019; Torres-Giner et al., 2017). Bio-based HDPE or “green-polyethylene” could help reduce the issues associated with the depletion of fossil resources (Morcillo et al., 2021) although as previously highlighted, has its own challenges (see Section 3.1 on biodegradable and compostable plastics).

While plastics can be the most appropriate material for specific applications in the construction industry, other materials could help to reduce the usage of fossil fuel derived products, and ultimately mitigating environmental impacts. A reduction in the unnecessary use of plastics is to be encouraged and suitable alternative materials such as copper and aluminium in the case of pipework, ductwork and guttering could be more appropriate (Broad et al., 2023), although in any substitution, a full, standardised LCA would be needed to determine the most sustainable option.

Table 9. Interventions to transition to a circular system for HDPE in construction, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Clear labelling of recycled and recyclable building materials.	National, Regional, International	Industry, Consumers	Medium
Educating construction teams and businesses on the importance of sustainable practices and recyclability of materials used and how to classify waste in general.	National, International	Industry, Consumers, Government	High
Incentivise the use of reused or recycled materials in sustainable design appraisal tools in construction.	National	Industry, Government	High
Improve the clarity and enforcement of waste classification.	National	Government	High
Support research and development, and incentivise the production of bio-based HDPE in a way that is economically viable for the industry.	National, Regional, International	Industry, Academica, Government	Medium
The development and improvement of technology to facilitate the reuse of HDPE pipes rather than their excavation and replacement.	National, International	Industry, Academica, Government	Medium
Support research on alternatives to the use of chemicals such as plasticizers and additives in polyethylene, and ban toxic chemicals, based on the premise that chemicals and additives should be proven to be safe.	National	Industry, Academica, Government	High
Improve the properties of recycled HDPE in a sustainable manner for upcycling.	National, Regional, International	Industry, Academica, Government	Medium
Invest in the development of “HDPE-like” materials to achieve a closed-loop recycling of “high-density polyethylene-like” or “high-density polyethylene mimic” materials.	National, Regional, International	Industry, Academica, Government	Medium
Implement policies that facilitate the use of reused or recycled material in construction.	National	Government	High
Implement a national reuse system for construction material when applicable.	National	Government, Industry, Civil society	Medium
Set standards in line with building codes to facilitate the safe reuse of HDPE building material.	National	Government, Industry, Consumers	High

iv. Gaps in evidence and assumptions

A number of gaps in evidence exist in determining the circularity for HDPE in construction, including:

- The length of supplier contracts across the whole life cycle and how these impact circularity.

- How this material or product is packed for onward transport and associated impacts on the products' design or choice of material, the impacts on the volume that can be purchased, and whether the packaging for transport leads to excess stock or waste.
- The optimization of extraction and refining methods used to extract maximum value from the materials and the related trade-offs for extracting maximum value
- The design and manufacture of this material using alternative materials, changing product design to allow for or to promote refurbishment and reuse, the potential lack of availability of (alternative) materials a barrier to circularity
- The way this material is marketed or sold affects how much is used and in turn wasted

3.5 HDPE in packaging

i. Life cycle stages and circularity

After PVC and PP, HDPE is one of the most utilised and produced commercial plastics within the plastic industry (Morcillo et al. 2021). It is widely used in the packaging industry due to its versatility and effectiveness as a cost-effective, energy-efficient, lightweight and durable plastic easily produced (Awasthi et al. 2017). When compared to LDPE, HDPE exhibits less branching and linearity providing its high packing density and making it harder, opaque and more resistant to high temperatures (Awasthi et al. 2017). Commonly used for a range of bottle containers such as coloured milk bottles, oil containers, shampoo bottles and a multitude of everyday household goods as well as chemical containers, HDPE is considered one of the safer plastics due to its chemical resistance preventing chemical reactions in food-contact packaging between the HDPE packaging and its contents (Wani et al. 2020). Meanwhile, coloured HDPE is used for various packaging applications in the agricultural sector across Europe including pesticide cans and fertiliser bags (Scarascia-Mugnozza et al. 2011). Its high chemical resistance, production and popularity as packaging products make HDPE the ideal material for recycling (Nguyen et al. 2021). While most HDPE packaging products are discarded after five years since this is the expiration time of most chemical fluids (Papo & Corona, 2022), the time it takes for the complete degradation of a HDPE bottle is much longer with data varying depending on production type, intended use and environment (Chamas et al. 2020). For example, it is estimated to take 500 years in a land environment and approximately 116 years in marine environments for a HDPE bottle to completely degrade (Chamas et al. 2020).

In the UK, HDPE in packaging (i.e. milk bottles) has been at the forefront of recycling content for the last decade as a circular solution in the plastic industry. However, only a small percentage of HDPE plastic is recycled with packaging considered the greatest source of waste globally (Rosenboom et al. 2022). This raises environmental concerns due to the ineffectual methods of plastic waste disposal with a small percentage being incinerated while the majority is released into landfills (Rodríguez et al. 2021).

Across the life cycle of HDPE in packaging, the primary barriers exist in the natural resource, reuse, collection, disposal and loss to the environment stages. The main opportunities for circularity lie in the natural resource, recycling, and loss to the environment stages (Figure 10). A summary of the barriers and opportunities are presented in Table 10.

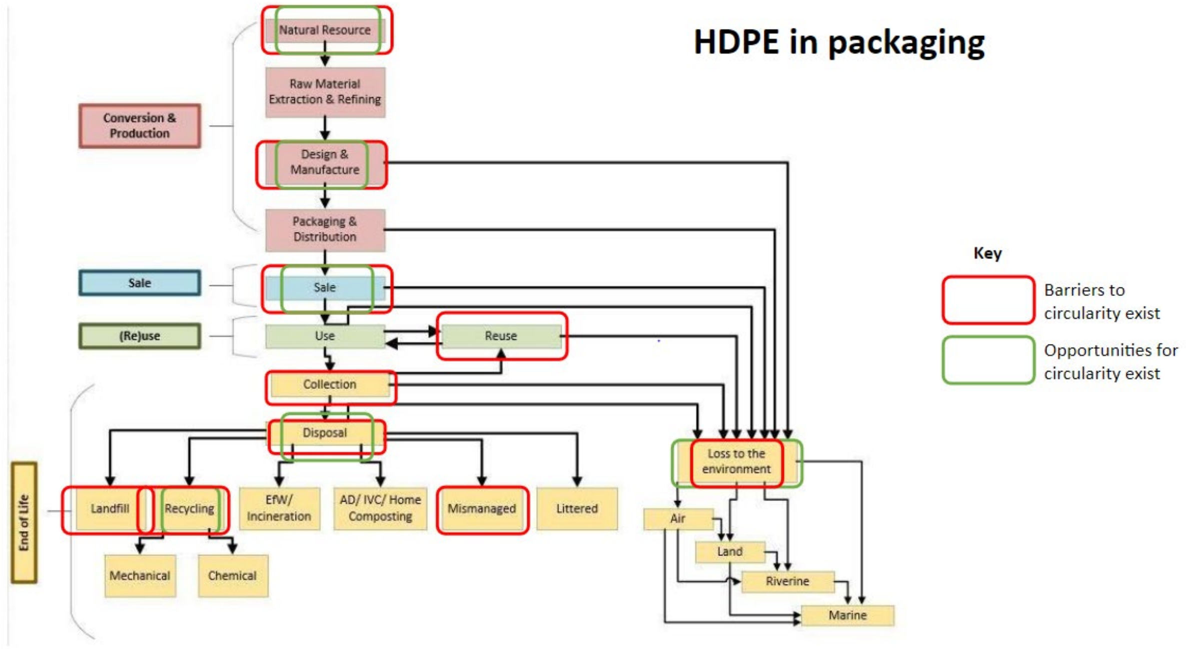

Figure 10. Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of HDPE in packaging exist.

Table 10. Overview of identified barriers and opportunities for the circularity of HDPE in packaging by life cycle stage.

Life cycle stage	Barriers	Opportunities
Natural resource	● The production of HDPE contributes to the pressure of fossil fuel extraction. HDPE is a petroleum-based plastic and is therefore dependent on a supply of fossil fuels (Morcillo et al. 2021). ● Increasing GHG emissions and global carbon footprint as a factor of HDPE production reliance on fossil fuels (Morcillo et al. 2021).	● The production of bio-based HDPE, also known as 'green-polyethylene' provides an alternative to the petrochemical HDPE without compromising the properties of the material. The use of the alternative helps to reduce the pressure on limiting fossil fuel resources (Morcillo et al. 2021). ● Binary blends of Bio-based HDPE and Polylactic acid (PLA) provide a cost-effective and fully bio-based material with improved physical properties (Quiles-Carrillo et al. 2019). ● The material itself limits circularity. HDPE along with other polyethylene grades are resistant to degradation in nature, meaning that the material is well suited to creating reusable products (Awasthi et al. 2017).
Raw material extraction & Refining	-	-
Design & Manufacture	● Production is associated with energy requirements (with most being dependent on fossil fuel resources), leading to a lack of clarity regarding their wider environmental benefits when considering carbon emissions (Ali et al., 2023; Ferreira-Filipe et al., 2021). ● The addition of components such as plasticizers and/or additives can negatively impact existing waste management systems and the environment, because of waste degradation and release of these components into the environment introducing ecotoxicological issues (Yao et al. 2022). ● Manufacturing costs are higher for recycled HDPE bottles (Papo & Corona, 2022). ● The use of post-consumer and post-processed plastic wastes of HDPE for making other plastic products such as bottles can generate additional plastic wastes, which will end up as rejected products unintentionally made due to difficulties in this production process (Techawinyutham et al. 2021). ● The use of recycled HDPE in packaging is often limited by the management of these products with high requirements for their use (Juan et al. 2020). In the EU, the product's recycling process is assessed by the EFSA and approved by the European Commission and must meet specific requirements to be used in packaging, especially when used in contact with food (Labib et al. 2023; Su et al. 2021).	● The ongoing development of new packaging designed to be easier to mechanically recycle with the example of a new grade of HDPE designed for recyclability from ExxonMobil (2023, August 16). This HDPE product most suited to the packaging of nuts, crackers, condiments, granola bars, and potato chips will help converters replace multi-material structures with mono-material laminates which are easier to mechanically recycle. ● ● The use of natural materials and fibres to reinforce HDPE matrixes can help improve material performance (Ihueze et al. 2023). ● Novel approach to HDPE production which incorporates CO_2 capture and utilisation, to help mitigate GHG emissions (Mufarrij et al. 2023). ● The use of renewable energy sources (e.g. solar, hydro, wind) can help to mitigate GHG emissions and ecotoxicological impacts associated with HDPE at landfills (Ferreira-Filipe et al., 2021).

Packaging & Distribution	-	-
Sale	● The lack of knowledge, a system of certification, and clear instructions for handling of HDPE packaging products has resulted in inappropriate disposal, littering behaviour, and contamination in the waste management systems hindering recycling systems (Hahladakis & Iacovidou, 2019). ● Sale and use of recycled HDPE products in food-grade packaging is restricted due to high requirements of packaging products, especially with respect to food in the EU (Juan et al. 2020).	● Opportunities exist in the sale and marketing of more circular HDPE products in packaging. For example, the french milk brand Lactel in collaboration with Ineos has released milk bottles made from recycled HDPE, thereby replacing the traditional fossil fuel derivatives (Official website, 2021, May 20).
Reuse	● Concerns of chemical leaching when reusing recycled HDPE beverage bottles (WebMD, 2024). ● The majority of reuse systems use more heat resistant plastics alternatives (i.e. PP) to HDPE. New cost-effective technology is needed to make HDPE reusable for food-grade products (Packaging Europe, 2023, July 25).	● Recent initiatives producing reusable bottles made entirely from post-consumer recycled HDPE claim that the bottles can be indefinitely refilled in over 300 stores across the UK (Berry Global, 2023).
Collection	● Lack of knowledge with respect to collection systems can create confusion amongst consumers and businesses alike which will ultimately result in misplacement of plastic waste, compromising the quality of the waste streams (Hahladakis, & Iacovidou, 2019). ● Differences in collection systems and infrastructure due to regional variations of waste management by local authorities or municipalities around the world can also create confusion and compromise the quality of plastic waste streams (Hahladakis, & Iacovidou, 2019). ● The high cost of transportation and collection due to the large volume of plastic products is a barrier to recycling (Morici et al. 2022).	● Plastics manufacturers could provide financial assistance to localities for equipment that can reduce plastics into a smaller form that would be more economical to transport. (Morici et al., 2022). ● Physical properties of the material itself help reduce the cost of collection and transportation. In the case of milk bottles, cost-efficient low bottle weights are the result of the ability of HDPE to remain rigid while maintaining thin walls (Selke & Hernandez, 2001).
Disposal	● The high cost of chemical and physical methods to dispose of used HDPE packaging is a barrier to circularity (Ojha et al. 2017). ● The most common form of disposal of HDPE products is burial in landfills (79% of polyethylene waste) (Yao et al. 2022) ● HDPE has a slow and incomplete degradation time in nature (Chamas et al. 2020) meaning that they persist as contaminants. ● The incineration through open burning of polyethylene releases toxic fumes including hydrogen chloride, dioxin, cadmium, and fine particulate matter, polluting the air and potentially the surrounding soil and ground-water (Awasthi et al. 2017). This is not relevant for modern engineered incinerators with advanced air pollution control systems (Damgaard et al., 2010). ● Difficulties in recycling include the correct sorting of different grades depending on the type of polymer and their grade (LDPE, LLDPE, MDPE, HDPE) as well as their transparency and colour (Cecon et al. 2021, Rodríguez et al. 2021).	● The mechanical properties of recycled HDPE are not that different from the original HDPE product and retain the high mechanical strength and ductility characteristic of the material (Tesfaw et al., 2022) ● In addition, using recycled HDPE can be cost-effective and environmentally viable by lowering material costs and limiting the waste of natural resources (Papo & Corona, 2022).

	● Certain additives may hinder the separation of polyethylene plastics' main polymer during re-processing compromising the quality of the new HDPE products (Rodríguez et al. 2021). ● Recycled HDPE materials lose their properties after multiple uses (Papo & Corona, 2022). Properties such as hardness have been shown to deteriorate after 10 reprocessing cycles, while thermal resistance exhibits deterioration after 30 cycles (Oblak et al. 2015). ● Other challenges include: technical difficulties of recycling (sorting into the type of polymer and their transparency and colour (Rodríguez et al. 2021) as well as contamination from other waste streams, etc.), low qualities of recyclates (Papo & Corona, 2022) as well as costs of recycling (Hassanian-Moghaddam et al., 2023).	
Loss to the environment	● Exposure to environmental factors causes polyethylene to partly degrade but for full decomposition, special conditions typically not found in the natural environment are needed leading to a problem with the remaining plastics in the environment, i.e., microplastics (Chamas et al. 2020; Yao et al. 2022). ● The extensive use of HDPE products in packaging can cause pollution leading to soil contamination (Yao et al. 2022). ● The release of the additives and plasticizers from HDPE into the environment due to exposure to natural factors at landfill sites generates greenhouse gases contributing to the ozone depletion and global change (Iskander et al., 2016). ● The pollution of the marine environment from plastic bags or polyethylene-contaminated fish can cause the deaths of large marine animals such as seals, seabirds, whales, dolphins and polar bears (Yao et al. 2022).	● The use of microorganisms such as bacteria and fungi in the degradation of HDPE and LDPE plastics present a natural alternative to chemical methods of degrading plastics (Ojha et al. 2017). ● Although still in development, the exploration into the use of the bacterial strain *Klebsiella* to increase HDPE biodegradation (Awasthi et al. 2017). ● Exploration into the ability of Cephalosporium strain in pre-treated (ultraviolet and chemical) HDPE and LDPE biodegradation (Chaudhary & Vijayakumar, 2020)

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

HDPE in packaging is one of the few plastics to incorporate post-consumer recycling with recycled HDPE commonly used in milk bottles. In the UK, the Dairy Road Map, where industry came together to produce uniform milk bottles for ease of recycling, is a successful example of designing for circularity of plastics in packaging. However, there is a lack of consumer awareness around these efforts towards circularity which may make potentially less sustainable options in packaging more attractive to consumers. The key consumer attitude and behaviour considerations for the circularity of HDPE in packaging include:

Consumers are already well accustomed to disposing of HDPE milk bottles in the correct manner for recycling, presenting potential for consumer accepted reuse systems. Currently, 80% of HDPE milk bottles are recycled (Dairy UK). When compared to the average plastic bottle recycling of 58%, it is clear that the Dairy Road Road Map is having some success in gearing consumers to increase recycling rates in the UK. This provides an opportunity to harness this behaviour for reuse systems. Furthermore, as an interim to the implementation of reuse systems, this consumer behaviour of correct disposal presents an opportunity to improve collection and recycling for a wider range of HDPE packaging products such as other bottle containers for households. Taking the example of the UK dairy industry, This can be achieved by providing the necessary infrastructure and enabling conditions through education, services and facilities.

Inconsistent labelling systems limit the recycling information and knowledge available to the general public, confusing consumers. There is no consistent system of labelling for HDPE packaging products, confusing consumers. Labels and logos in packaging do not always clearly indicate to the consumer (and retailer) when a plastic is recyclable and how to manage the plastic post-use. Outside of milk bottles, consumers can be confused by these inconsistencies and end up disposing of HDPE plastics incorrectly, presenting a challenge for the quality and HDPE recycling potential of plastic waste streams. Moreover, there is no label system communicating the recycled content of HDPE packaging products. Clearer labelling would enable consumer knowledge and ability to dispose of HDPE packaging products in the correct collection systems and has the potential to promote HDPE material recovery (Nemat et al., 2020).

Lack of consumer awareness of the sustainability of recycled HDPE packaging products. There is a lack of consumer awareness on the environmental impacts of other materials when compared to recycled HDPE in the UK. In the case of milk, it has been shown that HDPE is rated with PET as the least sustainable packaging option (Schiano et al., 2020). Furthermore, consumer perception is shown to be more favourable to paper compared to plastic in food-grade packaging (Lindh et al. 2016). Experts in the waste management of packaging products for businesses highlight that the use of recycled HDPE in packaging is more sustainable than some other bio-based packaging alternatives in the UK (i.e. Tetra Pak). Consumer perceptions of HDPE packaging products could be vastly improved if the efforts towards circularity and sustainability were better promoted through such methods as labels,logos and signage (Nemat et al., 2020; Wu et al., 2018).

There are limited, and inconsistent guidelines for the handling and disposal of HDPE packaging products post-consumer. Although there is a high production of HDPE products in packaging, there is a lack of clear universally understood and standardised disposal instructions. User guidelines for recycling receptacles are often unclear and consumers often get confused about which material to put in correct receptacles because of a wide range of different receptacles with different colours and labels provided by the local authorities (Oluwadipe et al. (2022; Jesson & Stone, 2009). This is especially true if householders move from one local authority area to another with different collection systems of provided receptacles in different colours and labels, leading to confusion and incorrect disposal of HDPE plastic waste which can create numerous issues such as contamination of the resultant waste streams. Moreover, this confusion extends to businesses that are not aware of correct recycling procedures (Hahladakis & Lacovidou, 2019).

Based on the consumer related barriers and opportunities for HDPE in packaging, the following key interventions have been identified:

- **Improved labelling standards and content that clearly states recycled content and recyclability of packaging products.** This should include where the product can be disposed of and the recycled plastic content of the product
- **Education and awareness raising activities to educate consumers and businesses on the recyclability of the materials used in HDPE packaging.** This should include guidelines on how to handle products, how to dispose of products correctly to ensure efficient waste management.
- **The introduction of bio-based or recycled HDPE adapted waste and sorting and collection infrastructure to remove waste separation from consumers.** Consumers should not carry the burden of further in-house systems for separating waste. Improved mechanisms post-consumer for sorting mixed recyclables is needed to separate recyclable and bio-based HDPE.

b. Economics

As one of the most popular plastics used in the plastic industry, HDPE has a high production rate with 6 million tons of HDPE produced for Europe in 2018 (Rodríguez et al. 2021). The high production of HDPE in packaging will be influenced by economic factors such as affordability of manufacturing, the cost of the base material and the economic viability of collection and recycling processes. Economic considerations for circularity include:

Reuse models for HDPE are economically viable, but to date are limited. Despite the initial financial investments required, many reuse solutions also have the potential to generate huge cost savings and are already technologically and commercially available**.** Substituting only 20% of single-use plastic packaging with reusable alternatives offers an opportunity worth at least USD 10 billion globally (Ellen MacArthur Foundation, 2019). This presents a great opportunity to adopt reuse models for HDPE in packaging. Reusable milk bottle schemes have recently been introduced made of polypropylene, from which lessons can be drawn for HDPE, especially given that HDPE currently dominates the market for milk bottles or containers.

The recycling of HDPE via chemical and physical methods is very expensive, energy intensive, and can produce persistent organic pollutants. For more details see HDPE in construction in Section 3.4.ii.b.

HDPE supply can be limited for recycling due to large export volumes of packaging products in the UK. Even though the recycling rate for certain products such as milk bottles is quite respectable (80%), HDPE supply for recycled products is often limited by the export of food-grade HDPE packaged products in the UK. This exportation of HDPE results in the material being lost by the UK market to countries where it is downcycled into non-food grade products. Experts in the waste management of packaging products for businesses highlight these sourcing issues and comment on their having to buy virgin HDPE on the open market to keep up with demand for food-grade HDPE packaging. This makes recycled HDPE susceptible to market conditions.

