Upcycling food & drinks packaging

A WHITE PAPER

How EU-funded research projects transform food and drink packaging to reduce waste.

About us

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The projects PRESERVE, UPLIFT, upPE-T, BioSupPack and MoeBIOS are funded by the European Commission under the European Union Research and Innovation Programme Horizon 2020, Horizon Europe and their European Partnerships, the Bio-based Industries Joint Undertaking (BBI-JU) and the Circular Bio-Based Europe Joint Undertaking (CBE JU).

Our Goal

We upcycle different combinations of food and drink packaging materials into new ones with improved properties.

PRESERVE https://www.preserve-h2020.eu/
UPLIFT https://upliftproject.eu/
upPE-T https://uppet.eu/
BioSupPack https://biosuppack.eu/
MoeBIOS https://www.cbe.europa.eu/projects/moebios

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Executive Summary

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In 2021, EU consumers spent €1,551 billion on food and drink, underscoring the sector's economic significance. The food and drink industry, with a turnover of €1,112 billion in 2023, leads EU manufacturing and global exports. However, its reliance on plastic packaging has led to significant environmental challenges. The average European produced around 189 kg of packaging waste in 2021 – a little more than half a kilo per day per citizen – amounting to almost 85 million tonnes in the EU, with plastics constituting 19%. Despite progress, the sector faces substantial hurdles in achieving EU sustainability targets.

This white paper by the PRESERVE, UPLIFT, upPE-T, BioSupPack, and MoeBIOS projects, funded by Horizon 2020, Horizon Europe, and their European partnerships - the Bio-based Industries Joint Undertaking (BBI-JU) and the Circular Bio-Based Europe Joint Undertaking (CBE JU) - focuses on advancing sustainable packaging solutions. These projects aim to upcycle various food and drink packaging materials into new, improved ones by 2030.

This white paper not only highlights the innovative technologies and materials developed by these four projects in circularity design, upcycling technologies and end-of-life options, but also provides targeted recommendations or EU policymakers and key stakeholders for the future. These include investing in specialised collection, sorting and recycling infrastructure, promoting clear labelling and standards, and harmonising regulatory frameworks. It also emphasises the need for enhanced public education and public awareness campaigns on sustainable packaging. Overall, achieving these goals requires a collaborative effort among researchers, industry leaders, policymakers, and the public to drive innovation and foster a resilient, sustainable packaging sector.

Summary

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Introduction

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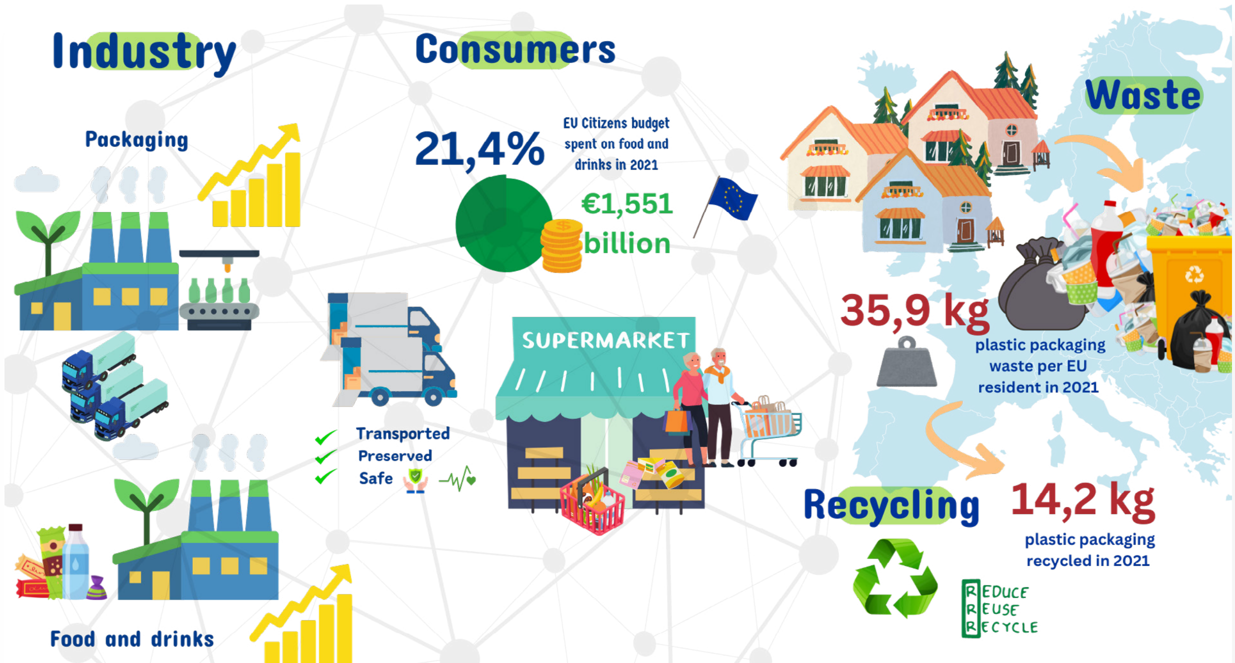
In 2021, consumers in the European Union (EU) spent €1,551 billion, or 21,4% of their budget, on food and drinks, either purchased in shops or consumed in restaurants and cafés.[1] The food and drinks products sector is the leading manufacturing industry in the EU, with a turnover of €1,112 billion in 2023 and €40,5 billion invested in 2020, marking the sector as the highest in capital spending.[2] The EU also leads globally as the top exporter of food and drinks, with exports totalling €182 billion in 2022. Given the sector' significance, the production of food and drinks packaging is likewise a major economic activity in the EU.[3]