Based on the above the following key interventions for economics should be considered:

- **Mandate the adoption of reuse models for packaging in closed systems.** Closed systems include food and drink establishments, hotels, sport and event venues, and public buildings. Evidence shows that adopting reuse systems in closed settings is a possible quick win, as much of the reuse infrastructure already exists.
- **Improve in-country systems for maintaining waste products rather than exporting waste to ensure a steady supply of recycling feedstock.** Most food grade HDPE in packaging is exported to be downcycled into non-food grade HDPE. Stronger regulations, such as bans, on export of waste would allow for better regulation towards a closed loop system and force more of a market for used packing items to be reused or fed in as recycling feedstock for high quality materials.

c. Technology and infrastructure

Significant gaps in technology and infrastructure exist for HDPE in packaging from production and processing to collection and recycling. The technological and infrastructure considerations for the circularity of HDPE in packaging include:

There are currently no reuse systems associated with HDPE in packaging. The main limitation to reuse of HDPE packaging are the high-quality standards of food-contact packaging with strict UK and EU legislation that determine which materials are safe to be utilised in contact with food. Currently very few recycled polymers have been approved for use in food grade packaging with the majority not meeting the requirements. This results in the downcycling of recycled material rather than reuse as the same grade of product. From an environmental standpoint, the main circular priority is to recycle food-grade HDPE back into food-grade HDPE packaging products to reduce the reliance on virgin feedstocks. However, the lack of reuse systems associated with HDPE packaging products will ultimately result in the production of lower quality HDPE with each reprocessing cycle and fail to reduce the supply of virgin HDPE needed for food-grade packaging. Development of reprocessing facilities, technology and infrastructure geared towards reuse with the potential to produce food grade recycled HDPE in packaging is an important step towards circularity.

The industry-led harmonisation of HDPE milk bottles is a success story for design for circularity. Despite the environmental challenges associated with plastics, plastic packaging is still considered the best and cost-effective packaging option for the UK dairy industry when considering product protection, food safety and quality and resource efficiency. Since 2008, The Dairy Roadmap has acted as a cross-industry initiative to improve the environmental sustainability of the UK dairy sector led jointly by AHDB, Dairy UK and the National Farmers Union and with the support of Defra and other industry stakeholders. 'Waste and recycling' is highlighted as a main theme of the Roadmap with targets to improve packaging design to maximise recycled content, reusability or recyclability of all tertiary packaging and eliminate single-use packaging in the dairy industry. A shining example within the roadmap is the use of HDPE in milk bottles. Currently, HDPE milk bottles are considered 100% recyclable, collected in 99% of local authority recycled collections with an estimated 80% recycled. In addition, HDPE milk bottles have a maximum recycled content of 30% and average around 25% (Błażejewski et al., 2021). Moreover, the dairy industry reported a significant decrease in the proportion of waste sent to landfill from 35% to only 4% in 2018. This umbrella initiative presents an example of industrial coordination towards a more sustainable use of plastics and circularity.

The presence of certain chemical additives such as stabilisers in HDPE in packaging can be environmentally damaging and can significantly affect the quality of the recycled material, resulting in downcycling. Recycling of polyethylene based plastics has challenges associated with additives such as stabilisers, flame retardants, and colourants used to improve the performance of polymers whereby some plastics cannot be recycled due to their structure and the amount of additives contained (Ferreira et al., 2021c; Undas et al., 2023). In most cases, the chemical additives are toxic, and they may hinder the separation of the main polymer and harm the quality of the new plastic products (Rodríguez et al. 2021). Furthermore, these chemicals can be released into the environment (Yao et al., 2022) as a result of the natural degradation of polyethylene waste and generate greenhouse gases (Iskander et al., 2016). Therefore, the development of techniques suitable for the removal of additives before the recycling process to obtain high quality recycled polymers is crucial. Currently, the most promising methods for that purpose include solvent extraction techniques, such as solid-liquid extraction and dissolution-precipitation due to their simplicity, the high purity of the recycled plastic obtained, and the potential to yield a plastic with the same quality as the virgin material (Ferreira et al., 2021).

The properties of recycled HDPE can match those of virgin HDPE, however these properties decrease with each reprocessing cycle, limiting circularity. For more details see HDPE in construction in Section 3.4.ii.c.

There are no established large-scale sorting facilities for different polyethylene grades due to collection and sorting difficulties, resulting in lower quality grades of recycled HDPE. The key barrier to replacing virgin HDPE with recycled is the contamination of the associated waste stream (Cecon et al. 2021). There is no consistent system for collection and sorting of post-consumer HDPE packaging products creating numerous issues such as contamination of the resultant waste streams from incorrect recycling practices (Hahladakis & Lacovidou, 2019). Experts in the waste management of packaging products for businesses highlight the theoretical feasibility of increased kerbside collection by existing waste management companies. However, this is dependent on a sufficient material volume to make the increased scale of operation cost-effect and of benefit to them. The rigorous effort needed to identify and sort polymer grades and their transparency and colour is the main challenge to recycling HDPE in packaging (Rodríguez et al. 2021). Experts in the waste management of packaging products for businesses highlight that separate streams for different polyethylene grades would need to be introduced to move towards replacing virgin HDPE with recycled HDPE and bio-based HDPE alternatives. But this would require improved technology and consumer compliance and may introduce further barriers to reuse and recycling. Furthermore the majority of HDPE products end up in landfills along with other grades of polyethylene, contaminating the waste stream and compromising the utilisation of recycled HDPE. If there is not sufficient volume of a material to introduce technological approaches to stripping or separation, the use of recycled HDPE becomes very expensive.

The potential of tag and trace technology towards efficient sorting of plastics would increase transparency and accountability. The advantages of using tags and traces across the supply chain include consumer awareness and understanding as well as increasing a company's ability to extract the desired plastic waste for efficient reuse and/or recycling of HDPE packaging products. However, the technology would need an international agreement to standardise the tagging system as the current waste system does not allow for the use of multiple types of tracing.

Based on the above the following key interventions for technology and infrastructure should be considered:

- **Implement a tag and trace on food grade items.** Ensuring traceability and the ability to identify and reject products that can contaminate reuse streams is essential for maintaining food safety standards.
- **Mandate DRS for food grade products.** Effective and nationwide roll out of DRS can facilitate the return of reusable products to producers. This can also ensure a clean recyclate for recovery at the end of the reusable items economic life reducing contamination and increasing resource value.
- **Introduce EPR taxes on products that can readily have reusable alternatives with a lower environmental impact.** A phased incorporation of taxes on products with environmental and human health superior alternatives. This needs to be placed in conjunction with the above interventions to be effective.
- **Re-invest tax and deposits collected from DRS and EPR into reuse systems.** Ensure that the value of tax and deposits is returned into the system to support commercial and industry transition to a reuse market.

d. Policy and regulation

In the UK, current recycled-content laws require players in the packaging industry to use a minimum amount of recycled material in their products before tax. At present, the following strategies or regulations relate to HDPE in packaging.

- Implementing the Packaging and Packaging Waste Directive are the Producer Responsibility Obligations (Packaging Waste) Regulations, 2007 and the Packaging (Essential Requirements) Regulations of 2015. This regulation requires packaging producers to meet annual recycling targets with the annual target of 61% of plastic in packaging to be recycled in 2023.
- Our Waste, Our Resources: A Strategy for England maintains a priority to raise recycling targets and improve recycling capacity with respect to plastics and mitigate environmental impacts.
- Packaging Waste (Data Reporting) (England) Regulations of 2022, includes a phased EPR regime to come into effect in 2023, requiring packaging producers to collect and report packaging data and contribute to the cost of collecting, treating, recycling and disposing of packaging waste.
- The plastic packaging tax came into effect from April 2022 and increased in 2023 impacting finished plastic packaging products produced in or imported into the UK that does not contain at least 30% recycled plastic.

The plastic packaging tax (PPT) has not had the desired effect across the recycling industry. As evidenced by a number of expert interviews, the tax does not incentivise recycled content to the desired degree in the UK because of the variance between the cost of virgin HDPE and recycled HDPE content. It is considered the right type of legislation by experts in the waste management of packaging products for businesses, but the tax should be higher and progressively increased to have a real impact on the recycling industry. PPT income as reported by HM Revenue and Customs (HMRC) in the financial year 2022 to 2023 totaled £276 million, representing less than 50% of the tonnage of plastics placed on the market that contain the 30% minimum recycled content. This income is higher than anticipated which shows a willingness by industry to pay the tax instead of making changes to the infrastructure of the recycling systems (Hudson et al., 2023; Stakeholder interviews, 2024). The tax has resulted in an increased demand for recycled content but most of this demand is being fulfilled by overseas suppliers. There is a major issue around the transparency of the true recycled content of imported plastics, where the requirement for ensuring recycled content is simply the checking of a box on the customs import forms (Expert interview, 2024).

Food-grade recycled HDPE packaging products are restricted by the high level of requirements. To be used in packaging especially as a food contact material, recycled HDPE must meet specific requirements retained from the EU food safety legislature (Juan et al. 2020). This in combination with the fact that at present in the UK there is no current legislative requirement to use recycled plastics in food and cleaning product packaging are barriers to the use of recycled HDPE over less sustainable plastic alternatives.

Expert interviews identified that the UK landfill tax has had a positive effect on developing the recycling industry. The UK landfill tax aims to reduce the amount of waste being sent to landfills by businesses and industry alike and promotes alternative disposal mechanisms such as recycling and reuse. As HDPE stands as one of the recycling success stories in the UK, its example is expected to lead this change in thinking with respect to plastic-related waste. Experts in the waste management of packaging products for businesses comment that for many waste management companies, the use of landfills for plastic waste is decreasing in priority. However, despite this movement, progress is slow with landfills still being the main means of polyethylene waste disposal, with 79% of polyethylene waste is estimated to end up in landfills globally (Yao et al. 2022).

Based on the above the following key interventions for policy and regulation should be considered:

- **Introduce a minimum recycled content mandate to replace the PPT.** A minimum recycled content of at least 40% would drive the decline in virgin content significantly, and act as a push for innovation and safe recycling.
- **OR Increase the cost of the PTT.** The tax needs to be high enough to incentivise an actual shift to more recycled content, and could be combined with bans on certain items of virgin materials.
- **Improve requirements and monitoring for proving the recycled content of imported products.** Through collaboration with Customs, an improved mechanism for identifying the recycled content of imported products is needed, which may also require technological advancements to provide regulators with a means of checking the recycled content level.

e. Waste hierarchy

The current system for HDPE in packaging is predominantly placed at the recycling stage of the waste hierarchy (Figure 11). Although recycled HDPE is already utilised in the construction industry, its use in packaging is more restrictive due to the high requirements of these products, especially in the case of food grade packaging (Juan et al. 2020). The current goal of HDPE in packaging is to be able to depend on a fully recycled system for HDPE that returns products to the same product again. Currently, the quality of waste stream is not sufficient to create a closed loop and the production and re-processing of recycled HDPE products still requires inputs of virgin HDPE. Another barrier to realising the full recycling potential of HDPE in packaging is the dual stream collection allowing contaminants into the stream. There have been considerable efforts towards upscaling recycling, however, the full recycling potential of HDPE has not been realised due to poor infrastructure and high cost of the additional sorting and separation required to increase the quality of the recycled HDPE in packaging.

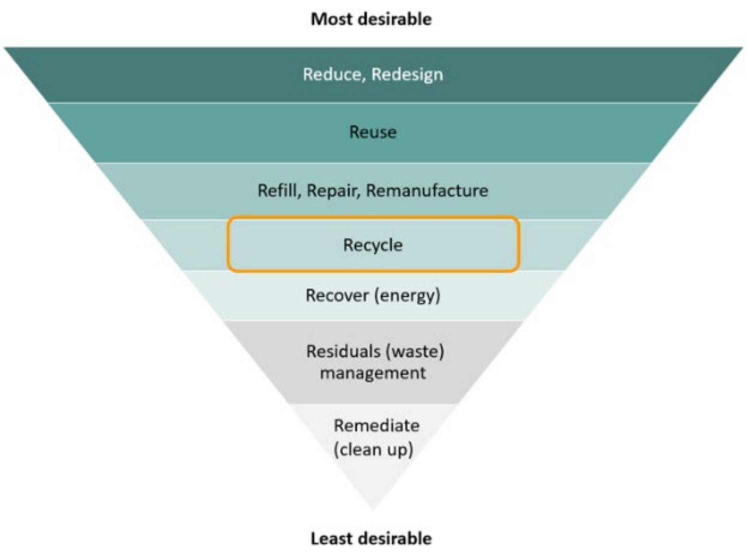

Figure 11. Current position of HDPE in packaging on the waste hierarchy.

In terms of moving HDPE in packaging up the waste hierarchy to reuse, there are a number of barriers, the primary one involving economic viability and the material itself. The reuse of HDPE in packaging is possible, however, it is not economically viable in the current system. High regulatory requirements for the reuse of food-grade HDPE products in packaging as well as the need for more advanced technology and infrastructure are barriers to the cost-effective reuse of HDPE in packaging. Another barrier to reuse is the material itself and issues of human health with concerns of chemical leakage as a block to moving up the waste hierarchy, especially when dealing with food and beverage packaging. However, there is little chance of chemical leaching in HDPE bottles with the right storage and they are considered safe to reuse if they are well washed and undamaged (King, 2018). Meanwhile, in 2023, Berry Global has announced the release of reusable bottles claimed to be produced from post-consumer HDPE and said to be refillable to up to 300 cycles (Packaging Europe, 2023). This initiative signals the movement from recycle towards reuse on the waste hierarchy system.

There are no further interventions identified beyond those listed in the previous sections to improve the overall circularity of HDPE in packaging.

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for HDPE in packaging (Table 11).

Overall potential for circularity

To be considered circular, certain aspects of the current system for HDPE in packaging would need to meet a number of criteria. Firstly, HDPE manufacturing processes would need to be designed to become more circular and reliant on renewable energy with a full analysis of innovative and environmentally friendly production pathways such as CO_2 capture and utilisation to mitigate GHG emissions (Mufarrij et al. 2023). The literature suggests that for HDPE in packaging to fit a circular materials flow, the challenges associated with waste infrastructure and systems would need to be addressed with special attention to disposal and recycling of plastics. Having these systems in place would enable HDPE in packaging to contribute to the circular economy, and reduce detrimental impacts such as plastic leakage into the environment. The successful examples of recycled HDPE products (i.e. milk bottles) should be noted and better communicated alongside the adaptation of recycled-content laws and financial incentives to companies recycling HDPE or investigating ways to improve its circularity. At present, while material costs are lower for recycled bottles, manufacturing costs are higher when compared to virgin HDPE (Papo & Corona, 2022). Governmental support in the form of financial incentives toward more advanced technology for cost-effective re-processing of HDPE for recycled products may bridge this gap. Methods should be investigated to improve the quality of recycled HDPE to better match properties of virgin HDPE in various industry sectors such as food-contact material requirements for packaging. At present, no other material that can match HDPE's mechanical properties is considered more sustainable. Currently, the literature suggests that this material is not circular but has high potential towards contributing to a circular economy for plastics.

Table 11. Interventions to transition to a circular system for HDPE in packaging, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Improved labelling standards and content that clearly states recycled content and recyclability of packaging products.	National, Regional, International	Industry, Government	Medium
Education and awareness raising activities to educate consumers and businesses on the recyclability of the materials used in HDPE packaging.	National	Civil society	Medium
The introduction of bio-based or recycled HDPE adapted waste and sorting and collection infrastructure to remove waste separation from consumers.	National, Subnational	Government, Industry	Medium
Mandate the adoption of reuse models for packaging in closed systems.	National	Industry, Civil society, Innovation	High
Improve in-country systems for maintaining waste products rather than exporting waste to ensure a steady supply of recycling feedstock.	National, Regional, International	Government, Industry	High
Implement a tag and trace on food grade items.	National, Regional, International	Industry, Innovation	Medium
Mandate DRS for food grade products	National	Government, Industry	High
Introduce EPR taxes on products that can readily have reusable alternatives with a lower environmental impact	National	Government, Industry	High
Re-invest tax and deposits collected from DRS and EPR into reuse systems.	National	Government	High
Increase the tax on plastic packaging.	National	Government	High
Improve requirements for proving the recycled content of imported products.	National, Regional, International	Government	High

iv. Gaps in evidence and assumptions

A number of gaps in evidence exist in determining the circularity for HDPE in packaging, including:

- The length of supplier contracts across the whole life cycle and how this impacts circularity.
- How this material or product is packed for onward transport and associated impacts on the products' design or choice of material, the impacts on the volume that can be purchased, and whether the packaging for transport leads to excess stock or waste.
- Whether the extraction and refining methods used for HDPE processing extract maximum value from their feedstock and the associated tradeoffs.

3.6 PET in packaging

i. Life cycle stages and circularity

PET is one of the most widely used polymers within the plastics industry and particularly in relation to packaging at 9% of the market share (Wang et al., 2021). In the last few decades, virgin PET has gained significance as one of the most important engineering polymers due to its exceptional properties such as tensile and impact strength, chemical resistance, clarity, processability, colorability, and reasonable thermal stability (Awaja and Pavel, 2005). It is highly valued for its versatility and is widely used in various applications, and has emerged as a promising material for food packaging due to its outstanding characteristics, including high clarity, good barrier properties against moisture and oxygen, and its potential for reuse after recycling processes, particularly in food contact applications (Rossi and Bianchini, 2022).

Despite the functional benefits of PET, its intended use primarily as packaging for beverages results in a short lifespan, which can be as short as hours after purchase. Examples of such products include water and soft drink bottles, take-away containers, disposable cups and plates (World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company, 2016). Currently the PET system is not fully circular, with around 75% of the material lost through leakage at different stages (Eunomia & Zero Waste Europe 2022). Within PET packaging, only bottles show the greatest level of circularity with 17% recycled content on average (Eunomia & Zero Waste Europe 2022). The rest of the recyclate produced from PET bottles 'cascades' into other product categories such as trays, other packaging or fibres. It is then lost when these products reach end-of-life, as these product types are predominantly linear with no large scale reuse, refill or recycling taking place. However, it has been argued that utilising an open loop recycling system can have greater environmental benefits in comparison to the current closed loop systems that exist when undertaking a combined material flow analysis and LCA (Lonca et al., 2020). This presents an opportunity for sorted and collected PET to enter more markets retaining the material.

Across the life cycle of PET, the barriers to circularity exist in the conversion and production, sale, reuse, collection, disposal and loss to the environment stages. The main opportunities for circularity lie in the conversion and production, sale, reuse, recycling, and loss to the environment stages (Figure 12). A summary of the barriers and opportunities are presented in Table 12.

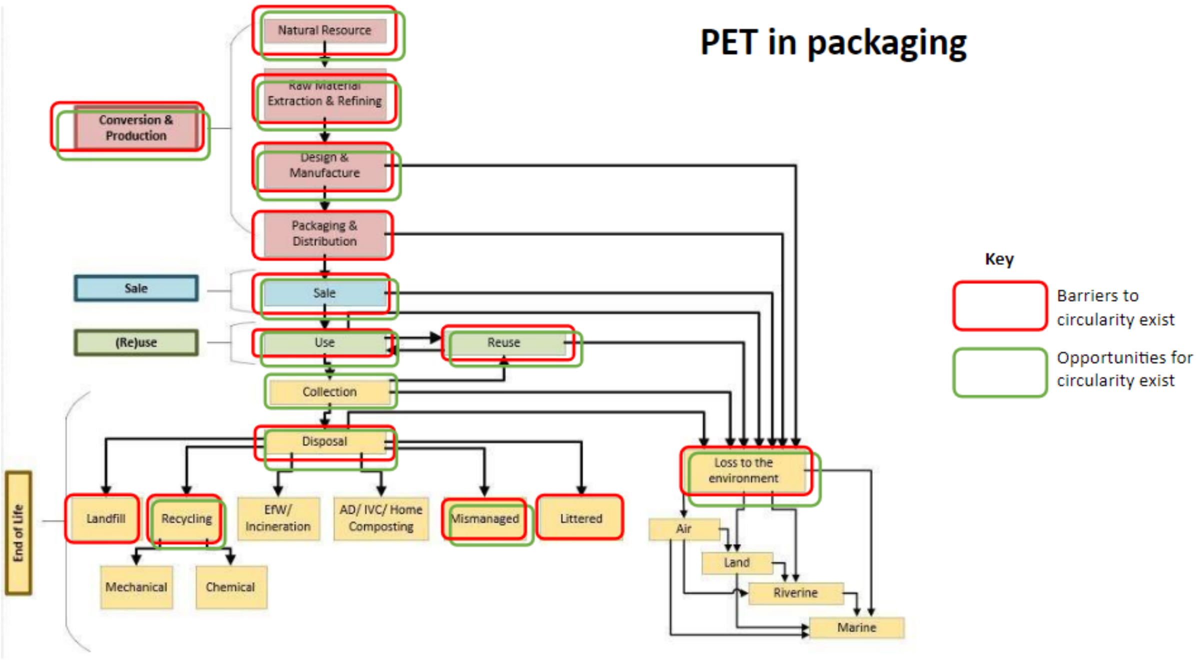

Figure 12. Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of PET exist.

Table 12. Overview of identified barriers and opportunities for the circularity of PET in packaging by life cycle stage.

Life cycle stage	Barriers	Opportunities
Natural resource	● Virgin fossil fuel is often cheaper than recycled PET (rPET) or other sources of PET, often to a point where current plastic levels do not tip the balance in favour of purchasing rPET. An aspect of this is the need to ensure rPET of a certain quality and the reliable continued sourcing of recycled material. ● Currently a higher cost to produce bio-based PET than that produced from virgin fossil fuels (Rybaczewska-Błażejowska & Mena-Nieto, 2020). ● Similar to traditional plastics, bio-based PET also raises concerns about the leaching of monomers, oligomers, and additives (García-Velásquez & van der Meer, 2022). ● Limited capacity for domestic recovery of plastic can create an over reliance on virgin fossil fuel resources for PET (BPF 2021).	● Utilising an open loop model as opposed to a closed loop to ensure that rPET value is maintained and sold competitively to that of virgin, reducing potential losses (Lonca et al., 2020). ● Utilising alternative resource streams for PET production have shown to have lower global warming potential accompanied with lower fossil fuel consumption at 21% and 22% respectively. Further decarbonisation of the production process can have further impacts in reducing emissions (Chen et al., 2016). ● The successful transition to a large-scale bio-based plastic market application from the current fossil-based one requires clear regulations and financial incentives. However, investment and scaling of bio-based plastic technologies are deemed high-risk due to uncertain demand despite the fact that larger scales have the potential to reduce prices and create incentives for recycling infrastructure (Rosenboom, Langer, & Traverso, 2022). ● Improvements can be made in the raw material extraction supply chain of bio-based plastics. These can include implementing measures that do away with substantial use of pesticides use and forest burning practices which can considerably lessen these negative impacts (García-Velásquez & van der Meer, 2022)
Raw material extraction & Refining	● Traditionally, the monomers of PET are manufactured from fossil-based resources which are associated with negative environmental impacts associated with carbon emissions.	● The use of bio-based plastics for manufacture of PET as opposed to synthetic plastics, which rely on a significant portion of the global crude oil supply, requires less energy input and emits fewer CO_2 emissions (Nanda et al., 2021).
Design & Manufacture	● The PET-polymer production phase is the stage with the largest environmental impacts (Ingrao & Wojnarowska, 2023). This stage, referred to as the PET P stage, includes all the activities that take place from the cradle to the gate of the PET production factory. In China, the largest producer of PET globally, this stage is estimated to have contributed 74.9% of the total GHG emissions from 2000 to 2018 (Chu et al., 2022), although the specific portion of which is packaging is unclear.. ● Studies show that the production of PET and PET bottles has substantial effects on human health and the environment . Environmental impacts include GHG emissions and air pollution while those on human health may include respiratory problems and birth effects (Dhaka et al. 2022). Further, the upstream production of chemicals and consumption of energy during manufacturing contribute significantly to global warming (Chu et al., 2022).	● The most critical stage for achieving carbon neutrality in the life cycle of PET plastics is between the raw material exploitation to the end of PET chip production (Chu et al., 2022). Utilising renewable energy sources during this stage could substantially reduce plastic-related emissions by up to 62% (Rosenboom, Langer, & Traverso, 2022). ● Lightweighting in packaging involves reducing the material used while still maintaining functionality resulting in products with significantly lower environmental impacts particularly if mismanaged (Ncube et al., 2021). For example, Coca Cola redesigned their water and soda bottles, which are made from PET to be smaller, lighter and shorter necked, while Walmart has thinned the protective plastic covering used to ship clothing. ● To increase the recovery and recyclability of PET products, it is crucial for

	● In the current plastic materials market, the extent to which the packaging is recycled is influenced by the design of plastic packaging (Rybaczewska-Błażejowska & Mena-Nieto, 2020).	manufacturers to ensure that mono materials rather than non readily-recyclable multilayers are used. This could be through easier separation of multilayer thin films (Rosenboom, Langer, & Traverso, 2022). Products also need to be easily identifiable to facilitate separation and recovery at sorting.
Packaging & Distribution	-	-
Sale	● The marketing and sales strategies of materials and products influence their usage and subsequent waste generation considerably. Food packaging, particularly single-use plastics, most of which is manufactured from PET, contributes to environmental pollution due to increased on-the-go consumption habits. When consumers purchase food on-the-go, they often throw away the packaging wherever they finish eating or drinking the packaged food (Ncube et al., 2021). The waste arising is then subject to the waste management facilities and services at the point of generation.	● There is a need for proactive measures to promote sustainable packaging alternatives and discourage disposable culture. (Study - United Nations Development Programme, 2023). Appropriate purchasing patterns and low-carbon product substitution within food product categories can reduce greenhouse gas emissions (Zhuo et al., 2023). ● Educating consumers and companies about "life cycle thinking" can promote a holistic view of plastic products beyond their immediate impacts and motivate consumers to practise better reuse and disposal habits as this approach encourages considering the entire lifecycle of products, from production to disposal, and emphasises the importance of environmental considerations at every stage (Rosenboom, Langer, & Traverso, 2022). ● Environmental problems can be mitigated by the enforcement of bylaws banning the usage of single-use plastic (Nanda et al., 2021)
Reuse	● PET is widely used as a single use product, but due to the mechanical properties of the polymer it has a relatively low glass transition temperature of 69 to 85℃ that limits disinfection (Liciardello 2024). As such other polymers are better suited for longer term reuse (Interviews). ● PET reuse has often been associated with increased exposure to additives and plasticizers (such as phthalates) which can have negative health implications Jayaweera et al., 2020).	● Reusable plastic packaging offers additional benefits, including cost reduction and versatility for primary, secondary, and tertiary packaging purposes. Such packaging can be reused multiple times before eventual disposal or recycling (Ncube et al., 2021). Utilising other suitable plastics or alternative materials can help increase reuse. ● Designing products for reusability, repairability, or remanufacturing further reduces the volume of products entering the waste stream, potentially enhancing economic sustainability (Hopewell, Dvorak, & Kosior, 2009).

Collection	• Consumers are sometimes confused by the types of plastics they can segregate for recycling, and end up mixing different materials, therefore affecting the quality of high value recyclates collected (Hahladakis & Iacovidou, 2018). Within the UK it is generally accepted that bottles can be recycled, with trays and pots dependent on the local regions facilities and services (interviews).	• Educating consumers and companies about "life cycle thinking" can promote a holistic view of plastic products beyond their immediate impacts and motivate consumers to practise better reuse and disposal habits as this approach encourages considering the entire lifecycle of products, from production to disposal, and emphasises the importance of environmental considerations at every stage (Rosenboom, Langer, & Traverso, 2022). • Deposit-refund systems and EPR schemes can increase return and collection rates for post-consumer plastics and increase the quality of the plastic collected (Rosenboom, Langer, & Traverso, 2022). Norway has demonstrated in excess of 93% rate of collection with drinks packaging, of which these products can contain over 65% recycled content (Raadl et al., 2023). • Standardisation in product design and collection across regions can help with user behaviours and create improved value chains for the recyclate (Burgess et al., 2021).
Disposal	• Potential contamination of target streams, such as PET and HDPE, with other polymers makes closed-loop recycling unlikely due to incompatibility. Even low levels of contamination can lead to poor adhesion properties and deterioration in overall macroscopic properties. For example, the presence of minor amounts of PVC in a PET bottle batch can make PET brittle and yellowish when recycled. Contaminated batches are often diverted to landfill or energy recovery facilities, causing short to medium-term issues for reprocessors facing high costs of contamination and sorting of poor-quality plastic packaging (Hahladakis & Iacovidou, 2018).	• Educating consumers and companies about "life cycle thinking" can promote a holistic view of plastic products beyond their immediate impacts and motivate consumers to practise better reuse and disposal habits as this approach encourages considering the entire lifecycle of products, from production to disposal, and emphasises the importance of environmental considerations at every stage (Rosenboom, Langer, & Traverso, 2022). • There is a need for proactive measures to promote sustainable packaging alternatives and discourage disposable culture. (Study - United Nations Development Programme, 2023) • Introducing new sorting technologies to improve the sorting of different types of plastic packaging, including opaque PET, PET trays, and food-grade r-PET will further enhance the market uptake of recycled plastics at various stages of the supply chain (Hahladakis & Iacovidou, 2018). • Innovations in sorting and processing technologies can enhance closed-loop recycling in order to improve recyclability of plastic packaging material such as PET (Hahladakis & Iacovidou, 2018). • By segregating waste correctly, it is possible to increase the efficiency of waste disposal, better recycle and reuse recyclable materials and reduce dependence on natural resources (Antonopoulos et al., 2021) • Encourage people to actively participate in recycling activities by providing appropriate recycling facilities and education (Zhuo et al., 2023). • Develop relevant policies and regulations to promote packaging waste management. This may include regulation of waste disposal, environmental taxes or incentives, and restrictions on unsustainable packaging. (Zhuo et al., 2023) • Incineration taxes that steadily but cautiously increase equally with the external cost caused by incineration can discourage this form of treatment and encourage

		investment in recycling facilities and redesign for recyclability (De Weerdt et al., 2022).
Loss to the environment	● Plastic packaging materials, including PP, polyethylene (PE), PET, polystyrene (PS), and PVC, contribute to micro- and nano-plastic pollution in food and beverages (Sohail et al., 2023)These plastics degrade over time, leading to the formation of microplastics and nanoplastics. The degradation processes, both abiotic and biotic, include chemical, physical, and biological reactions triggered by factors such as UV radiation (Zhuo et al., 2023). ● Food takeaway waste includes disposable trays and containers, alongside food residues. The chemical materials themselves, which are difficult to degrade, can create direct or indirect pollution to the atmosphere, water, and soil (Zhuo et al., 2023)	● Prevention of the mismanagement of plastic products through inadequate waste disposal will directly reduce the harmful effects of maco, micro- and nano-plastics on our health and environment (Zhuo et al., 2023). ● The serious ecological and economic consequences of disposable takeaway containers require the implementation of effective interventions, and the use of reusable takeaway boxes (often manufactured from alternative polymers or material) is an effective way to reduce the negative environmental impacts of disposable plastic containers (Zhuo et al., 2023). However, this action should also ensure a full life cycle approach to avoid unintended consequences and ensure adequate and suitable reuse systems and waste management processes are available. ● If single-use packaging was replaced with reusable PP packaging (food containers and carrier bags), emissions could be 63% lower than the current situation (Zhuo et al., 2023). ● Develop innovative materials that can replace traditional packaging materials, (Zhuo et al., 2023). Any alternative material and associated products would need to undergo a full life cycle analysis to ensure no unintended consequences such as resource use or greenhouse gas emissions at end of life. ● Promote and enforce design for recycling to improve quality of collected waste

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

Given that PET is one of the most widely used polymers in packaging for day to day products such as water, soft drinks, trays, and pot containers, consumers are a key stakeholder in the plastics value chain (Wang et al., 2021). Below are some key findings on how consumer attitudes and behaviour towards packaging (PET) influences its circularity:

The adoption of reusable/ refillable options will require a holistic approach. Consumers are becoming increasingly aware of the environmental impacts of plastic mismanagement and are consciously choosing alternatives (Biswas & Roy 2015). A combined education campaign alongside adequate deposit refund infrastructure and reverse logistics can help with user uptake (Numata & Managi 2012).

Consumers are already well accustomed to disposing of PET, particularly PET bottles, in the correct manner for recycling. Given that PET bottles are one of the most widely recycled plastic products, there is an opportunity to increase the collection and recycling of other PET food packaging materials such as take-away containers, disposable cups and plates by providing the necessary infrastructure and enabling conditions through education, services and facilities.

The increasing demand for food deliveries in the UK presents an opportunity for reverse logistics for reuse or deposit return schemes. Consumers are increasingly interacting with PET through online food delivery purchases, driving demand for packaging (Zhuo et al., 2023). This behaviour means consumers are increasingly refraining from leaving their homes to purchase food items, and will be less likely to return packaging to collection points within DRS schemes purchased in this manner. The increasing interaction by consumers with online delivery systems present an opportunity for these services to provide the reverse logistics for the collection of their packaging products for reuse or DRS collection points.

There is a lack of uniform and consistent waste collection processes for different PET packaging materials. Sorting, collection and recycling of on-the-go plastic packaging is dependent on the behaviour of the individual user, services available at the time of waste generation and the subsequent infrastructure availability of the area (Timlett & Williams 2011). Given that most food packaging, particularly single-use plastics, is manufactured from PET, this behaviour is one of the biggest contributors to environmental pollution (Ncube et al., 2021). This presents a potential barrier to the circularity of PET in packaging due to the dependence of correct behavioural practice to sort and separate the waste, as well as the availability for its collection and recovery. Customers have begun to purchase alternatives that are marketed as eco-friendly packaging options on offer, saying no to extra/ unnecessary packaging, and making use of reusable containers and alternative materials (such as aluminium) (Zhuo et al., 2023).

Consumers often lack awareness on how to properly sort different types of PET packaging materials which leads to contamination thus hampering recycling efforts. As with all recyclable municipal waste streams, PET is often not source segregated beyond a combined stream. This in turn can impact the quality of material collected for recycling due to contamination from other waste products, residues within the stream and other similar density polymers, resulting in a potential barrier to circularity (Hahladakis & Iacovidou, 2018). This presents an opportunity for educating consumers for better sorting and capture of waste as a resource.

Based on the above the following key interventions for consumer attitudes and behaviour should be considered:

- **Action education and awareness campaigns targeting the general public on reuse, sorting and recycling of PET products.** Engagement and education with consumers and the general public on better handling of PET packaging products through reuse, refill, return, correct separation and disposal of PET items can help to capture and retain their value. This can be done in conjunction with brand owners, retailers, municipal governments and through media channels in order to drive behaviour change and consequently move the material further up the waste hierarchy.

- **Provide incentives to various players in the PET value chain that promotes behaviour change at the consumer level.** This can be done through tax incentives or other economic subsidies to manufacturers and retailers of PET packaging who adopt circularity in their value chain such as lightweighting, changing product design, using renewable energy sources, installing reuse and refill stations etc that trickle down to the consumer in the form of price reduction or coupons for reused/ refilled / returned PET packaging.

b. Economics

The cost of shifting from the current linear production of PET to a circular one is currently prohibitive. For example, making a shift to a circular economy that features reuse schemes for PET packaging products at scale calls for financial investments to make them viable during the transition period. A lot of reuse solutions are still at the initial development stage and require both effective policy and economic incentives in order to make the shift to such an economy (Ellen MacArthur Foundation, Reuse – rethinking packaging (2019)

Reuse models present an opportunity to generate huge cost savings despite the initial financial investments required. Many reuse solutions, which have the potential to greatly increase the circularity of PET packaging, also have the potential to generate huge cost savings and are already technologically and commercially available**.** According to the Ellen MacArthur Foundation, substituting only 20% of single-use plastic packaging with reusable alternatives offers an opportunity worth at least USD 10 billion globally (Ellen MacArthur Foundation, Reuse – rethinking packaging (2019). This presents a great opportunity to adopt reuse models for PET packaging, which is one of the materials for which reuse models are most applicable. This includes PET packaging for products such as beverages, home and personal care products, dried food, snacks and trays.

The economics of recycling in the current market pose a challenge to the circularity of PET. For example, while the recycling of clear PET is economically feasible, coloured PET plastics have a lower market value, which makes it difficult for recyclers to compete with the virgin material market (Hahladakis & Iacovidou, 2018). This presents an opportunity to introduce directives that increase the recyclability of PET materials such as material reduction during production and designing products for reuse and recycling in order to increase their circularity. Securing long term investment will depend on the development of a secure and consistent market for rPET. Fluctuations in demand and pricing of material can result in a loss in confidence and increased risk for investors. Legislation that requires the use of rPET (e.g. a virgin plastic tax) whilst mandating PET is adequately separated and collected can help facilitate this (e.g. via DRS). Currently, the higher than expected tax returns for plastic show that there is not a sufficient adoption of recycled content, and as such potential to do more to promote the utilisation of recycled content (CIWM 2023).

The large-scale adoption of depolymerization of PET, which involves recycling plastics into monomer feedstock for the production of virgin-quality polymers often through chemical recycling has limitations. It is hampered by the efficiencies of the process, and the current processing costs. This method should only be considered for difficult to mechanically recycle products that cannot be designed out and where the environmental and health benefits outweigh chemical recycling utilisation.

Based on the above the following key interventions should be considered:

- **Encourage economic investments required to adopt reuse systems for PET packaging**. Transitioning to a circular economy with reuse schemes for PET packaging products on a large scale requires significant financial investments to ensure their viability.
-

c. Technology and infrastructure

Reuse schemes present a great opportunity to increase the circularity of PET packaging but further research on the infrastructure and technology needed is required. Reuse and refill of PET will require further research and consideration to ensure that the potential health impacts associated with disinfection, contamination, and the leaching of additives or plasticizers is overcome. Utilising novel disinfecting technologies that maintain the mechanical properties of PET whilst preventing the leaching of additives and plasticizers is a potential option. As PET has demonstrated in Norway a high rate of recovery and recyclability, extending its useful lifespan through reuse would further decrease the environmental impact of the product and increase circularity. Opportunities exist to use refillable PET bottles, which are thicker than single use alternatives in place of refillable glass beverage containers. This offers several benefits over glass of reduced packaging weight for transport, increased safety through handling and lower energy consumption for recycling (Junior et al., 2019).

There is a lack of infrastructure for collection and sorting of select PET packaging materials other than bottles. Of the PET family, bottle recycling has the most advanced technology and infrastructure in Europe at present (Eunomia & Zero Waste Europe 2022). However, for other PET packaging material such as trays and films, the collecting and sorting are not standardised throughout the UK or Europe and are sometimes collected in separate recycling collections mixed with other plastics, and other times are not collected at all (Eunomia & Zero Waste Europe 2022). This implies that there is potential to establish or scale up similar infrastructures and technologies for other PET packaging material in the UK.

Investing in technology and infrastructure for recycling PET packaging materials can enhance circularity. According to Ding & Zhu (2023), investing in recycling technologies has the potential to disrupt demand for virgin materials and enable the separation of additives, thereby enhancing circularity. For PET, its future prospects involve advancements in recycling technologies and bio-sourced resins, aiming for carbon-negative solutions(Sarda et al., 2021). Additionally, introducing new sorting technologies for opaque PET, PET trays and food grade recycled PET (r-PET) have been deemed capable of improving the sorting of these different types of plastic packaging (Hahladakis & Iacovidou, 2018). However, some PET packaging materials such as trays and films are difficult to recycle due to their design and a lack of suitable sorting and recycling technology (Eunomia & Zero Waste Europe 2022). This presents a challenge to the circularity of the materials, but presents an opportunity for innovation in design, improvement in sorting, and recycling technologies.

The PET-polymer production phase poses one of the greatest challenges to circularity of PET. The PET-polymer production phase, for a start, is the stage with the largest environmental impacts (Ingrao & Wojnarowska, 2023). It includes all the activities that take place from the extraction of raw materials to the PET production factory and is estimated to have contributed 74.9% of the total GHG emissions of the PET lifecycle from 2000 to 2018 in China (Chu et al., 2022), although the percentage of packaging is unclear.. This significant contribution to GHG emissions presents a huge barrier to the circularity of PET, making emission reduction in this phase crucial for achieving circularity.

Widespread adoption of technological advancements at the production stage is inhibited by costs. For example, biotechnology offers opportunities to develop new bio-based plastics and engineered bio-based polymers, including PET, which can reduce energy demands and enhance sustainability (Nanda et al.. 2021). Moreover, technological developments can reduce energy demands in the production of PET. This presents an opportunity to provide incentives or investments to make technology more affordable and reward innovation (World Economic Forum, Ellen MacArthur Foundation, & McKinsey & Company, 2016).

Developing technology and strengthening infrastructure at the end of use stage is another opportunity to increase the circularity of PET by reducing material loss to the environment through waste. Investing in the development of reuse scheme logistics and infrastructure such as dispensers, refill stations and cleaning centres. When fully implemented, reuse models are projected to yield a 20 percent decrease in the overall annual leakage of plastic into the ocean by the year 2040 (United Nations Environment Programme (2023).

Based on the above the following key interventions regarding technology and infrastructure should be considered:

- **Mandate producers, brand owners, retailers and service providers of PET packaging to increase investments in setting up reuse and refill infrastructure.** Utilising the producer pays principle, requiring the aforementioned suppliers in the value chain to set up structures that enable the consumer to reuse, return and refill when appropriate will lead to a reduction in loss of PET packaging material to the environment. This can be in the form of DRS or EPR schemes.
- **Support technological innovations to address the single-use design of PET packaging and products.** The single use design of PET packaging and products have a significant impact on incorporating circularity, and technological innovations can extend their useful life to enhance circularity.
- **Invest in the expansion of infrastructure in order to standardise collection and sorting processes of PET packaging materials other than PET bottles.** This will reduce the amount of waste from PET packaging materials like trays and films and improve collection, reuse and recycling rates.
- **Mandate manufacturers to invest in emission reducing measures at the production stage.** For example, technological developments can reduce energy demands during production thus optimising the process for greater circularity.

d. Policy and regulation

In the UK, there are several policies that relate to plastic packaging made of PET:

- Upcoming DRS legislation and associated infrastructure will be incorporated in October 2025 within England, Wales and Northern Ireland. This will target all plastic bottles including those made from PET particularly. This will help address the current recycling deficit experienced within the UK of around 70% for beverage containers to that of comparable European nations (Germany, Norway, Finland) in excess of 90% (Defra 2023b).
- Upcoming consultations on the national standardisation of collections involving recyclable materials can help address the need to both widen the products that can be recycled, whilst identifying products that need to be addressed for reduction. This can then enable confidence in future infrastructure investment for recovery.
- The Environmental Protection (Plastic Plates etc. and Polystyrene Containers etc.) (England) Regulations 2023 which is being made to restrict the supply of single-use plastic plates, bowls, and trays and ban the supply of single-use plastic cutlery and balloon sticks and expanded and foamed extruded polystyrene food and drink containers, including cups.
- The Plastic Packaging Tax (Descriptions of Products) Regulations 2021 which amends the meaning of a "packaging component" that is subject to Plastic Packaging Tax, introduced by the Finance Act 2021 to include consumer facing single use plastic packaging and excluding 1) plastic storage containers, 2) packaging products which are designed to be an integral part of the good sold, such as printer cartridges, tea bags, mascara brushes, water filter cartridges and 3) packaging products that are designed to be re-used in the presentation of goods.