Packaging is essential for transporting food and drinks from producers to consumers, to ensure products are properly preserved and safe. Given the vast consumption of these products within



[1] Food and Drink Europe (2024/09), Data trends Report 2023, p. 14. https://www.fooddrinkeurope.eu/wp-content/uploads/2023/12/FoodDrinkEurope-Data-Trends-Report-2023-digital.pdf and also Eurostat, 2021; Statista, 2021, 2023b, as cited in Beaumais, O., Kirakozian, A., Lazaric, N., Bruns, H. and Dupoux, M., Behavioural insights for waste-sorting labels in the European Union, Publications Office of the European Union, Luxembourg, 2024, doi:10.2760/641099, JRC134206.

[2] Ibidem

[3] Directive 1994/12. European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, (OJ L 365, 31.12.1994, p. 10): https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022PC0677#footnote31

the EU, the production of its packaging and its waste has become a significant concern for citizens and policymakers and a danger to our environment. On the one hand, while not exclusively, food and drinks packaging hugely relies on plastics derived from fossil fuels which are inadequately recycled. Packaging uses high amounts of virgin materials: in 2021, 44% of the world´s plastic production -of a total of 390,7 MT- was used in packaging. Only a 9,8 % of the total plastic production that year was either recycled plastic (8,3 %) or biobased plastic (1,5%). [4]

On the other hand, from 2010 to 2021, the amount of packaging waste generated in the EU steadily increased. Although the rise varied across different materials, wooden, plastics and paper/cardboard waste saw the highest relative increases. In total, the EU generated 84 million tonnes of packaging waste, of which 40,3% were paper and cardboard. Plastic represented 19,0%, glass 18,5%, wood 17,1% and metal 4,9%.[5] While the recycling rate for packaging waste improved continuously from 2010 to 2016, it regressed to 2010s by 2020 and 2021.[6] In 2021, the average EU resident generated an average of 35,9 kg of plastic packaging waste, of which only 14,2 kg were recycled.[7] These high and growing levels of packaging waste, coupled with low re-use and recycling rates, present significant challenges to achieving a low-carbon circular economy.

Circular Economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The circular economy tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources.[8]

[4] Plastics Europe (2024/09), The Facts 2022, p.21. https://plasticseurope.org/de/wp-content/uploads/sites/3/2022/10/PE-PLASTICSTHE-FACTS_20221017.pdf

[5] Eurostat (2023/10), EU packaging waste generation with record increase, Eurostat Statistics explained. https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20231019-1

[6] Eurostat (2023/10), Packaging Waste Statistics, Eurostat Statistics explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics#Waste_generation_by_packaging_material

[7] Eurostat (2023/10), EU packaging waste generation with record increase, Eurostat Statistics explained. https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20231019-1

[8] Ellen MacArthur Foundation (2024/09), What is a circular economy?, Circular economy introduction. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

The use of multilayer structures in packaging, while effective in maintaining product shelf life, further complicates recycling due to the economic barriers associated with recycling these materials: the complexity of separation, the low market value of recycled markets, the inadequate sorting and collecting systems, the lack of incentives, the lack of economies of scale, etc. Technological advancements are crucial for identifying and sorting novel biobased packaging materials to ensure they can be integrated into the recycling system.