- The Packaging Waste (Data Reporting) (England) Regulations 2023 which require producers of packaging to collect and report data on the amount and type of packaging that they place on the market in order to calculate the fees that these producers will be required to pay to cover the cost of managing this packaging as part of the EPR for packaging scheme which is planned to start in 2024.

There is currently a lack of effective policy and economic incentives to shift supply chains and consumer behaviour to help overcome these transition costs.

The plastic packaging tax (PPT) has not had the desired effect across the packaging recycling industry. See Section 3.5 on HDPE in packaging for more details.

With PETs high recyclability and value as a food grade polymer, circularity has primarily been addressed at the industrial level through voluntary commitments. These commitments include examples such as light weighting products to minimise plastic per use and the incorporation of minimum recycled content targets. PET currently has one of the highest recycled contents for bottles at 53% and 41% for pots, tubs and trays (PTT), with the discrepancy primarily due to demand for recycled content in bottles outstripping supply of rPET (WRAP 2022). DRS will help to increase the recovery of PET bottles and in such increase the rPET content of products. Potential amendments and advances could be in addressing the recovery of PTTs, potentially through DRS to further increase the recovery and recycling of these products.

At present there are no policies that target the reuse and refill of PET products directly. The high recycled content of single use products resulting in no plastic packaging tax and the exclusion from EPR due to the incorporation into DRS (for PET bottles) means that there is currently minimal incentive for developing reuse systems.

Based on the above the following key interventions for policy and regulation should be considered:

- **Utilise plastic tax revenue to finance reuse and recycling infrastructure and services.** Return revenue raised by taxes into supporting the transition to a circular economy of PET through financing initiatives and infrastructure at both a local and national scale.
- **Introduce minimum recycled content mandates and enforce implementation also for imported plastics.** With the high recyclability of PET a staged increase in recycled content for single use products should be introduced creating further the market demand for rPET.
- **Increase the plastic packaging tax**. As the proportion of recycled content increases for PET the tax should increase both in minimum recycled content needed to avoid the tax and the value of the tax charge itself to ensure recycled content is competitive and favourable to virgin fossil based.
- **Mandate the adoption of reuse models for packaging in closed systems.** Closed systems include food and drink establishments, hotels, sport and event venues, and public buildings Evidence shows that adopting reuse systems in closed settings is a possible quick win, as much of the reuse infrastructure already exists.

e. Waste hierarchy

The majority of PET is not currently managed in a circular model and leakage from the system is high (Eunomia & Zero Waste Europe 2022). Currently, PET exists at the residuals/ waste management, recovery (energy) and recycling levels of the waste hierarchy (Figure 13). This is due to the presence of various barriers including: design for single use thus having a short life span, consumer behaviour (improper disposal), inadequate collection, sorting and recycling infrastructure and absence of reuse systems. Moreover, the reuse of PET is limited due to the mechanical properties of the polymers to conventional disinfection techniques that often require high temperatures (Liciardello 2024). In the UK, 75 % of PET bottles are recycled, while 36% of pots, tubs and trays are collected for recycling (BPF 2024). There is potential to increase this further for bottles with DRS, as demonstrated in nations such as Norway where recycling rates are in excess of 93% (Raadl et al., 2023). This collected waste should not be exported.

Some aspects of redesign have occurred with the reduction in the thickness of PET through lightweighting. However, this has now reached optimal levels that limit the compromise of the properties whilst reducing material use and costs. Further lightweighting is unlikely to occur or have the scale of benefits seen (WRAP, 2018). To enable a reuse or refill system it is likely that a redesign of products will be needed to increase the thickness to increase durability and longevity. Through this, the use of PET could reach the reuse aspect of the waste hierarchy and have a high level of material recovery when the product reaches the end of its useful and economical life.

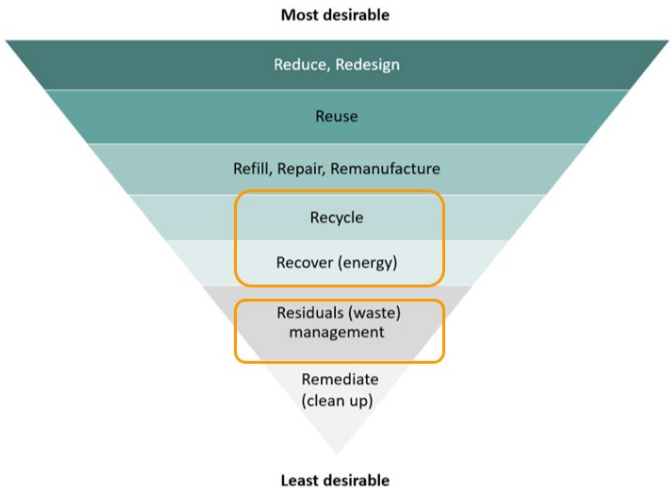

Figure 13. Current position of PET in packaging on the waste hierarchy.

Based on the above, the following key interventions should be considered:

- Enforce bylaws **banning the use of single-use plastic PET packaging** and promote **sustainable packaging alternatives** and discourage disposable culture.
- **Develop relevant policies and regulations to promote PET packaging waste management.** This may include regulation of waste disposal, environmental taxes or incentives, and restrictions on unsustainable packaging.
- **Reducing material use** in PET packaging products through actions like substituting heavy packaging formats with lighter ones or light-weighting existing packaging to decrease the volume of material entering the waste-management system

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for PET in packaging (Table 13).

Overall potential for circularity

PET is a highly recyclable material when designed for reuse, collection and recycling. Reuse schemes have in some instances shown to be successful when deployed in certain circumstances. There is a clear need to further investigate the migration of additives into products and contaminants into plastics when undertaking reuse and recycling. Not all use cases for PET will be suitable for reuse, but these should be explored, and where better performing alternative polymers or materials exist for this task they should be adopted. PET as a whole has a high potential for reuse and recycling, reducing losses to the environment and end of life waste management practices.

Table 13. Interventions to transition to a circular system for PET in packaging, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Action education and awareness campaigns targeting the general public on reuse, sorting and recycling of PET products	National	Civil society Industry Government	High
Promote or mandate the incorporation of circularity in stages of the value chain to provide enabling conditions for consumers to promote circularity of PET packaging materials and reduce waste	National	Government Industry Civil society	High
Provide incentives to various players in the PET value chain that promotes behaviour change at the consumer level	National International	Government Manufacturers Retailers Civil society	Medium
Encourage economic investments required to adopt reuse systems for PET packaging	National	Government, Industry	Medium
Provide economic incentives to PET packaging manufacturers to reduce the cost of changing manufacturing processes to enable greater circularity of PET production processes	National International	Government Industry	High
Increase the viability of PET recycling through financial incentives.	National International	Government Industry	High
Encourage economic investments and financial incentives for bio-based plastics.	National International	Government, Industry	Medium
Mandate producers, brand owners, retailers and service providers of PET packaging to increase investments in setting up reuse and refill infrastructure	National	Government Industry	High
Technological innovations to address the single-use design of PET packaging and products	National International	Government Industry Academia	High
Investing in expansion of infrastructure in order to standardise collection and sorting processes of other PET packaging materials other than PET bottles	National	Government Industry	High
Mandate PET manufacturers to design products for reuse and refill.	National International	Government Industry	High
Mandate manufacturers to invest in emission reducing measures at the production stage	National International	Government Industry	High

Utilise plastic tax revenue to finance reuse and recycling infrastructure and services	National	Government Industry	High
Introduce minimum recycled content mandates and enforce implementation also for imported plastics	National International	Government Industry	Medium
Increase the plastic packaging tax	National International	Government	High
Mandate the adoption of reuse models for packaging in closed systems.	National	Government Industry	High
Enforce bylaws banning the usage of single-use plastic PET packaging and promote sustainable packaging alternatives	National International	Government	High
Develop relevant policies and regulations to promote PET packaging waste management.	National	Government	High
Reducing material use in PET packaging products	National International	Industry	Medium

iv. Gaps in evidence and assumptions

A number of gaps in evidence exist in determining the circularity for PET in packaging, including:

- The length of supplier contracts across the whole life cycle and how these impact circularity.
- How this material or product is packed for onward transport and associated impacts on the products' design or choice of material, the impacts on the volume that can be purchased, and whether the packaging for transport leads to excess stock or waste.
- Utilisation of PET packaging within refill systems, particularly aspects of sterilisation and product performance.
- Formal reuse systems and the potential cross contamination of products or leaching of additives.
- Substitution of PET with other polymer types to facilitate reuse and refill.
- Use of the informal reuse of packaging and any associated disadvantages.
- Potential increase in utilisation of PET to replace polystyrene products that are not as readily or easily recyclable.

3.7 LDPE in packaging

i. Life cycle stages and circularity

Low Density Polyethylene (LDPE) is a flexible thermoplastic polymer. LDPE is more flexible and transparent than HDPE, and is used commercially and industrially. As a robust and malleable plastic, industrial uses include pallet wrapping, industrial strength containers, laboratory equipment and computer manufacturing. Globally, LDPE is the second most produced plastic (Izhar and May, 2020), reaching 22.8 million tonnes in 2022, and is expected to grow at a rate of 4.5% until 2032 (ChemAnalyst, 2023). This prevalence is attributed to its popularity as a commercial packaging resource, with its products including grocery and garbage bags, juice containers, frozen food packaging and cling film amongst a plethora of other single use and convenience based items, due to its barrier properties against water, light weight and low cost of production (Kyaw et al., 2012). In general, these products range from lifespans of a few months to a few minutes before disposal (OECD, 2022). Most plastic film that is commercially available is also made of LDPE. Although LDPE can be degraded by bacteria, bacterial degradation as a viable and large-scale solution to LDPE waste remains a knowledge and technological gap (Kyaw et al., 2021). Therefore, current end of life options include disposal to landfill where LDPE will take centuries to degrade naturally (Izhar and May, 2020) or recycling.

Across the lifecycle of LDPE in packaging, key barriers exist across design and manufacture, collection and end of life, as indicated in Figure 14. Opportunities for circularity also exist within these stages of the LDPE lifecycle. A summary of the barriers and opportunities are presented in Table 14.

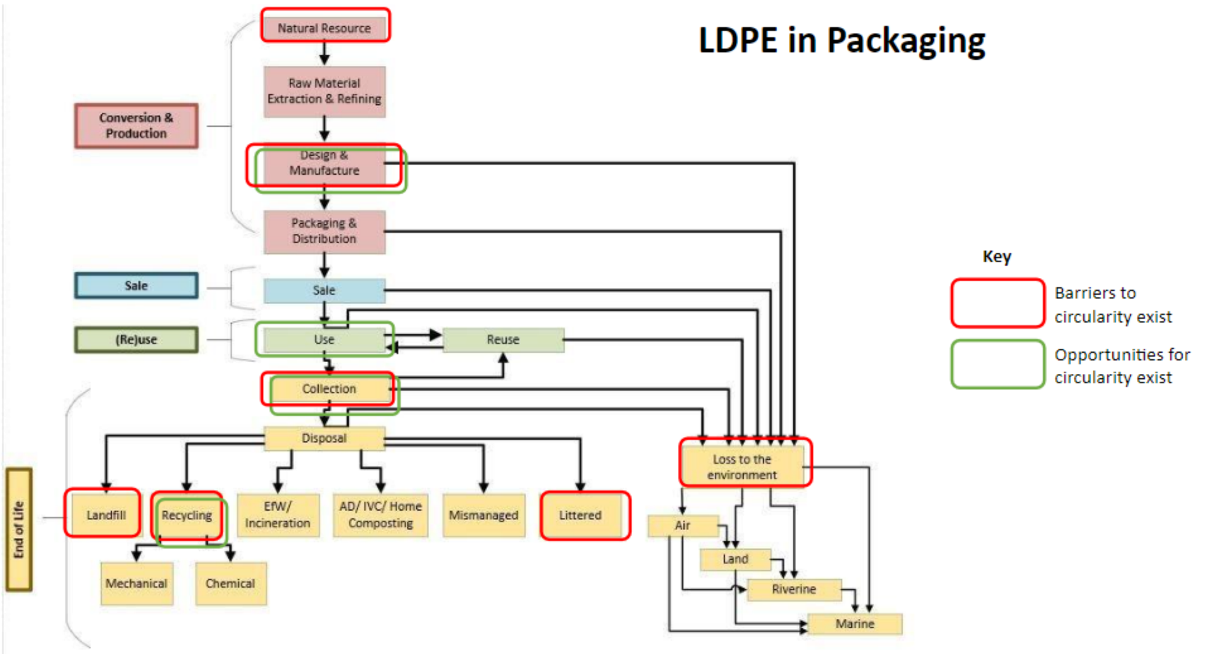

Figure 14: Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of LDPE in packaging exist.

Table 14. Overview of identified barriers and opportunities for the circularity of LDPE in packaging by life cycle stage.

Life cycle stage	**Barriers**	**Opportunities**
Natural resource	● LDPE production is dependent on petroleum, which is a finite resource.	● Bio-based LDPE is an alternative to petroleum based LDPE, reducing fossil fuel usage although bio-based LDPE also raises sustainability challenges in production (Abbate et al., 2022). Bio-based LDPE uses natural materials such as corn, sugar cane and switchgrass (Posen e al., 2015).
Raw material extraction & Refining	● Processing LDPE from petroleum has a high environmental impact through carbon emissions.	-
Design & Manufacture	● LDPE has manufacturing limitations, such as poor mechanical properties, easy deformation and low surface hardness (Wang et al., 2019) ● Food contamination restricts recyclability of LDPE products, and requires chemical recycling ● LDPE cannot be used in food products that are susceptible to oxidation due to low oxygen barrier properties (Moura et al., 2018) ● LDPE can leach chemicals into food and water, presenting health risks (Zimmerman et al., 2021).	● ● Manufacturing LDPE with renewable electricity could reduce biodiversity impacts over 96 % (Leppäkoski et al., 2023) ● LDPE can be generated from chemical recycling of non recyclable plastic waste, although the environmental impacts of this are poorly understood (Santagata et al., 2020). ● LDPE could be produced with a negative carbon footprint when using renewable energy sources and if the carbon stored in the product is considered (Leppäkoski et al., 2023)
Packaging & Distribution	-	-
Sale	-	-
Reuse	-	● LDPE products, excluding films, have significant potential for reuse but this is under explored in literature. ● Products could be designed with circularity in mind, such as for reuse (Interviewee). This includes preventing additives such as chalk or marble which changes the density of the polymer.
Collection	● Plastic film is often not collected by local authorities, and is therefore not recycled (RECOUP, 2021) ● Collection does not presort plastic, leading to contamination of recyclate. This is linked to a lack of regulation requiring presorted collection, a lack	● Infrastructure needs to be designed that is informed by consumer behaviour to enable the efficient collection sorted streams of LDPE (e.g., separating contaminated LDPE, plastic film) (Novakovic et al., 2023)

	of infrastructure to support sorted collection, and lack of consumer awareness regarding the differences in LDPE recycling (Brahmi, 2018)	
Disposal	● Incineration of LDPE releases significant carbon emissions (Izhar and May, 2020). ● Recyclability of LDPE is limited to a number of cycles. Processability of the plastic was impacted after the 40th recycling cycle (Jin et al., 2012) ● Recycled LDPE contains a higher number of additives and their degradation products, some of which may cause safety concerns (Horodytska et al., 2020). A total of 56 chemical additives were tentatively identified in five commonly used plastic polymer pellets, which included LDPE (Chen et al., 2022) ● LDPE waste from packaging films presents low index of mechanical recycling (Moreno and Saron, 2017) ● Interviewees felt that a lack of market for recyclate presented a large barrier for industry (Brahmi, 2018) ● Interviewees felt that without some form of support of intervention, recycling LDPE doesn't stand up economically (Interviewee) ● There is a lack of understanding regarding non-intentionally added substances to post-consumer LDPE, which presents hazards for recycling with the intent of reuse, particularly in food packaging (Horodytska et al., 2020).	● Biodegradation of LDPE is an emerging but diverse research area with over 100 species being analysed to date, most of which focuses on LDPE (Burelo et al., 2023). While not yet at industrial or commercial viability, research into different forms of degradation with early positive results spans microbial degradation (Sen and Raut, 2015), fungal decomposition in composting environments and biodegradation in seawater (Dmassi et al., 2024). ● It is possible to generate recycled composite from LDPE waste and pine wood waste, which are both abundant, inexpensive and are classified as pollutants. The use of these wastes as recycled composites represents a contribution for environmental saving and an economic alternative for industrial production using raw material of low cost, and showed viability for production of low cost materials from recycled waste (Moreno and Saron, 2017)
Loss to the environment	● LDPE packaging poses the same environmental threats of contamination as other plastic pollution. ● When exposed to sunlight, LDPE releases methane and ethylene, two greenhouse gases at a rate more unsustainable than any other plastic (Royer et al., 2018)	-

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

There was little information regarding consumer attitudes and behaviour towards LDPE specifically available in literature. However, as one of the most dominant forms of packaging material globally, and one of the most consumer accessible through the prevalence of LDPE products such as cling film and plastic bags, consumer behaviour and attitudes to domestically available commercial plastic in general can likely be considered as directly relevant to LDPE.

Consumer based reuse as a waste management strategy of LDPE products is limited in literature and expert opinion. Designing products for reuse (without depending on recycling into new products) is an under-explored reuse pathway of LDPE. No experts interviewed identified this as a viable pathway for LDPE products, and no literature regarding reuse of LDPE products could be identified despite many LDPE products being naturally reusable (plastic shopping bags, bottles).

Consumer awareness of recyclability of plastic plays a critical role in the effectiveness of recycling. Options for circularity for LDPE products are often recycling oriented in literature and expert opinion, meaning that presorting at the domestic scale to avoid cross contamination is critical (Horodytska et al., 2020). This depends on multiple factors, such as consumer awareness regarding local authority recycling capabilities and awareness of the fact that materials must be cleaned prior to collection. Therefore, priority should be given to ensuring effective education and awareness raising of the importance of sorting plastic recycling.

LDPE products are 'designed for disposal', representing a significant risk of littering and non-recyclable end of life pathways. The average lifespan of LDPE products is between six months and a few minutes before disposal due to their single-use design (OECD, 2022). This perpetuates the linear economic model of disposal which impacts consumer behaviour, and encourages the use of single use products. Design-for-disposal LDPE products can also shape consumer attitudes and behaviour, most notably through littering and loss to the environment (Ocelić Bulatović et al., 2019). LDPE is one of the most prevalent environmental contaminants and sources of litter (Hadiuzzaman e al., 2022; Lwanga et al., 2018).

Based on the above, the following key interventions for consumer attitudes and behaviour have been identified:

- **Investigate reuse from a consumer perspective for LDPE products.** There is a significant gap in current expert recommendations and literature regarding the feasibility of consumer based reuse of LDPE products.
- **Educate consumers regarding recyclability of LDPE products.** This would decrease contamination of existing LDPE recycling processes through limiting the inclusion of food and film waste.
- **Disincentivize design for disposal LDPE products to prevent littering.** Enhancing incentives for collection of LDPE products could include deposit return schemes to prevent loss to the environment.

b. Economics

Recycling soft LDPE is expensive and requires specialist technology. Tesco began a scheme in 2021 that collects soft LDPE plastic for recycling in store, which is used to produce bin liners which are also sold in-store. However, these bin liners are sold at a premium which could restrict the sale of recycled products, thereby limiting the feasibility of sale of recycled products. One expert explained that the scheme requires an advanced wash plant which adds around £450 per tonne, and requires a greater input of water and energy. Additionally, Tesco's experience highlights the need for investment in national recycling infrastructure. A report by Bloomberg (Chellel and Moskwa, 2022) showed that the soft plastic recycled as part of this scheme was shipped to Poland and Turkey, which has been attributed to a lack of sufficient and available infrastructure in the UK.

LDPE recycling is more expensive than producing new LDPE, although much of this depends on collection and sorting of waste. There are often multiple additional steps to LDPE recycling. For example, LDPE products are often commercial items that have labels which must be removed, or the product must be cleaned prior to recycling. When borne by the recycling company, many of these steps require additional energy and infrastructure which increases the cost of recycling (Vogt et al., 2021). An option to increase the efficiency and decrease the cost of recycling industrially is to incentivize better sorting and cleaning at the domestic scale.

Based on the above, the following key interventions for economics have been identified:

- **Invest in soft LDPE recycling infrastructure.** Currently, LDPE is often not recycled or is shipped abroad due to lack of national infrastructure.
- **Incentivize LDPE recycling by reducing the cost of recycling.** This would enable recycled LDPE products to be economically comparable or cheaper than non-recycled products.

c. Technology and infrastructure

Significant gaps in the technology and infrastructure of LDPE exist from processing to collection and recycling. In general, LDPE products are mechanically recycled. Soft LDPE products, such as film and plastic bags, are often not recycled**.** This is attributed to two factors: concern regarding food contamination of film, and lack of collection.

LDPE products are currently designed for disposal and not marketed for reuse. LDPE is generally considered safe for reuse within conditions. For example, non-food storage products are not advised to be reused as food storage due to food contact regulations. Despite this, products are almost never marketed or sold with multiple uses in mind. Significant potential exists to develop infrastructure to allow for recapture and reuse of common LDPE products, such as incentivising deposit return schemes, although LDPE is often not included in deposit return scheme studies (Global Plastics Policy Centre, 2023). Designing products for multi-use would also reduce the costs and environmental impact associated with recycling (Ragaert et al., 2017).

In 2021, only 13% of local authorities in the UK offered kerbside collection for LDPE plastic film recycling. This represented a five year decline in the total number of authorities offering kerbside collection for plastic film recycling (RECOUP, 2021). Of the 13% of local authorities who do collect plastic film, 24% only accept plastic bags (RECOUP, 2021). Thus, a major gap in infrastructure or technology exists in the UK for soft LDPE plastic recycling. Considering that by 2027, all local authorities in the UK will have to collect LDPE film, this represents an urgent gap in infrastructure that needs addressing as collecting plastic film without the capacity to sort or recycle.

LDPE film is difficult to recycle. Concerns about LDPE film packaging stem from food contamination, which reduces the quality of the recyclable product significantly. LDPE film must be decontaminated prior to recycling, which adds cost. Finally, when LDPE film is collected and recycled, the end product is usually a black colour which restricts resale and reuse, with the cost of adding a de-inking process adding a prohibitive cost per tonne (Interviewee statement). Chemical recycling of plastic film is proposed as a solution to food contamination to capture plastic film without increasing recyclate cost (Tullo 2019). However, currently chemical recycling has greater energy and financial requirements than mechanical recycling (li et al., 2022).

Bio-based LDPE utilises plant based materials to create LDPE, which can be an alternative to virgin LDPE production. Bio-based LDPE has been commercially used in packaging products (Leppäkoski et al., 2023). As bio-based LDPE is structurally the same as conventional LDPE it is not biodegradable and as such would follow the same life cycle processes post production. (Abbate et al., 2022). The environmental advantages of bio-based LDPE are therefore unclear in comparison to conventional LDPE, given the environmental implications of generating feedstock (explored in Section 3.1 and 3.2). The environmental impact of bio-based LDPE in a lifecycle analysis was shown to vary significantly between countries, more than general LDPE production (Abbate et al., 2022). In short, considering the environmental impacts of bio-based LDPE in comparison to petroleum based LDPE is not a simple comparison as significant variability exists regarding the cultivation and conversion of the feedstock, and readiness of end of life pathways. Thus, further research regarding the environmental benefits of using bio-based LDPE needs to be undertaken. Additional limitations, including poor solubility characteristics, mechanical properties, moisture barrier properties, bad processing, brittleness, and a highly crystalline structure limit widespread market viability (Sid et al., 2021). Current and future research could focus on using cellulose based polymers as a potential substitute for LPDE based food packaging (Sid et al., 2021).

Based on the above, the following key interventions for technology and infrastructure have been identified:

- **Develop and standardise soft LDPE recycling infrastructure nationally.** The inconsistency of recycling infrastructure means that soft plastic contaminates recyclate or ends up in landfill.
- **Create stronger and stricter standards regarding the use of additives in LDPE products is needed.** The lack of transparency and awareness of chemical additives in recycled products makes it difficult to identify toxicity and could present health risks.
- **Invest in standardised analysis of the environmental benefits of bio-based LDPE.** Currently, high variability of types of bio-based LDPE means that determining positive impact compared to conventional LDPE is difficult.

d. Policy and regulation

Current recycling laws in the UK require a minimum amount of recycled content in products and materials before tax. The following strategies and regulations specifically relate to LDPE in packaging:

- The Packaging and Packaging Waste Directive is implemented by the Producer Responsibility Obligations (Packaging Waste) Regulations, 2007 and the Packaging (Essential Requirements) Regulations of 2015. This regulation requires packaging producers to meet annual recycling targets with the annual target of 61% of plastic in packaging to be recycled in 2023.
- Our Waste, Our Resources: A Strategy for England, 2018, maintains a priority to raise recycling targets and improve recycling capacity with respect to plastics and mitigate environmental impacts.
- Packaging Waste (Data Reporting) (England) Regulations of 2022, includes a phased EPR regime to come into effect in 2023, requiring packaging producers to collect and report packaging data and contribute to the cost of collecting, treating, recycling and disposing of packaging waste.
- The plastic packaging tax came into effect from April 2022 and increased in 2023 impacting finished plastic packaging products produced in or imported into the UK that does not contain at least 30% recycled plastic.
- The Materials and Articles in Contact with Food (England) Regulations 2012 regulates the materials that come into contact with food materials, such as packaging and utensils.

LDPE regulation and policy currently does not incentivise circular designs for products. As noted above, direct reusability, that does not include recycling to create a new product, is rarely discussed in

LDPE literature. Mandating that LDPE products, such as plastic bags and containers, be designed to be multi-use and reusable by containers or through deposit return schemes, would have a significant impact on circularity.

The plastic packaging tax (PPT) has not had the desired effect across the packaging recycling industry. See Section 3.5 on HDPE in packaging for more details.

There are currently no standards or regulations for additives (whether migrated or intentionally added) into recycled products. There is a lack of understanding about how additives from initial product manufacture migrate to the final recycled product. Horodytska et al., (2020) identified substances commonly added to LDPE as a plasticizer in a final recycled LDPE product that was not included in a list of additives accepted for food contact products, which represents a significant and alarming gap in understanding.

Food contact materials, such as LDPE film, are difficult to recycle, often contaminated with food, and are often not collected in domestic recycling. Separate targets for food contact materials should be created, such as LDPE film. Creating targets specifically for food contact material collection and recycling will incentivise innovation in both collection and recycling technology. This could also be realised by having separate targets for chemical recycling which addresses contaminated LDPE and mechanical recycling that allow for both to coexist and complement each other.

Based on the above, the following key interventions for policy and regulation have been identified:

- **Regulate additives in recycled plastic through legislative standards.** Migration of additives in recycled plastic is poorly understood, and represents a health risk to the use of recycled plastic.
- **Create separate soft LDPE regulations and recycling targets to rigid LDPE.** This would incentivise recycling infrastructure and collection of an often disposed of plastic and prevent it from becoming landfill.
- **Introduce a minimum recycled content mandate to replace the PPT.** A minimum recycled content of at least 40% would drive the decline in virgin content significantly, and act as a push for innovation and safe recycling.
  OR increase the cost of the PTT. The tax needs to be high enough to incentivise an actual shift to more recycled content, and could be combined with bans on certain items of virgin materials.

e. Waste hierarchy

Currently, LDPE exists at the residuals / waste management level of the waste hierarchy due to the limitations and challenges associated with recycling LDPE film meaning that LDPE is most often disposed of in landfill (Figure 15). As detailed throughout Section 3.7, there are various opportunities for innovation to move LDPE up the waste hierarchy. Given that recycling of LDPE does occur in some capacity, both reuse, and then recycling are identified as potential pathways for LDPE products.

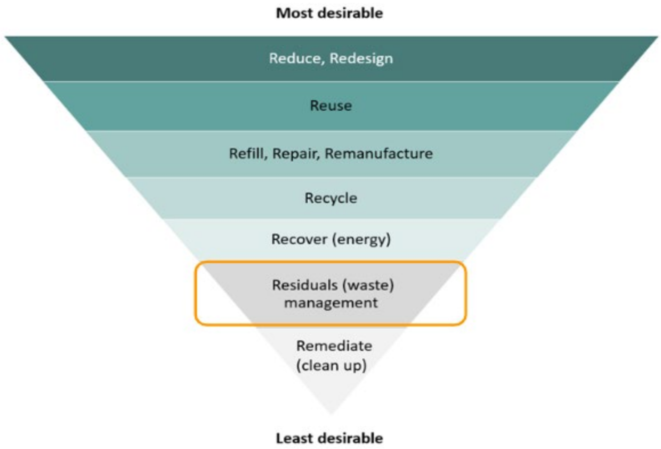

Figure 15. Current position of LDPE in packaging on the waste hierarchy.

The prevalence of LDPE as a packaging material raises significant challenges for its end of life pathway (Kyaw et al., 2012). Recycling is the current status quo for LDPE, although other end of life options exist, these include: mechanical or chemical recycling, incineration, and enzymatic degradation or biodegradation. The end of life process used depends on the type of LDPE, and its collection and sorting, all of which present barriers to recycling. In general, the more flexible a product, the more difficult it is to recycle due to contamination of the item being packaged (such as cling film or plastic film). After the 40th recycling cycle, however, processability and durability of LDPE was affected (Jin et al., 2012). This suggests that LDPE recycling is not a long term solution for generating reusable polymers, and should be considered when regulating or advocating for mechanical recycling of LDPE. It also suggests that recycling is not a fully circular process and raises questions about how many recycling cycles a product must undergo to be considered circular.

Given that mechanical recycling leads to polymer degradation over time, there is increasing interest in chemical recycling of rigid LDPE products. LDPE generated from chemically recycled materials is in its infancy. Santagata et al., (2020) detail a method of producing LDPE through chemical recycling of mixed, non-recyclable plastic materials, and argue that steering production towards “such a useful polymer (LDPE)” will supply increasing plastic demand while also providing a non-fossil based fuel product. However, the environmental impacts of chemical recycling are still substantial, even if portrayed positively in comparison to environmental impacts of mechanical recycling. Chemical recycling is more energy intensive than mechanical recycling, and there is a lack of transparency regarding the chemicals used within chemical recycling, and associated waste outputs and pollution (Davidson, 2023).

To achieve a truly circular economy, the direct reuse of LDPE products should be explored for viability and incentivised throughout the design and manufacture process. Additional incentives for reuse could be deployed by targeting consumer behaviour through deposit return schemes, although there is a lack of evidence or research regarding LDPE and deposit return schemes.

Based on the above, the following key interventions for overall circularity should be considered:

- **Support research and innovation for reuse options for LDPE.** Incentivising innovation at the design and manufacturing stage would allow for products that do not require recycling to generate a new product.
- **Create guidance and standards surrounding the true lifespan and recyclability of materials.** The narrative that recycling is a panacea solution to plastic needs to change, which can be supported through the exploration of the true recyclability of materials.
- **Create standards that necessitate designing for reuse where possible in single use LDPE products.** Products that are designed to be reusable without needing to be mechanically or chemically recyclable should be encouraged.

iii. Levers for change

Overall potential for circularity

LDPE products are vast in function and design, representing a major component of the plastics economy. Phasing out LDPE as a material seems unlikely given its material characteristics and widespread use, but innovation in feedstock type and other mechanisms for circularity may decrease some environmental impacts (Table 15). Concerns arise regarding the role of migrated additives in recycled LDPE, and experts identify concerns in market demand for LDPE as a recycled product. In general, policy interventions and innovation in infrastructure to ensure consistent supply of recyclate would aid LDPE in becoming more circular, but recycling alone is not a fully circular solution.

Table 15. Interventions to transition to a circular system for LDPE, their levers and priority.

Intervention	Geographic lever	Sectoral lever	Priority
Investigate reuse from a consumer perspective for LDPE products	National	Government	High
Educate consumers regarding recyclability of LDPE products	International	Industry	High
Disincentivize design for disposal LDPE products to prevent littering	National	Industry	Medium
Invest in soft LDPE recycling infrastructure	National	Government	High
Incentivize LDPE recycling by reducing the cost of recycling.	National	Industry	High
Develop and standardise soft LDPE recycling infrastructure nationally.	International	Industry	High
Create stronger and stricter standards regarding the use of additives in LDPE products is needed.	International	Industry	High
Invest in standardised analysis of the environmental benefits of bio-based LDPE.	International	Academia	Medium
Regulate additives in recycled plastic through standards.	International	Industry	High
Create separate soft LDPE regulations and recycling targets to recycling to rigid LDPE	National	Government	High
Support research and innovation for reuse options for LDPE.	National	Government	Medium
Create guidance and standards surrounding the true lifespan and recyclability of materials.	National	Government	High
Create standards that necessitate designing for reuse where possible in single use LDPE products			

iv. Gaps in evidence

A number of gaps in evidence exist in determining circularity for LDPE packaging:

- Whether extraction and refining methods used extracting maximum value from the materials
- Whether changing product design to allow for or to promote refurbishment and reuse was being considered or being actively used for LDPE
- Whether length of supplier contracts impact circularity
- Whether how LDPE is packed for onward transport impacts its design or choice of material
- Whether the method of distribution of LDPE impacts its design or choice of material
- Whether length of supplier contracts impacts circularity

3.8 PP in packaging

i. Life cycle stages and circularity

Polypropylene (PP) in total accounts for 16 % of the worldwide plastics market (Alsabri et al., 2022; Bora et al., 2020). PP is classified as a thermoplastic, which has a semi-crystalline resin (Alsabri et al., 2022; Maddah, 2016). PP is a downstream petrochemical product, which is prepared catalytically from the olefin monomer propylene also referred to as propene (Maddah, 2016).

In 2021, PP accounted for approximately 24% (344 kt) of the consumer (grocery and non-grocery retail) plastic packaging placed on the UK market (1439 kt), with PP film being the most common format arising from the consumer sector, accounting for 40% of the total PP share (344 kt) (WRAP, 2023). In contrast, PP accounted for roughly 13% (101 kt) of the non-consumer (grocery and non-grocery retail) plastic packaging placed on the market (779 kt), with PP pot, tub and trays (PTT) being the most common format arising from the non-consumer sector, accounting for approximately 64% of the total PP share (101 kt) (WRAP, 2023). The non-consumer market includes agriculture, construction & demolition, retail back of store, hospitality, and manufacturing & other).

Across the life cycle PP in packaging, primary barriers exist in the use of natural resources, disposal, and loss to the environment stages. The main opportunities for circularity lie in the use of natural resources, recycling, and loss to the environment stages (Figure 16). A summary of the barriers and opportunities are presented in Table 16.

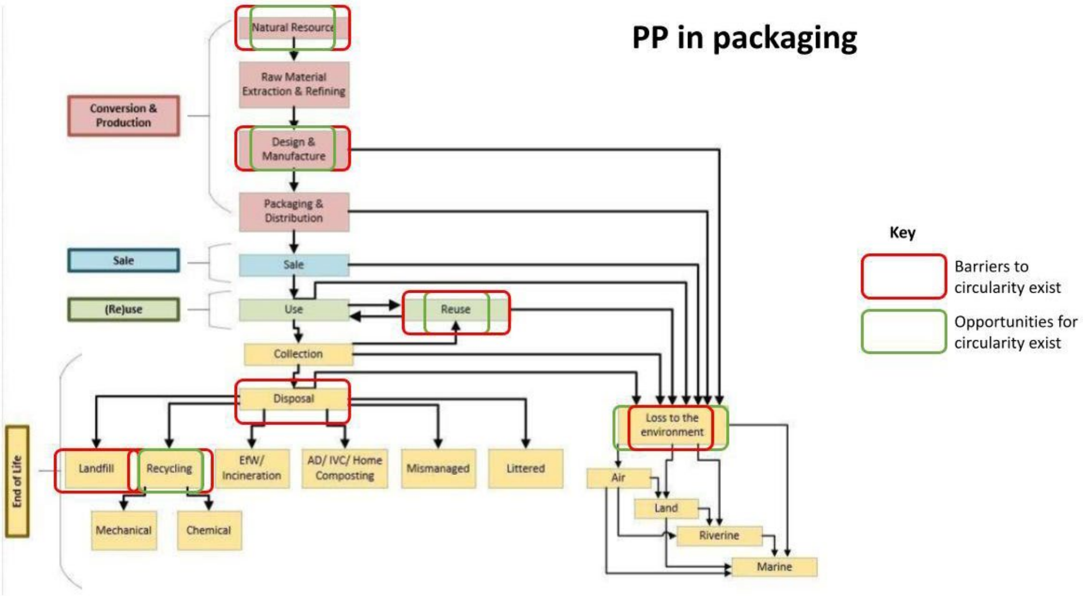

Figure 16. Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of PP in packaging exist.

Table 16. Overview of identified barriers and opportunities for the circularity of PP in packaging by life cycle stage.

Life cycle stage	Barriers	Opportunities
Natural resource	● The primary building block of PP, propylene, is traditionally generated as a byproduct from the steam cracking process of naphtha and gas oils to produce ethylene, or from the fluid catalytic cracking process for oil refinery, both of which emit significant amounts of greenhouse gases (Wang et al., 2023). PP production consumes about 64% of the propylene supply (Farshi, 2008). ● As large-scale manufacturing of bio-based PP only began in 2019, the market is therefore still in its infancy, accounting for 1.9% of the bio-based plastic market. Other barriers include the development of technologies for the production of bio-based PP that are cost-competitive with PP produced from fossil fuels, ensuring that their environmental impact is lower than that of conventional fuels, and avoiding competition with arable lands (Wang et al., 2023)	● Bio-based PP can be generated from corn, vegetable oils, and sugarcane and has the same balanced characteristics as regular PP from fossil fuel, and can be used in the same way (Interviewee).
Raw material extraction & Refining	-	-
Design & Manufacture	● Based on a lifecycle analysis which included consideration of emissions emitted and energy consumed, Mannheim and Simefalvi (2020) identify that 91% of environmental impact occurs during production of PP, 3% during use, and 6% at the end of life. ● The majority of synthetic plastics including PP contain additives (stabilizers, plasticizers, foaming agents, colourants, etc.), to improve their material properties, which are known to be endocrine disruptors and carcinogens, affecting human health (Adeniran and Shakantu, 2022; Gaston and Tulve, 2019; Hahladakis et al., 2018).	● PP manufacturing needs stricter regulations and better technology to ensure the use of methods that are sustainable, efficient and environment-friendly in the future and to ensure the safe recycling of plastics and petrochemicals (Alsabri et al., 2022). ● There is opportunity for the production of composites using virgin PP blended with recycled PP for material engineering applications (Jamnongkan et al., 2022).
Packaging & Distribution	-	-
Sale	-	-
Reuse	● The properties, performance, and aesthetics of PP are negatively affected by repeated mechanical recycling (Schyns, & Shaver, 2021), and as a result often becomes landfill	● There are opportunities for PP closed loop recycling, as opposed to 'open loop' where the recycled material is used in another sector. Berry Superfos has won a Plastics

	(Nordahl et al., 2023). ● The quality of recycled PP can be compromised by high migration rates and the absorption of contaminants from other waste. As a result, the recycling infrastructure for PP is often underdeveloped and it ends up in landfills (Nordahl et al., 2023). ● PP can be more difficult to recycle than other plastics such as PET, which has a well-established recycling infrastructure and has been associated with lower migration rates and absorption of contaminants from waste (Mannheim, & Simenfalvi, 2020). Consequently, the majority of PP ends up in landfills or as environmental litter (Nordahl et al., 2023). ● Additives are frequently used in plastics to improve their functionality. However, these compounds can be a major bottleneck for chemical recycling (Eriksen et al., 2019; Ügdüler et al., 2020).	Industry Award for its closed loop recycled paint containers initiative (Berry Global, 2023). ● NextLooPP, along with other international organisations, is trialling food-grade recycled PP and inert resins in injection moulding, extrusion, and thermoformed package manufacturing. This aims to close the loop on food-grade, post-consumer PP (NEXTLOOP, 2024) ● In Europe, packaging recycling is often more economically feasible than other sectors of the plastic market due to high turnover rates of the collected post-consumer waste (Schyns, & Shaver, 2021). ● Reusable PP packing mixed with sawdust can be used as a bulking agent to improve sewage sludge composting (Li et al., 2021).
Collection	-	-.
Disposal	● Repeated mechanical recycling of PP degrades its properties, performance, and aesthetics (Schyns, & Shaver, 2021). Recycling infrastructure for PP is underdeveloped and it often ends up in landfills. (Nordahl et al., 2023) ● Plastic from household waste is often heterogeneous and contaminated, leading to recycled plastic with reduced quality, limiting the potential for closed-loop recycling (Eriksen et al., 2019).	
Loss to the environment	● Microplastics can be leached from PP products intended for daily use. For example, microplastics can be released from PP baby feeding bottles through natural degradation during infant formula preparation (Li et al., 2020) ● Additionally, Hussain et al. (2023) identified that the highest release of microplastics and nanoplastics from PP products into food was caused by microwave heating compared to other usage scenarios (refrigeration, room-temperature storage, etc.).	● Results from a recent study indicate that 'the natural environment may possess, under appropriate conditions (here the presence of iron in the natural matrix in which the MPs are dispersed, combined with intensive sun exposure), effective self-cleaning ability, and thus a better than expected resilience to the ever increasing pollution in the so-called plastisphere' (Castelvetro et al., 2023, p. 26). Therefore, the development and scale up of technology that can recreate such natural conditions, which have the potential to reduce the concentration of microplastics can help to reduce the impact of PP MPs released in the environment . ● Results from a recent study indicate that biodegradation of PP by *Lysinibacillus* species JJY0216 could be used as a starting point for developing technologies for soil remediation (Jeon et al., 2021).

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

There is no evidence or research studies that highlight the role of marketing as an influencing factor in the use, sales, or waste management of PP based packaging products.

Research indicates that for reusable packaging to have a more positive environmental impact, consumers' perceptions of packaging with visible wear (e.g., scratches from cutlery, stains, etc.) need to change. Collis et al., (2023) explain that reusable containers typically require more raw material to ensure that they are more durable than their single-use counterparts, and so need to be used multiple times to counteract the increased resources needed to produce them. Therefore, increasing the acceptance of packaging with visible wear by consumers would ensure that each piece of packaging is able to complete enough use cycles to surpass its environmental break-even point (Collis et al., 2023). Different studies that compared single-use plastic lined paper cups to a reusable plastic alternative, normally PP (Almeida et al., 2018; Foteinis, 2020; VTT Technical Research Centre of Finland Ltd., 2018) have shown that the breakeven point for a reusable plastic cup could range from 10-41 uses. Therefore, a reusable plastic cup can have a lower equivalent carbon impact than using the same number of single-use cups and disposing of them. Other findings from Foteinis, (2020) indicate that a switch from disposable cups to reusable cups could save 52,000t CO_2e annually in UK terms.

Post-consumer PP waste can be recycled in the UK, but is a council dependent process. Recycling is currently devolved to local authorities in the UK (RECOUP, 2021). Most councils collect plastics including PP usually through a kerbside collection system, and the 'post-consumer' packaging waste is then sent to waste management and recycling companies. However, councils can choose whether to collect PP for recycling and often base their decision on the cost at which they can sell it and whether the nearby recycling facilities have the capacity to process it (British Plastics Federation, 2024; Greenwood, 2021). Statistics show that plastic bottles are the only product that is collected by all UK local authorities, and only 13% of local authorities accept to collect plastic film as part of their kerbside collection service (RECOUP, 2021). Additionally, user guidelines for recycling receptacles vary depending on the local authority which creates confusion among consumers about where to put PP due to the wide range of different receptacles with different colours and labels provided by the local authorities (Jesson, & Stone, 2009; Oluwadipe et al. 2022).

Plastic from household waste is a heterogeneous and contaminated resource, which leads to recycled plastic of lower quality that limits the potential for closed-loop recycling which is an important step towards circular economy. Several product types in PP waste hinder closed-loop recycling into new packaging, because the homogeneity of the PP waste stream is crucial to ensure quality for closed-loop recycling into new packaging products (Eriksen et al., 2019). Therefore, local authorities could provide guidelines that explain how to dispose of PP in a way that minimises contamination from other household waste or provide separate bins for recyclable PP or other plastics.

Consumer tastes and preferences drive the demand for the production and use of PP which can be leveraged to reduce the use of PP in the packaging sector. Research indicates that UK consumers are increasingly demanding more refillable and reusable solutions. An example of consumer demand driving innovation in reusable PP products is the Cif ecorefill initiative, launched by Unilever as a response to the concerns of UK consumers regarding the lack of access and awareness about existing refillable products in store, which can reduce the carbon footprint of businesses (Poole, 2019). The ecorefill is a 10x concentrated formula, retailing less than the price of conventional Cif spray bottles. It allows customers to reuse their Cif spray bottle indefinitely by diluting a small amount of the concentrated formula with 700 mL of water. Studies have shown that using Cif ecorefill has resulted in 87% fewer trucks on the road (Circular Economy Portugal, 2024). The Cif ecorefill uses 75% less plastic than standard cleaning products like the regular Power & Shine kitchen spray bottle, and is made of recyclable PP and HDPE (Poole, 2019), which could be a model for future PP products.

Based on the above, the following key interventions for consumer attitudes and behaviour have been identified:

- **Organise campaigns to change the perception of used PP in packaging.** The majority of consumers are used to purchasing packaging from virgin PP, which is usually pristine (in appearance) unlike reusable packaging.
- **Provide clear guidelines for consumers on how to handle and dispose of PP.** Ecoliteracy and environmental awareness can play a significant role in influencing positive recycling activities of PP based products and how to minimise waste stream contamination.
- **Align policy and decision-making tools with citizen or public behaviour.** Local authorities could conduct surveys to gather perceptions and any related matters that create confusion among the public.
- **Provide technical assistance for UK local authorities to have the capacity to collect all plastic items.** UK local authorities can choose the waste that they collect resulting in gaps in what is currently recycled.

b. Economics

In 2021, PP accounted for approximately 16.6% of the European plastics production (Plastics Europe, 2022). The price, demand for, and use of PP can be affected by many factors such as the availability of propylene, naphtha, and crude oil; the price associated with the extraction of these resources (Farshi, 2008; Wang et al., 2023), and the demand for PP products in the packaging sector.

There is a market for reusable PP products in the UK. There are multiple examples of reusable PP innovations from industry. CauliBox, one of the UK's first tech-enabled reusable food & drink packaging solutions, provides BPA free PP boxes within a closed-looped system, where containers are used, collected, washed, and repeatedly re-used up to 400 times (Cauli, 2023). The CauliBoxes are free to borrow as long as customers return them within a week. Data indicates that a PP container (like a CauliBox) has to be reused at least four times to equal the impacts of aluminium containers, and nine times to equal the impacts of EPS (Gallego-Schmid et al., 2019). Other companies in the UK such as Tri-pak offer solutions to businesses and customers to help them reduce their carbon footprint and offer them an eco-friendly packaging alternative. Tri-pak offers reusable and returnable PP boxes for packaging that can be reused up to 20 times (Tri-pack Packaging Systems Ltd, 2019).
Research indicates that there is a growing demand for reusables PP products, and local businesses could use this opportunity to make profit while reducing the environmental impact of PP products.

Closed-loop recycling of PP is expensive and can be complex in terms of recycling processes. The price of advanced mechanical recycling is comparable to the price of conventional mechanical recycling unlike chemical recycling, which is a lot more expensive, and has higher energy requirements. A key factor that affects the cost of PP recycling processes is the use of chemicals such as additives. Additives that are frequently used in plastics to improve their functionality can be a major bottleneck in their 'second life' for chemical recycling (Eriksen et al., 2019; Ügdüler et al., 2020). However, chemical recycling usually provides higher quality of recycled materials compared to conventional mechanical recycling. Within the fraction that is currently recycled, best practices focus mainly on open-loop recycling or 'downcycling', meaning that the application after recycling is different compared to the original application, which is usually of lower quality. As such, open-loop recycling does not completely eliminate the need for new raw materials or virgin feedstock (Huysman et al., 2015). That is why closed-loop recycling is considered to be a more circular option since materials can be kept at their highest value (Ügdüler et al., 2020). Common challenges associated with closed-loop recycling processes of plastics include several types of contaminations such as cross contamination of other polymers due to imperfect separation or odour caused by organic contamination, but also the presence of additives can be an issue (Ügdüler et al., 2020). The recycling of polyolefins such as PP requires advanced standard operating procedures due to its highly absorbent properties, which have been associated with increasing migration rates and increasing sorption of contaminants from its environment. Keeping PP materials at their highest value therefore usually requires more resources and efforts from companies.

The major challenges facing bio-based PP producers are developing process technologies that are cost-competitive with PP produced from fossil fuels, ensuring that environmental impact is lower than that of conventional fuels and avoiding competition with arable lands. Propylene may be generated in a variety of ways from bio-based sources (Bio-based PP can be generally generated from corn, vegetable oils, and sugarcane) (Wang et al., 2023).

In food contact materials, virgin polymers are usually cheaper and easier to use. When it comes to packaging, restrictions on the recycled material such as the food contact material regulations make the reuse of PP difficult in packaging. To get recycled PP to higher grades would be costly in terms of additives and additional processes. Therefore, legislation would need to focus on making it economically viable to repurpose recycled material into the same initial product. Appropriate legislation and incentives are therefore required for recycled PP to achieve parity with virgin PP, especially in food contact instances.

Based on the above the following key interventions for economics should be considered:

- **Provide technical support and economic incentives for the development of bio-based PP**. The production of propylene from bio-based sources can reduce the use of fossil fuels and the environmental impact linked to the high energy requirements associated with the production and conversion of ethylene to PP.
- **Implement economic incentives or legislation to help recycled PP compete with virgin PP as a product.** Recycled materials are often under more stringent regulation meaning that it is often easier for businesses to turn to virgin PP.
- **Implement stricter regulations for PP manufacturing that limit the use of synthetic additives and promote the use of alternative additives.** The use of natural additives could be considered as an eco-friendly alternative to synthetic additives.

c. Technology and infrastructure

At the end-of-life stage, most PP products can be treated via disposal, incineration, or recycling processes, however currently only around 1 to 3% of it is recycled in the UK which is mainly attributed to underdeveloped recycling infrastructure (Nordahl et al., 2023). The waste management of PP faces several other economic and ecological barriers which limit the large-scale application of improved recycling processes. Alternatively, several PP products also have the potential to be reused within the packaging industry, as discussed below.

The reuse of PP products in packaging requires advancement in technology to facilitate large-scale applications. Many studies have demonstrated the feasibility of implementing reuse systems with some PP products and their environmental benefits compared to their single-use counterparts (Almeida et al., 2018; Bradley, & Corsini, 2023; Cauli, 2023; Collis et al., 2023; Foteinis, 2020; Gallego-Schmid et al., 2019; Tri-pack Packaging Systems Ltd, 2019; VTT Technical Research Centre of Finland Ltd., 2018). However, the use of technology could further increase the capacity of reuse systems to divert PP waste from landfills, incineration, or recycling. For instance, López-Gálvez et al., (2021) explain that the handling of fresh fruits and vegetables in reusable PP crates usually has a lower environmental impact than single-use containers (cardboard and wooden boxes) and as such has the potential to increase the sustainability of packaging in the fresh produce supply chain. However, the reuse of PP crates has been linked to a higher risk of cross-contamination with *Salmonella* compared with cardboard and medium-density fiberboard crates (López-Gálvez et al., 2021). Consequently, the wider availability of technology to sanitise reusable PP crates or other containers that ensures food safety would enable the scale up of reuse systems in the packaging industry.

The use of tracking technology and infrastructure to facilitate the return of reusable PP containers within a closed loop system can encourage the implementation of more reuse systems in the UK.

Ellsworth-Krebs et al., (2022) explain that Digital Passports can be used to gather information on materials of products and to facilitate their recovery and reuse. Digital passports can be used to determine the barriers associated with investing in reusable packaging, such as by identifying packaging lifespans, assisting in meeting health and safety standards through batch coding and evidencing cleaning checks, addressing reputational concerns by providing clear documentation regarding the environmental impact of reusable items, and making reusable packaging competitive through waste taxation which measures reuse (Ellsworth-Krebs et al., 2022). Investing and regulating such technology could therefore alleviate many barriers associated with industrial investment in reuse approaches.

Increasing the recycling of PP products is not necessarily economically viable for businesses due to other end of life pathways being more convenient and cheaper. This is primarily due to the lack of infrastructure and suitable technology for recycling and other disposal methods. The quality of the recyclate is largely affected by the physicochemical properties of the PP, as well as the processing conditions and the purity of the input PP waste (Mannheim, & Simenfalvi, 2020). The recycling of polyolefins such as PP requires advanced standard operating procedures due to its highly absorbent properties, which have been associated with increasing migration rates and increasing sorption of contaminants from its environment, as noted above. In terms of infrastructure, collection of PP is not consistent across the UK and there is no national policy that addresses this issue. Many councils do not have access to the adequate sorting technology to get purer streams of PP, which would increase the recycling capacity for higher grade materials. Consequently, it can be difficult for businesses to have access to a steady supply of recycled PP of high grade or even produce a supply consistent enough to create recycled products.

Mechanical recycling is usually easy for PP packaging, however studies have shown that repeated mechanical recycling degrades the properties, performance, and aesthetics of PP. One of the reasons behind it is cleanliness, which is a major issue. Despite cleaning processes, PP has excellent absorbent properties and therefore the material recycled contains some of the absorbed chemicals, whether these chemicals are from residual compounds from various sources of contamination or cleaning products used during the recycling process. The resulting colour of the recyclate can also limit its application and use in industry due to aesthetics, which can be a decisive sales factor. Some companies use colour additives, however this can also add complexity to the recycling process and result in additional costs. Additionally, there are over 1000 different grades of PP commercially available on the market (each with different copolymers and homopolymers) and when these different types of PP are recycled in an open loop, the resulting recyclate often ends up being of lower quality than the initial product unless higher expenditures are allocated towards the purification process to get a similar grade to the initial product (Bora et al., 2020; Nordahl et al., 2023).

Properties of recycled PP may differ from those of virgin PP, which can limit the use of recycled material in applications where performance and stability are critical. To achieve performance similar to virgin material, additives such as stabilisers, plasticizers, foaming agents, and colourants are often used, similar to additives used in PHAs and other general plastics. These additives can improve the properties of the recycled material and compensate for any loss of functionality caused by repeated recycling processes, but these compounds are also known endocrine disruptors and carcinogens, affecting humans via contact with the skin or if swallowed or inhaled (Adeniran and Shakantu, 2022; Gaston and Tulve, 2019; Hahladakis et al., 2018). For example, when used for food packaging, these can drift into food items and can thus enter the human body upon consumption (Gaston and Tulve, 2019). These additives can also have negative impacts on the environment however (Eriksen et al., 2019).

Based on the above the following key interventions for technology and infrastructure should be considered:

- **Invest in technology and infrastructure that can facilitate the scale up of reuse systems.** Digital Passports have the potential to facilitate the reuse of PP products at a larger scale by addressing diverse barriers to operationalisation from an industrial perspective.
- **Support research for technology that can ensure the safe reuse of reusable containers, especially in food contact products.** Increased understanding of the barriers to reuse in food safety for recycled and reusable products will encourage businesses to choose reuse over other potential end of life for PP products.
- **Invest in specific reuse infrastructure, such as collection systems.** Since PP can be washed and easily reused in most cases, investment could be provided for the construction of infrastructure for the purpose of reuse in addition to appropriate transportation and collection systems for consumers.
- **Invest in sustainable technology that minimises the negative impacts of repeated mechanical recycling of PP.** Current reliance on additives and chemicals used to overcome the impacts of repeated recycling represents risks to human health and the environment.

d. Policy and regulation

The current plastic policy landscape has been referred to as disjointed, fragmented, and complex since the UK comprises a number of devolved administrations (England, Wales, Scotland, and Northern Ireland). Currently, there are no policies, which are specific to the use of PP in packaging, but the main plastic policies include:

- The UK Plastics Pact – A Road Map to 2025 (2018): The main focus of The United Kingdom Plastics Pact – A Road Map to 2025 is to eliminate problematic plastics and increase recycling and recycled content. The policy framework is voluntary and allows individual businesses to sign up. Since its implementation, the recycling rate has increased from 44% to 52% and there has been an increased construction of recycling plants (Global Plastics Policy Centre, 2022).
- The UK Plastic Packaging Tax (2022): It aims to encourage the use of recycled plastic and applies to plastic packaging produced in, or imported into, the UK and that does not contain at least 30% recycled plastic. The tax applies to businesses that manufacture or import plastic packaging components or import packaged goods into the UK, however smaller businesses who import or manufacture less than 10 tonnes of plastic packaging per year are exempt from paying the tax.
- The food contact materials (FCM) regulations set by the Food Standards Agency (FSA): These regulations provide requirements for materials and articles that are likely to come into contact with foods or have chemical migration of FCM to food.

The following policy and regulatory considerations for the circularity of PP in packaging have been identified:

The UK Plastic Packaging Tax presents several issues that may compromise the potential circularity of PP. Chemically recycled PP usually does not count towards recycled content, because the use of chemical recycling methods makes it difficult to determine the actual amount of recycled material in a specific output from the process (HM Revenue & Customs, 2023). The reason is that chemical recycling processes break down plastic to a molecular level to produce a recycled feedstock that can be mixed with virgin polymer to make chemical compounds, which are used to make plastics. The issue is that mixing virgin and recycled feedstocks makes it impossible to differentiate between the two compounds or to calculate the actual amount of chemically recycled material. Therefore, making provisions for mass balanced accounting for chemically recycled materials could help solve this issue, because it would allow businesses to track recycled material mixed with virgin material during the whole recycling process and allocate to them particular outputs (HM Revenue & Customs, 2023).

The plastic packaging tax (PPT) has not had the desired effect across the packaging recycling industry. See Section 3.5 on HDPE in packaging for more details. The standards set in the tax do not always encourage the industry to put recycled content in products as it can be cheaper for them to pay the tax compared to increasing the recycled content of their products. This represents a significant loophole for plastic policy to contend with in general when using taxes. Furthermore, there are no measures to evaluate the content of products manufactured outside the UK claiming a 30% recycled content, and therefore it is the responsibility of the importer and companies that buy products from outside the UK to verify these claims.

Food contact regulations stipulate that it is illegal to mechanically recycle PP into food contact products, but that chemical recycling is an acceptable option. Research shows that the most common method of recycling PP is mechanical recycling (Mannheim, & Simenfalvi, 2020), and therefore a portion of food grade PP waste cannot be recycled back into food grade PP packaging limiting the circularity of this material. To tackle this challenge, a UK-based company Berry Global Circular Polymers, one of the largest plastics recyclers in Europe has developed CleanStream, the world's first closed-loop system to mechanically process domestically recovered household waste PP back into food-grade packaging (Berry Global Circular Polymers, 2023). Currently, the company is seeking to obtain EU approvals for the use of CleanStream, and they have received a Letter of No Objection from the U.S. Food & Drug Administration (Berry Global Circular Polymers, 2023). Results from their LCA analysis indicate that this technology has the potential to achieve the following: 35% lower CO_2 emissions than virgin PP production, 50% less water consumption required compared to virgin PP, 60% less in acidification versus virgin PP, 90% less in fossil fuel resource usage than virgin PP production, and packaging with a 20% lower CO_2 impact than virgin PP (Berry Global Circular Polymers, 2023). Consequently, investment in the scale up of such technology could help increase the circularity of food grade PP.

Based on the above the following key interventions for policy and regulation should be considered:

- **Implement mechanisms of inspection and verification measures of products manufactured outside the UK claiming a 30% recycled content.** There could be evaluations to assess the composition of exported products when feasible.
- **Introduce a minimum recycled content mandate to replace the PPT.** A minimum recycled content of at least 40% would drive the decline in virgin content significantly, and act as a push for innovation and safe recycling.
  OR Increase the cost of the PTT. The tax needs to be high enough to incentivise an actual shift to more recycled content, and could be combined with bans on certain items of virgin materials.
- **Implement legislation that allows the use of mechanical recycling for the production of food-grade packaging while ensuring safety standards and sustainability.** Companies like Berry Global have shown that technology can be used to mechanically recycle household waste into food grade PP.

e. Waste hierarchy

Currently, the system for PP in packaging is predominantly placed at the recovery stage of the waste hierarchy (Figure 10). As previously explained, the recycling process of PP in packaging is costly, and complex mainly due to the lack of appropriate infrastructure. Research suggests that the majority of PP ends up in landfills or waste incinerators. Data from WRAP indicates that PP film is one of the most common formats used in the consumer sector (grocery and non-grocery retail) of plastic packaging (WRAP, 2023) while data from the UK Household Plastics Collection Survey 2021 shows that the kerbside recycling collection rates for plastic films by local authorities were among the lowest in 2020 (RECOUP, 2022). Results from the survey indicate that out of 379 local authorities, 39 (13%) offered a kerbside recycling collection for plastic film in 2020, in the UK.

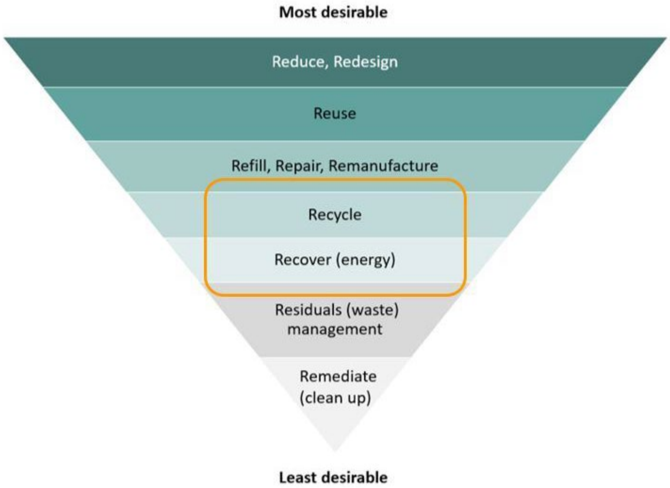

Figure 17. Current position of PP in packaging on the waste hierarchy.

However, there is potential for the closed loop recycling of PP products and their reuse as well. For example, findings from interviews with experts in the field indicate that PP is easy to wash and clean and when designed properly, it can easily be reused in a closed loop system as opposed to open loop recycling where the recycled product is of lower quality. For example, Berry Superfos has won a Plastics Industry Award for its closed loop recycled paint containers initiative (Berry Global, 2023). The solution involved the establishment of a partnership between Berry Superfos, Paint360, and Berry Circular Polymers, which allows them to reuse both the paint and the paint cans. They can collect waste paint, re-engineer it into new paint, and recycle the used paint plastic containers into new paint cans for the recovered paint. The paint cans can contain up to 30-50% recycled post-consumer recycled material (Berry Global, 2023). Reuse schemes for bottles made from HDPE (milk bottles) and PET (clear bottles) have been used with success, and are described in sections 3.5.ii.a. of HDPE in packaging and 3.6.ii. of PET in packaging. Significant opportunity exists to learn from these experiences to create a wide scale system of PP packaging reuse in the UK. Currently, in the UK, kerbside recycling of plastic bottles was offered by all local authorities in 2020 although the proportion of PP packaging in bottle form is much lower in comparison to other plastics such as PET and HDPE (WRAP, 2023). Therefore, momentum and capacity for such a programme has existed previously, and requires innovation within existing infrastructure to rebuild.

To move PP in packaging up the waste hierarchy there is significant potential to reduce and redesign packaging, primarily by determining if packaging is needed in the first place. Adding loose yields can create higher profits for the retailer and lower relative waste at the consumer level (Kirci et al., 2023). For fresh foods, there are several trade-offs when removing plastic packaging from fresh products such as fruits and vegetables or other types of products, which is the resultant reduction in shelf life and therefore potential increase in food waste. For instance, the shelf life of new potatoes can be extended by 3 days if packaged in a modified atmosphere plastic bag, selling grapes in trays or bags can reduce in-store waste by 20% (White, & Lockyer, 2020). However, for dry goods, and non-perishable items, this would be a quick and easy win.

Research indicates that reusable packaging products made of PP can reduce waste and the broader impacts of single-use packaging. In their research, Greenwood et al., (2021) show that both refill and return systems that use plastic containers including two made of PP for take-away food have a lower climate impact than single use plastic containers after just two to four uses. The results from their life cycle assessment included eight different takeaway containers used within the UK such as single use aluminium trays and PP microwave trays, bio-based bagasse containers and returnable containers such as PP return tupperware and mess tin made of steel (Greenwood et al., 2021).

One of the difficulties about reusing PP are the reverse logistics and the cost of the initial product. Reverse logistics of a reuse system for PP would require infrastructure for collection points and drop-off points for both consumers and businesses, in addition to appropriate transportation and collection systems that can be easily scaled up and economically viable for businesses. In regards to costs, the value of the reusable item would need to be kept to a minimum so that losses do not impact the business significantly in the event of loss. Investment for the construction of infrastructure for the purpose of reuse could facilitate their implementation at a larger scale.

Based on the above the following key interventions for the overall circularity should be considered:

- **Implement legislation promoting the sale of unpackaged items and provide incentives for companies, as well as retailers which opt for unpackaged goods.** Waitrose, Ocado, Morrisons, Marks & Spencer and the supply-chain company CHEP have joined the Refill Coalition group, run by Unpackaged, and plan to roll out both unpackaged options in-store. Therefore, providing incentives could encourage other supermarkets to follow their examples.
- **Mandate the adoption of reuse models for packaging in closed systems.** Closed systems include food and drink establishments, hotels, sport and event venues, and public buildings. Evidence shows that adopting reuse systems in closed settings is a possible quick win, as much of the reuse infrastructure already exists.
- **Learn from and partner with existing networks of charitable organisations dedicated to reuse like the Reuse Network.** The creation of an online platform like the reuse network could help businesses, charities, and individuals to donate items or look for specific items that would have otherwise been sent to a landfill. This would formalise and build upon existing grassroots momentum for reuse.
- **Implement a deposit return system for specific PP products, which are not bottles.** The UK DRS applies to drinks containers, but research indicates that the proportion of PP packaging in bottle form is much lower in comparison to other plastics such as PET and HDPE. Consequently, a deposit return scheme, which applies to other products could facilitate the reuse of PP packaging with minimal reprocessing and encourage the public to participate by washing and returning their PP products.

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for PP in packaging (Table 17).

Overall potential for circularity:

PP in packaging is not yet circular, but has many points of intervention through which to contribute to a circular plastics economy. Although PP in packaging should ideally be reused (as will be discussed below), recycling is what is often advocated for in literature and expert opinion. Recycling of PP has a place in a circular plastics economy, but designing for reuse should be prioritised and incentivized at the design and retail stage. Barriers to recycling currently include a lack of sufficient and available recycling infrastructure, which is necessary to provide a steady pipeline of recyclate to create products with recycled content. Investment in infrastructure nationally is needed, along with regulations and campaigns to ensure recyclate collected are of good quality and not contaminated. Investing in research for bio-based PP and achieving price parity with PP should also be promoted.

In a high ambition scenario for circularity, as noted above, PP packaging should be designed for reuse. There is significant precedent with similar items being made reusable within different material types. This can be supported by innovation in technology such as Digital Passports for PP products, and changing policy to emphasise the need for PP products to be designed for reuse if not designed for recycling.

Table 17. Interventions to transition to a circular system for PP in packaging, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Organise campaigns to change the perception of used PP in packaging.	National	Government, Civil society	Medium
Provide clear guidelines for consumers on how to handle and dispose of PP	National, Sub-national	Government, Civil society	Medium
Provide technical assistance for UK local authorities to have the capacity to collect all plastic items	National, Sub-national	Government	Medium
Provide technical support and economic incentives for the development of bio-based PP	National	Government, Academia, Industry	Medium
Implement economic incentives or legislation to help recycled PP compete with virgin PP as a product	National	Government, Industry	High
Implement stricter regulations for PP manufacturing that limit the use of synthetic additives and promote the use of alternative additives.	National, International	Government, Industry	Medium
Invest in technology and infrastructure that can facilitate the scale up of reuse systems.	National	Government, Academia, Industry	High
Support research for technology that can ensure the safe reuse of reusable containers, especially in food contact products.	National, Regional, International	Government, Academia, Industry	High
Invest in specific reuse infrastructure, such as collection systems.	National	Government	High
Invest in sustainable technology that minimises the negative impacts of repeated mechanical recycling of PP.	National, International	Government, Industry	High
Implement mechanisms of inspection and verification measures of products manufactured outside the UK claiming a 30% recycled content.	National, International	Government	High
Introduce a minimum recycled content mandate to replace the PPT OR Increase the cost of the PTT	National	Government, Industry	High
Implement legislation promoting the sale of unpackaged items and provide incentives for companies, as well as retailers which opt for unpackaged goods.	National	Government, Industry	High
Mandate the adoption of reuse models for packaging in closed systems.	National	Government, Industry	High
Learn from and partner with existing networks of charitable organisations dedicated to reuse like the Reuse Network.	International	Government, Industry	Medium
Implement a deposit return system for	National	Government	High

specific PP products, which are not bottles.			

iv. Gaps in evidence and assumptions

A number of gaps in evidence exist in determining the circularity for PP in packaging, including:

- The length of supplier contracts across the whole life cycle and how these impact circularity.
- How this material or product is packed for onward transport and associated impacts on the products' design or choice of material, the impacts on the volume that can be purchased, and whether the packaging for transport leads to excess stock or waste.
- The design and manufacture of this material using alternative materials, changing product design to allow for or to promote refurbishment and reuse, and the design of the product set for use, with little to no flexibility.
- The way this material is marketed or sold affects how much is used and in turn wasted

3.9 PP in textiles

i. Life cycle stages and circularity

As previously stated, PP is a thermoplastic, which belongs to the olefin polymers. The use of PP fibres can be dated back to the 1970s, and PP fibre is among the largest volume artificial fibre after polyesters, nylons, and acrylics (Menyhárd et al., 2020). Unlike the other fibres, which are commonly used as apparel, PP is predominantly used for industrial applications such as carpets, geotextiles, sanitary commodities, and surgical sutures (Menyhárd et al., 2020).

PP can be used in nonwoven or woven fabric. Nonwoven fabric is a fabric-like material that is not made by weaving, knitting, or other similar methods but by chemical, mechanical, heat or solvent treatments (Polaris Market Research, 2024). PP is used in nonwoven materials, such as sanitary products and diapers, and is among the most common category of materials used to achieve high filtration efficiency in certified masks (Allison et al., 2021). Other non-woven uses include filters for air, gas, and liquids in which the fibres can be formed into sheets or webs. Woven PP is more commonly used in the manufacture of packaging, the most common products in the industrial sector include rolls and woven fabric bags (Alyousef et al., 2023).

The global PP nonwoven fabrics market size and share was valued at USD 28.77 billion in 2023 and is anticipated to generate a revenue of USD 50.84 billion by 2032 (Polaris Market Research, 2024). The rising demand for PP fabrics market can be mainly attributed to two factors: its moisture conveyance potential and the escalating demand in the hygiene industry, more specifically facemasks (PP constitutes the primary component in the fabrication of most disposable masks), surgical gowns, and drapes in the healthcare industry (Morris, & Murray, 2020; Polaris Market Research, 2024).

Across the life cycle of PP in textiles, the primary barriers exist in the use of natural resources, design and manufacture, reuse, disposal, and loss to the environment stages, but the main opportunities for circularity are also found in the same areas: the use of natural resources, recycling, reuse and loss to the environment stages (Figure 18). A summary of the barriers and opportunities are presented in Table 18.

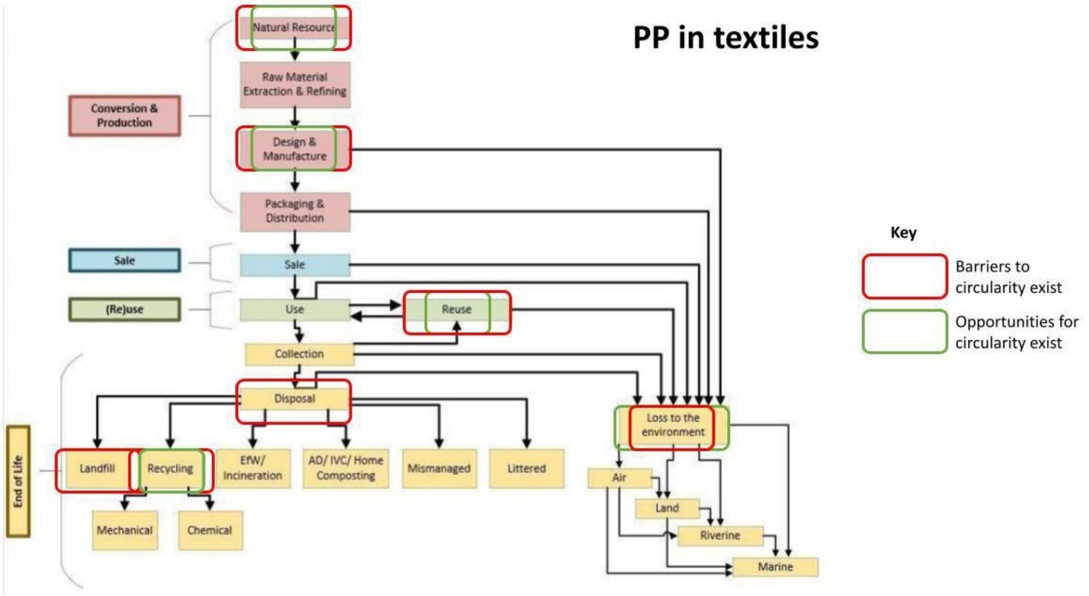

Figure 18. Life cycle diagram indicating at which stages the most prevalent barriers and opportunities for the circularity of PP in textiles exist.

Table 18. Overview of identified barriers and opportunities for the circularity of PP in textiles by life cycle stage.

Life cycle stage	Barriers	Opportunities
Natural resource	● The primary building block of PP is traditionally generated as a byproduct from the steam cracking process of naphtha and gas oils to produce ethylene, or from the fluid catalytic cracking process for oil refinery, both of which emit significant amounts of greenhouse gases (Wang et al., 2023). ● Petroleum is the key raw material used to produce synthetic polymers, so the cost of polypropylene is affected by fluctuations in crude oil prices. ● As large-scale manufacturing of bio-based PP began in 2019, the market is therefore still in its infancy, accounting for 1.9% of the bio-based plastic market. Other barriers include the development of technologies for the production of bio-based PP that are cost-competitive with PP produced from fossil fuels, ensuring that their environmental impact is lower than that of conventional fuels and avoiding competition with arable lands. (Wang et al., 2023)	● Bio-based PP can be generated from corn, vegetable oils, and sugarcane and has the same balanced characteristics as regular PP from fossil fuel, and used in the same way (as detailed in Sections 3.1, 3.2 and similar to other forms of bio-based plastic such as LDPE).
Raw material extraction & Refining	-	-
Design & Manufacture	● Based on a lifecycle analysis which included consideration of emissions emitted and energy consumed, Mannheim and Simefalvi (2020) identify that 91% of environmental impact occurs during production of PP, 3% during use, and 6% at the end of life. ● The majority of synthetic plastics including PP contain additives (stabilizers, plasticizers, foaming agents, colourants, etc.), to improve their material properties, which are known to be endocrine disruptors and carcinogens, affecting human health (Adeniran and Shakantu, 2022; Gaston and Tulve, 2019; Hahladakis et al., 2018). ● There are a variety of contaminants that can occur in recycled plastics and textiles such as hazardous chemicals and dyes (Rahman et al., 2022), which can limit their use for the same or different purposes.	-
Packaging & Distribution	-	-

Sale	-	-
Reuse	• Assessing the quality of textiles to evaluate the reusability and recyclability of the waste can be an expensive and tedious process. • There are a variety of contaminants that can occur in recycled plastics and textiles such as hazardous chemicals and dyes (Rahman et al., 2022), which can limit their use for the same or different purposes.	• Fashion rental can minimise waste production associated with the textiles industry and enable consumers to adopt more sustainable practices (Amasawa et al., 2023; Niinimäki, 2021). • The use of technology such as the antimicrobial photodynamic dye coating technique can enable a safer and extended use of personal protection equipment (PPE), and a reduction of plastic waste generated by PPE (Merkes et al., 2023). • The reuse of PP face masks can be achieved in certain settings (Hu et al., 2022). • The market for second-hand selling clothes apps has been steadily growing, reducing the need for the production of new textiles (Calaza et al., 2023)
Collection	-	-
Disposal	• There are a variety of contaminants that can occur in recycled textiles such as hazardous chemicals and dyes, which can limit their use for the same purpose, or a different purpose (Rahman et al., 2022; Undas et al., 2023).	• Waste bags, fishing nets, and waste carpets made of PP or nylon have been recovered and used in cementitious mortars for improving the corrosion resistance and avoiding crack formation or for augmenting the tensile strength and the toughness (Patti et al., 2020). • Textile waste fibre can be used in the construction and geotechnical industries to produce insulators, polymer concrete, asphalt concrete, composite material manufacturing, etc (Saleem et al., 2023; Jamnongkam et al., 2022).
Loss to the environment	• Microfibers released from synthetic textiles are one of the major contributors to microplastic pollution in the environment. The main pathways of textile microfiber deposition in the environment is during home laundering via sewage effluents and/or sludge. During conventional washing of textile garments, microfibers are released into wash water (Acharya et al., 2021).	• Washing fabrics at lower temperatures can reduce the release of microplastics into the environment (Interviewee). Correlations between high temperature and greater microplastic release have been observed, but no explanation has been identified (De Falco et al., 2018; Napper and Thompson, 2016). • Cheap and efficient oil-sorbent pouches can be designed using PP waste to tackle water pollution due to oil spills (Saleem et al., 2023; Alassod et al., 2022).

ii. Broader impacts on circularity

a. Consumer attitudes and behaviour

Consumers need to be informed of the existing recycling markets to enable them to make informed choices for textile waste disposal. Textile reuse or recycling is a two-way process in which the duty of consumers and lawmakers act as a driving force (Rahman et al., 2022). Rahman et al. (2022) highlight that a key factor in the disposal of hazardous textile waste fibre into municipal landfills is insufficient public awareness.

Fashion rental is a business model, which can minimise waste production associated with the textiles industry and enable consumers to adopt more sustainable practices (Amasawa et al., 2023; Niinimäki, 2021). Renting fashion is an increasingly common practice for occasion wear, where consumers hire, lease or borrow an item for a set fee and time such as wedding dresses, suits and graduation gowns.

There is a lack of public and consumer awareness regarding the impacts of PP textiles on the environment. The relationship between microplastics and PP textiles is poorly understood by consumers (Herweyers et al., 2020). A lack of awareness about effective clothing care practices means that textiles are ineffectively washed which decreases longevity and releases more microplastics than necessary into the environment. Equipping younger generations with the knowledge and the skills to make basic repairs to clothes would increase the longevity of textiles, and washing fabrics at lower temperatures would reduce the release of microplastics into the environment. Both of these actions would have significant impacts on circularity and would facilitate a reduction in the amount of textiles purchased and wasted (West et al., 2021). The creation of workshops by organisations such as WRAP by any retailer would also help the public to develop more upcycling practices and encourage the required mind-set shift to foster a circular economy for PP in textiles (West et al., 2021). Clothing care practices should be given freely by brand owners, retailers, and included in the National Curriculum, and incentives given for retailers to create repair-and-reuse workshops.

PP as a textile has significant environmental concerns surrounding extraction and manufacture. As discussed in the preceding section, the production and use of PP derived from hydrocarbon fuels has a negative impact on the environment due to the use of limited fossil fuels, and its extraction and use is linked to high energy requirements and carbon emissions (Mannheim and Simefalvi, 2020). An additional issue is that the chemicals released in the production of this type of plastic can affect factory workers who are exposed to it or the surrounding population (Tounsadi et al., 2020). To increase transparency and foster a sense of trust, the government could organise campaigns to inform the public on the current issues associated with the use of PP.

Innovation and behavioural change are important methods of preventing textile waste. An opportunity for change is through incentivizing activities such as wardrobe audits as a way to consolidate information about personal clothing practices among consumers. A wardrobe audit has the potential to help change behaviour linked to individual consumption among the general public and open their eyes on how much they actually use, buy compared to what they actually need (West et al., 2021). Apps such as 'Save Your Wardrobe' are designed to encourage circularity by providing a platform to document items within your wardrobe and connecting individuals with clothes care specialists to assist with repairing, customising and upcycling items (Save Your Wardrobe, 2024). By tracking and logging wardrobe items, the app also aims to reduce unnecessary purchases by providing statistics of what is worn and with what frequency, preventing duplicate buying of unnecessary items. While Save Your Wardrobe is currently operating as a paid business model, significant opportunity exists to incentivize the creation and use of such technology.

There is a market for second-hand selling apps in the UK which will decrease the importance of fast fashion as a clothing option. As will be detailed throughout the remainder of this section, fast fashion is a significant and alarming cause of environmental harm which requires intervention at every step of PP textile lifespan. The clothes resale market (or second hand clothing resale) in the UK represents a significant area of opportunity from a consumer behaviour perspective. According to GlobalData, the clothes resale market in the UK grew by 149% between 2016 and 2022 and it is forecast to rise by 67.5% from 2022 to 2026 (Cochrane, 2023). Popular apps in the UK include eBay, ASOS Vintage, Depop, Vinted, Vestiaire Collective, reGAIN, Edit Second Hand, Loopster, Oxfam, Thriftify, and Hardly Ever Worn It. Figures indicate that Vinted now has more than eight million registered members in the UK, up from 1.2 million in 2021(Jordan, & McFarlane, 2023). This data indicates a shift in consumer behaviour when it comes to slow fashion (Pookulangara, & Shephard, 2013). However, the tax requirements for individuals who sell over £1000 a year online (including through the resale of pre-used clothes) has been described as a "deterrent for being more sustainable" by essentially taxing individuals twice on clothing (Glover, 2024). Regardless of the specifics of the tax, this perception amongst the resale community is a major area of intervention to improve consumer based circularity.

Based on the barriers and opportunities for polypropylene, the following key interventions have been identified:

- **Establish guidance and standards to help customers to choose safe low impact materials that are recyclable and use recycled content.** Identifying low impact from a consumer perspective is complicated, but making information accessible will enable informed choices to be made prior to purchase.
- **Subsidise rental and subscription services for textiles to decrease demand for new PP textiles.** Customers can rent clothing attire for special occasions such as wedding dresses or graduation gowns to minimise production and waste in textiles.
- **Incentivize the creation of spaces where consumers can learn about clothing care and upcycling practices.** Organising campaigns to inform the public on the current issues associated with fast fashion such as plastic pollution can prevent waste and microplastic leaching at a consumer scale.
- **Remove tax on online resale of second hand clothes**. This will enable a larger market for sustainable clothing.

b. Economics

The cost of PP is affected by fluctuations in crude oil prices. The increased costs of acquiring raw materials raise the overall cost of polypropylene nonwoven fabrics, potentially decreasing demand for these fabrics in the production of masks, sanitary pads, sanitary napkins, and baby diapers (Polaris Market Research, 2024). The use of bio-based polypropylene could help solve some of these problems, however bio-based plastic is also subject to high production costs (Moshood et al., 2021).

'Fast fashion' relies on cheap materials (such as PP based textiles) to meet rapidly changing trends and promotes short-lived textile use, which has major impacts on environmental health. Over 92 million tonnes of waste are generated per year solely from the fashion industry (Niinimäki et al., 2020). Yearly consumption of garments has doubled over the past 20 years, and global consumption has increased by 400% (Shedlock and Feldstien, 2023). PP textiles have negative environmental impacts due to microplastic release, as detailed above (Dris e al., 2017). A recent report by the Changing Markets Foundation and Clean Up Kenya (2023) has identified the significant environmental impact of exports from low quality clothing, 40% of which have been shown to be from the UK. Studies led by WRAP have shown that extending the active life of 50% of the clothing purchased in the UK by nine months could lead to an 8% reduction in the total carbon footprint and 10% reduction in the total water footprint of clothing in the UK (WRAP, 2017). Economically, incentivising sustainable materials, targeting consumer behaviour regarding fashion choices (detailed in the following section) and decelerating manufacturing of 'fast fashion' items will significantly limit the impact of fast fashion. Additionally, regulating for garments to be designed for long-term use or to be fixable rather than poorly made for quick disposal will also influence consumer behaviour. However, these interventions cannot unfairly increase the cost of garments for consumers - costs should be borne by manufacturers and retailers.

Sanitary products made of PP are usually cheaper than their reusable counterparts, which either contain less PP or another plastic free material. Traditional sanitary products are often made from PP textiles (Gao and Kannan, 2020), and an estimated 200kg of menstrual products are used in an average lifetime (London Assembly, 2018). In the UK, it is estimated that 28,114 tonnes of waste is generated annually from sanitary products, with 26,903 coming from disposal products, the majority of which is plastic-based (including PP) (Blair et al., 2022). The environmental impacts of plastic-based sanitary product disposal is well identified. For example, a study in 2014 identified that 20% twenty percent of the subsurface debris trapped over a three-month period in the River Thames were identified as intact or partially intact sanitary products (Morritt et al., 2014). Alternatives to traditional plastic -based sanitary products exist, but are often sold at a premium price and not as widely accessible. There is significant opportunities for incentivising the development, sale, and use of alternatives, such as reusable products.

Based on the above the following key interventions for economics should be considered:

- **Subsidise sustainable textile materials to achieve price parity with PP textiles.** Alternative materials to PP are often expensive, reducing the price gap will foster sustainable choices.
- **Invest in the development of bio-based PP in textiles.** The use of bio-based PP can suppress or at least reduce the need for fossil fuels in PP production.
- **Establish guidelines for the use of second-hand selling apps.** The voluntary code of practice for app developers and operators will enable consumers to better protect themselves from malicious apps and make informed choices when deciding to download an app or assessing its integrity especially in the fashion industry where there can be a lack of transparency in terms of design and manufacturing.

c. Technology and infrastructure

Some textiles are made of PP fibre blends with biotechnological recycling pathways for these products requiring more research and development. At the end of life, blended textile waste often ends up in landfills due to the difficulty of fractionating and or separating the fibres from each other to be sorted according to their type (Kahoush & Kadi, 2022). One emerging strategy focuses on the high specificity of enzyme catalysis under mild reaction conditions to achieve selective depolymerization of individual components from material blends, however the use of this technique at an industrial scale has its own challenge (Jönsson et al., 2021; Kahoush & Kadi, 2022).

Assessing the quality of textiles to determine the reusability and recyclability of the waste can be an expensive and tedious process. The textile condition, how it was manufactured, and composition of the fabric usually determines its recyclability or reusability. Another barrier to these assessments is the sorting of textile waste, which is a time-, cost-, and labour-intensive process (Rahman et al., 2022).

Textile waste fibre can be used in the construction and geotechnical industries to produce insulators, polymer concrete, asphalt concrete, composite material manufacturing, etc. In geotechnical engineering, textile fibre waste can be used to strengthen the physical properties of construction material (Rahman et al., 2022). However, the quality of the collected waste often determines its potential application, the fibres in the apparels can lose their integrity and strength properties when they are washed multiple times during their service life (Rahman et al., 2022).

The use of technology such as the antimicrobial photodynamic dye coating technique has the potential to enable a safer and extended use of personal protection equipment) (PPE), and a reduction of plastic waste generated by PPE. Merkes et al. (2023) provided evidence that the use of (5%) thiomorpholino-methylene blue on polypropylene fleece-based PPE can extend its durability without compromising its breathability and filtration efficiency compared to uncoated masks. More specifically, the use of TMB coating on PPE can eradicate bacteria on the PPE surface, providing a visually aesthetic colour without hampering safety and efficacy of PPEs.

Based on the above the following key interventions for technology and infrastructure should be considered:

- **Invest in infrastructure for recycling technology of textiles.** Investing in sufficient technology and collection systems for PP textiles will decrease the amount in landfill.
- **Regulate manufacturing practices to minimise and/ or reduce waste in textile production, or capture it for recycling.** Textile waste can be recycled and used in construction providing a steady and sufficient stream of availability.
- **Create policy that stipulates that products should be designed to be able to be repaired, reused and then finally recycled, not designed for disposal.** PP textiles can be recycled if made of good quality originally.

d. Policy and regulation

Currently, most policies and regulation for PP in textile address labelling:

- EU Regulation No 1007/2011 on Textile Labelling and Fibre Composition Regulation and the subsequent Textile Products (Labelling and Fibre Composition) Regulations 2012. These regulations require manufacturers to clearly label products with textile composition.
- UK REACH: Chemical & Heavy Metals, which places restrictions on products with chemical substances and heavy metals (and includes plastic which may contain phthalates which can be used on PP)

The following policy and regulatory considerations for the circularity of PP in textiles have been identified:

There are a variety of contaminants that can occur in recycled textiles such as hazardous chemicals and dyes, which can limit their use for the same purpose, or a different purpose. These contaminants can include intentionally added substances like pigments and additives or unknown non-intentionally added substances and contaminants (Undas et al., 2023). Contaminants that have been detected in textiles during recycling include; detergents, resistant coatings, flame retardants, plastics coatings, antibacterial and anti-mould agents, pesticides, dyes, volatile organic compounds and nanomaterials (Rahman et al., 2022; Undas et al., 2023). Consequently, extending the life cycle of textiles also increases the risk of contaminants accumulating in reusable products (Leslie et al., 2016).

Based on the above the following key interventions for policy and regulation should be considered:

- **Set standards for the evaluating risk of potential contaminants in recycled textiles to facilitate recycling practices while ensuring consumer safety.** Implementing regulations that require toxicological and life cycle assessment of recycled products will be beneficial to ensure more sustainable production and practices.

e. Waste hierarchy

Currently, PP in textiles is predominantly at the waste management level of the waste hierarchy (Figure 19). Textiles made of PP are mostly discarded in landfill due to insufficient or unavailable recycling infrastructure, and leakage to the environment through simple use and washing is difficult to manage. Significant barriers to circularity have been identified throughout this section, but many of these directly lead to practical interventions which can facilitate moving PP based textiles upwards in the waste hierarchy. Given the diversity of products made of PP based textiles, opportunity exists to aim high. Mandating the redesign of products to be created from more sustainable materials is a logical step in scenarios such as sanitary products, where disposal is often a practical necessity. Alternatively, coupled with consumer awareness and subsidies, reusable products can also be incentivised and used to reduce plastic waste.

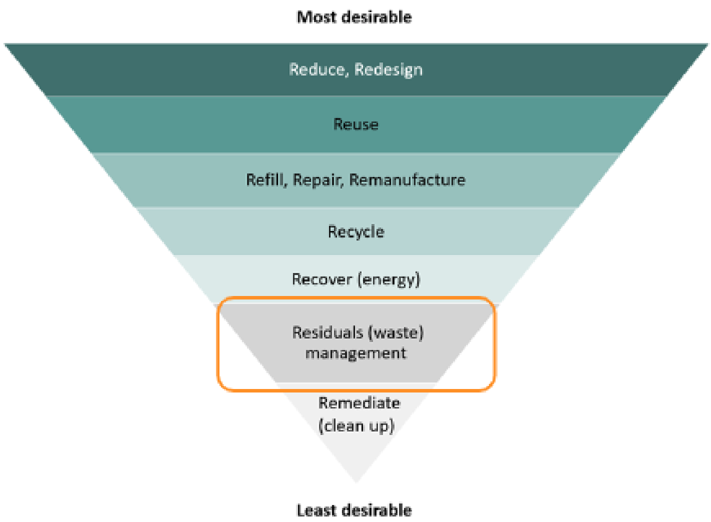

Figure 19. Current position of PP in textiles on the waste hierarchy.

The reuse of PP face masks can be achieved in certain settings. In their study, Hu et al. (2022) demonstrated that the reuse of meltblown polypropylene-based high-performance planar face masks could be achieved with appropriate disinfection methods and could help to address the shortage in face masks while simultaneously decreasing the consumption of single-use masks. Their results showed that, even after 24 h of mask wearing followed by three disinfection cycles using hot water at 70 °C for 30 min, the particle filtration efficiency and microbial indicators remained above the acceptable standard for a reusable civil mask (Hu et al., 2022). Furthermore, they observed that the spreading of breathed air was still efficiently suppressed by the masks. However, they do not recommend the use of such masks ,in some cases, as disposable surgical masks, especially among high-risk groups, such as persons with upper respiratory symptoms, or during other droplet- or aerosol-transmitted infection or disease outbreaks (Hu et al., 2022).

Reusables are often perceived as a greener alternative to single-use versions although this is not always the case. In the context of reuse, it is important for different types of reusable items to be evaluated individually and compared to their single-use alternatives (Lee et al., 2021). In their evaluation of the environmental impact of face mask usage, Allison et al. (2020) showed that the environmental impact of face mask usage largely depends on the type of reusable face mask. The emissions associated with single-use face masks with reusable cloth face masks with and without single-use filters were compared and results revealed that, the reusable cloth face mask without filters was the most environmentally friendly option while the reusable cloth face mask with filters was the least environmentally friendly option (Lee et al., 2021).

Based on the above the following key interventions for the overall circularity should be considered:

- **Build collection infrastructure for reuse and recycling to encourage donation rather than disposal when feasible.** Support increasing provision of readily-accessible collection, donation and takeback facilities (local charities such as the Salvation Army or the British Red Cross, etc.).

iii. Levers for change

Across consumer attitudes and behaviour, economics, technology and infrastructure, and policy and regulation, a number of actions have been identified as opportunities to enable the transition to circularity for polypropylene in textiles (Table 19).

Overall potential for circularity:

Currently, findings from the literature indicate that this material is not yet circular but does contribute to a circular economy for plastics. However, there is notable opportunity for PP based textiles to become more circular with interventions outlined for every step of the plastic lifecycle. Firstly, fast fashion should be addressed through a carefully designed mix of interventions that address consumer behaviour, deficiencies in product design and manufacture (such as cheap manufacturing which is disposed of due to inability to repair), and incentives to produce durable goods that can be reused, repaired and finally recycled. Additional sources of textile based PP should be subject to similar interventions to increase circularity, such as redesigning sanitary products to be reusable. Opportunity also exists for capitalising on existing innovation from NGOs and retailers by subsiding or investing in apps that promote reuse and removing barriers to online resale of clothing.

Table 19. Interventions to transition to a circular system for polypropylene in textiles, their levers and priority

Intervention	Geographic lever	Sectoral lever	Priority
Establish guidance and standards to help customers to choose safe low impact materials that are recyclable and use recycled content	National	Government, Retailers	Medium
Subsidise rental and subscription services for textiles to decrease demand for new PP textiles.	National	Government	Medium
Incentivize the creation of spaces where consumers can learn about clothing care and upcycling practices.	National	Government, Retailers	Medium
Remove tax on online resale of second hand clothes	National	Government	High
Subsidise sustainable textile materials to achieve price parity with PP textile	National	Government, Industry	High
Invest in the development of bio-based PP in textiles.	National	Government	High
Establish guidelines for the use of second-hand selling apps.	National	Government, Industry	Medium
Invest in infrastructure for recycling technology of textiles	National	Government	High
Regulate manufacturing practices to minimise and or reduce waste in textile production, or capture it for recycling	National	Government	High
Create policy that stipulates that products should be designed to be able to be repaired, reused and then finally recycled, not designed for disposal.	National	Government	High
Set standards for the evaluating risk of potential contaminants in recycled textiles to facilitate recycling practices while ensuring consumer safety.	National	Government	High

iv. Gaps in evidence and assumptions

A number of gaps in evidence exist in determining the circularity for PP in textiles, including:

- The length of supplier contracts across the whole life cycle and how these impact circularity.
- How this material or product is packed for onward transport and associated impacts on the products' design or choice of material, the impacts on the volume that can be purchased, and whether the packaging for transport leads to excess stock or waste.
- The design and manufacture of this material using alternative materials, changing product design to allow for or to promote refurbishment and reuse, and the design of the product set for use, with little to no flexibility.
- The way this material is marketed or sold affects how much is used and in turn waste.

4 Cross-cutting findings

None of the materials assessed are circular at present, and in most instances, the current consumer attitudes and behaviour, economics, technology and infrastructure or policy and regulation do not present the right enabling environment for these materials to be circular. This section summarises the key findings across the materials, highlights the common priority interventions, and the consistent evidence gaps.

4.1 General findings

The findings of this study can be synthesised into four general findings for circularity opportunities across the materials.

General finding #1. All materials have the potential to move up the waste hierarchy

Most materials currently exist at the lower end of the waste hierarchy and focus on waste management mechanisms such as recycling, waste to energy, composting in the case of compostables, and landfill or incineration (Table 20), none of which are circular approaches and contribute to roughly 10% of associated greenhouse gas emissions globally (OECD 2022). Existing infrastructure, policy and economic systems favour these end of life pathways. For the packaging materials, most approaches are currently focused around recycling as a solution. Recycling in the current system can be highly pollutive, contributing a significant amount to greenhouse gas production globally along the plastics life cycle of around 3% (OECD 2022). Furthermore, mechanical recycling has high microplastic emissions, associated accumulation of additives and contaminants, with chemical recycling currently producing a range of by-products, including sludges, waxes, and residues that may contain toxic substances. The management and disposal of these by-products pose significant environmental challenges. Both recycling approaches require significant amounts of energy and water, significantly more than reuse systems, for example. For these reasons, recycling should not be seen as a truly circular solution, and should rather form part of a more systemic shift that addresses the recirculation of materials only after other avenues of reuse, repair, remanufacture, and refill have been exploited.

All materials have opportunities for reuse, redesign, and in some instances, recycling, indicating that all materials can move towards a more circular future following significant intervention and prioritisation.

Table 20. Position of materials on the waste hierarchy and their potential to move up to higher stages

Material	Current position on waste hierarchy	Most feasible shifts up the waste hierarchy
Biodegradable & Compostable	Recovery (waste to energy) and waste management (disposal)	Reuse
PHA	Waste management	Redesign, Reuse
PVC (Construction)	Recovery (waste to energy) and waste management (disposal)	Reduce, Repair, Recycle
HDPE (Construction)	Waste management (disposal)	Repair, Recycle
HDPE (Packaging)	Recycling	Reduce, Reuse
PET (Packaging)	Recycling	Reduce, Reuse
LDPE (Packaging)	Waste management (disposal)	Reduce, Recycle
PP (Packaging)	Recycling	Reuse
PP (Textiles)	Waste management (disposal)	Reduce, Reuse

General finding #2. Recycling is often misrepresented as reuse, with the terms used interchangeably. Yet in reality they are inherently different approaches.

Reuse is considered as a system in which reusability is a deliberate objective and in which the packaging item is used multiple times for its originally intended purpose. Within a reuse system, all packaging is owned and managed by the reuse system provider, not the consumer (Global Plastics Policy Centre, 2023). Reuse is different from refill or repair, and a completely different management approach to recycling, which typically requires substantial alteration of the original material, usually through mechanical or chemical treatment, to recover raw materials or create new substances, usually with added virgin materials needed to maintain the quality.

Their misrepresentation, often due to the interchangeable use of terms, not only causes confusion but also opens avenues for misleading claims, a lack of transparency, and greenwashing.

General finding #3. Reuse is a key strategy to enhance circularity for all plastics

For most materials, reuse has been identified as an alternative to the current waste management approaches. Particularly regarding packaging, consumer behaviour exhibits a growing inclination towards reuse practices, indicating a shift in societal values towards sustainability and a preference for reducing waste. However, despite the apparent consumer interest and the evidenced benefits (Global Plastics Policy Centre, 2023) of reuse for enhancing circularity, there is a notable scarcity of action and innovation in the domain.

The current body of literature and the solutions being proposed and implemented remain predominantly focused on recycling. Innovation in reuse practices tends to be concentrated in areas where public demand is most pronounced, such as the use of PP in packaging. This suggests that while there is awareness of the advantages of reuse, significant efforts and resources are still being directed towards recycling as the primary strategy for waste management.

On the industry front, numerous companies have demonstrated their commitment to these principles by initiating major pilot projects at both national and local levels, aiming to integrate reuse practices into their operations. These initiatives highlight the industry's readiness to adopt and scale up reuse models. However, companies frequently report that the broader systemic support and consumer backing necessary to sustain a viable market for reuse are currently lacking. Various industry representatives in the expert interviews indicated that industry is awaiting more definitive legislative frameworks to enable them to transition to reuse systems, where consumers would have more incentive to adopt these models. This situation points to a significant role for policy and regulation in catalysing the shift towards reuse. Legislation can provide the necessary incentives and mandates required to transition to a reuse system at the national and sub-national levels.

General finding #4. Additives and plasticizers remain a critical unknown, inhibiting plastics circularity.

Part of the primary principles associated with circularity is to reduce harm to human health and the environment. The presence of additives and plasticizers in plastic materials represents a profound challenge to achieving circularity within the plastics industry. These substances are often incorporated into plastics to enhance their performance, durability, or flexibility. However, their exact composition and potential effects on human health and the environment remain largely unknown. There is an overwhelming lack of clarity and transparency regarding the chemicals, additives, colourants, and plasticizers used in materials and products (Horodytska et al., 2020).

The precautionary approach should be adopted, where the burden of proof should be shifted to plastic producers, in partnership with their value chains, to demonstrate that any plastic they propose to manufacture or use meets at least minimum standards of safety and recyclability. This would also prompt sharing of information on chemicals of concern along the plastics value chain to control exposure, support plastic recycling and avoid the cycling of legacy substances into new materials (UNEP, 2023).

General finding #5. Diverse interventions across the entire plastics lifecycle are required to generate a shift towards plastic circularity

Transitioning to plastics circularity necessitates a multifaceted approach that spans the entire lifecycle of plastic materials. Singular solutions are insufficient to address the diverse challenges inherent in plastic waste management.

At present, the norm is to focus on recycling as a solution towards circularity, likely due to its long-standing presence in the plastics value chain. While recycling plays a crucial role in mitigating the volume of plastic waste, it merely delays the eventual disposal of materials. Rather, a reduction in the production of plastics at the source is paramount (Zink and Geyer, 2019).

Transformational change towards plastic circularity requires the recognition that there are no silver bullets or one-size-fits-all solutions (Evans et al., 2023). Instead, diverse interventions tailored to specific contexts and challenges are essential. This nuanced approach acknowledges the scale and complexity of the problem and recognises the need for a combination of strategies to effect meaningful change. As such, the interventions presented in this study should not be treated in isolation, but rather should be adopted as a suite of solutions to achieve the circularity of the materials assessed.

4.2 Common gaps in evidence

Across the 9 plastic materials, there are some persistent evidence gaps, particularly regarding circularity at certain stages of the life cycle of materials. These gaps, while not exhaustive, highlight areas where further research and exploration could yield significant insights for enhancing circularity. Material specific gaps in evidence are presented in Section 3.

There is a notable lack of detailed understanding regarding the packaging processes for products, especially how these processes influence the selection of materials and designs, and the consequent effects on the feasibility of onward transport. This applies to all materials assessed.

Information on the duration of supplier contracts and its impact on circular economy practices was unavailable. The length and terms of these contracts could significantly affect the ability of businesses to adopt circular practices, such as material reuse and recycling, across all materials. This aspect requires deeper examination to understand how contractual relationships can be optimised for better circularity. This applies to all materials assessed.

How LDPE in packaging, bio-based plastics, HDPE in construction and PP in textiles are designed or manufactured for reuse or refurbishment is unclear, largely because there is limited evidence on these approaches given their nascency.

There is a significant shortfall in comprehensive data regarding the extraction and refinement processes of materials. This kind of information is essential for understanding the full lifecycle impacts of products and identifying opportunities for reducing environmental footprints through more sustainable material sourcing and processing techniques.

5. Limitations

There are a number of limitations that exist in this research that should be considered when interpreting the results

- This research was restricted to open access literature, or that which is available behind paywalls to academic institutions, which may not encompass all available or relevant information on the topic. Important insights and data found in paywalled or unpublished studies were not included, especially in instances regarding the more foundational thinking of circularity.

- Given the time constraints, the literature review conducted may not be fully exhaustive or comprehensive.

- Limiting research to English-language sources excludes a significant body of work in other languages, potentially overlooking valuable insights, case studies, and approaches adopted in non-English speaking regions.

- The interviews with materials experts took place without equally parallel inputs from environmental and human health specialists. This selective consultation may have resulted in an incomplete view of the circularity of plastics, particularly overlooking the environmental health implications of various interventions discussed.

- Similarly, there may exist a degree of directionality bias in favour of potential interventions that do not fully capture the full suite of options.

- Overall there is limited accessible data and statistics in the UK in terms of production, use, and waste generation per material or general type (for example, distinct data for bags, bottles, films, trays). The absence of detailed data impedes the ability to draw precise conclusions about the national landscape of plastic use and waste. Some plastic materials, such as LDPE, are heavily limited in the literature regarding their circularity, making it difficult to fully assess the current system and the potential for circularity.

- There is a lack of studies and data on reuse, repair, and remanufacture of plastics, most of the literature available focuses on recycling.

- There is much conflation between reuse and recycling in the literature, with these terms often being used interchangeably in many papers. This complicates the task of collecting and interpreting data relevant to each approach, skewing the representation of the impacts and benefits of these distinct approaches to waste management, and misrepresenting the reality of the approach being taken.

- There is variability in waste management trends and policies across different UK administrations, with, for example, recycling rates differing significantly among England, Northern Ireland, Scotland, and Wales. This diversity presents a challenge in developing uniform recommendations that are applicable across the UK.

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Annex 1 - Database of literature review findings by material

[see spreadsheet attached]

Annex 2 - Materials expert interview questions

Introduction

- Please describe your (or your organisation's) role in dealing with this material.
- Are there any examples that you know of where the use of this material is circular? Does it cover the full life cycle of plastics?

Barriers and enablers of circularity

- What are the primary barriers that exist for the circularity of this material?
  - Considerations include (among others): cost, length of supplier contracts, excess stock or waste, average lifetime of use, consumer attitudes and behaviour, the material itself (including additives or molecular structure etc.), packaging and distribution of products.
  - What are some of the day-to-day challenges that exist in working with this material?
- What technology or material innovation would enable or inhibit the circularity of this material?
- Do you know of any policies or standards (national, regional, or global) that exist as either enablers or barriers to the circularity of this material?
- From your perspective, are there any priorities for policy or regulation that would enable the shift to more circularity of this material?
  - OR Is there a lack of regulation currently that inhibits the circularity of this material?
- What are the challenges associated with reusing products made of this material? (Where a reuse system refers to one in which businesses are responsible for the replenishment of the product)

Moving towards circularity

- To what extent is it economically viable for this material to be kept higher up the waste hierarchy?
- In your opinion, does this material have a place in a circular economy for plastics? Why or why not?
- Would moving to an alternative material be more beneficial for a circular economy? If so, to what extent are alternatives technologically/economically viable?

Are there any other points you'd like to make beyond what has already been covered?

Further material specific questions might be asked where there are existing evidence gaps.