Over the past decade, research and innovation in biobased materials and packaging solutions has greatly contributed to making the European packaging sector more sustainable and competitive, decoupling economic growth from fossil fuel dependency. The European Commission (EC) has supported this progress through funding from the Horizon 2020 and the Horizon Europe programmes, also channelled through the European Partnership for a Circular bio-based Europe (CBE). These initiatives have driven the development of circular business models, products, and materials in line with the EU's plastics strategy. Simultaneously, European Member States and institutions have introduced various initiatives and legislation to promote sustainability, from safer food contact materials to eco-design, packaging, and waste management: the EU´s Plastic Strategy (2018), the Green Deal (2019), the Circular Economy Action Plan (2020), the Farm to Fork Strategy (2020), the EU Biodiversity Strategy for 2030 (2020), Zero Pollution Action Plan (2021), the regulation on recycled plastic materials and articles intended to come into contact with foods (2022), the Ecodesign for Sustainable Products Regulation (2024) , the

Packaging and Packaging Waste Regulation (2024), the Waste Framework Directive, the Directive on Substantiating Green Claims, and a long etcetera. These efforts aim to protect both citizens and the environment while supporting European industry and innovation.

In parallel, industry and market actors also contribute to these goals through their own advancements and investments and contribute to the specifications of requirements for products, production processes or test-methods by creating standards. Under the oversight of CEN, CENELEC, and ETSI, standards ensure interoperability and safety, lower costs, and help businesses integrate into the value chain and facilitate trade.

Achieving a packaging revolution that aligns with circular economy goals and advances innovation, sustainability, and industrial resilience requires close collaboration between research, industry (of all sizes), policymakers, and the general public. Without this collaborative effort, solving the problem of packaging waste and its environmental impact will remain an elusive goal.

Advancing Circular Solutions for Food and Drink Packaging

Our Ambition

Our ambition is to contribute to upcycling up to 60% of food and drink packaging plastic waste by 2030 while also developing a viable roadmap to ensure that 60% of food and drink packaging is produced from renewable sources.

Over the past years, the PRESERVE, upPE-T, UPLIFT and BioSupPack projects have been working to demonstrate the feasibility of achieving a circular economy in packaging that:

- Decouples economic development from reliance on natural resources and fossil-based traditional sources.
- Contributes to achieving climate neutrality by 2050, in line with the European Climate Law.
- Helps halt biodiversity loss.
- Reduces the EU economy's strategic dependency on critical materials.

Our Mission

Our mission is to contribute to these goals by:

- Designing and developing novel, sustainable packaging materials suited for various end-of-life scenarios that enhance circularity.
- Developing cutting-edge technologies aiming at transforming packaging waste into valuable secondary raw materials.
- Proposing technically doable upcycling solutions or packaging waste with minimal environmental impact.
- Providing holistic circular solutions by engaging all stakeholders and evaluating social, environmental, technical and economic impacts.

Innovative materials such as biobased materials and plastics, along with advanced technologies and processes, are key to addressing Europe's packaging waste problem and its associated environmental and climate challenges. These innovations will not only help meet the EU's climate and environmental targets but also ensure consumer safety and support a resilient European industry.

The EU-funded projects contributing to this paper are focused on developing strategies, biobased and/or renewable materials, technologies and processes to upcycle bioplastics for food and drink packaging applications, as detailed in the next section.

Our Strategies and Solutions

As we strive to revolutionise food and drink packaging, our approach is based on creating sustainable, circular solutions that address the entire lifecycle of packaging materials. This involves three key pillars:

I. A circular design
II. Upcycling strategies and solutions
III. Suitable end-of-life options

I. Circularity by Design

The challenge

"Circular material use, including recycling, reuse and refurbishment, aims to reduce the generation of waste as well as our economy's dependence on extraction and imports of raw materials. As such, it has the potential to bring both environmental and economic benefits, and it is increasingly recognised as the resource use mechanism that would allow societal and environmental sustainability." [9]

At the core of our strategies is the circular design of packaging. Our projects have focused on designing packaging that not only meets the functional needs of the product but that also prioritises sustainability from the outset, ensuring regulatory compliance and consumers safety along the way. Our circular designs, pre-conceptualised during the project proposal phase, consider the entire lifecycle of the packaging, with a particular focus on the upcycling of biobased materials. This is all supported by sustainability and economic assessments and business plans for the future.

State of the art

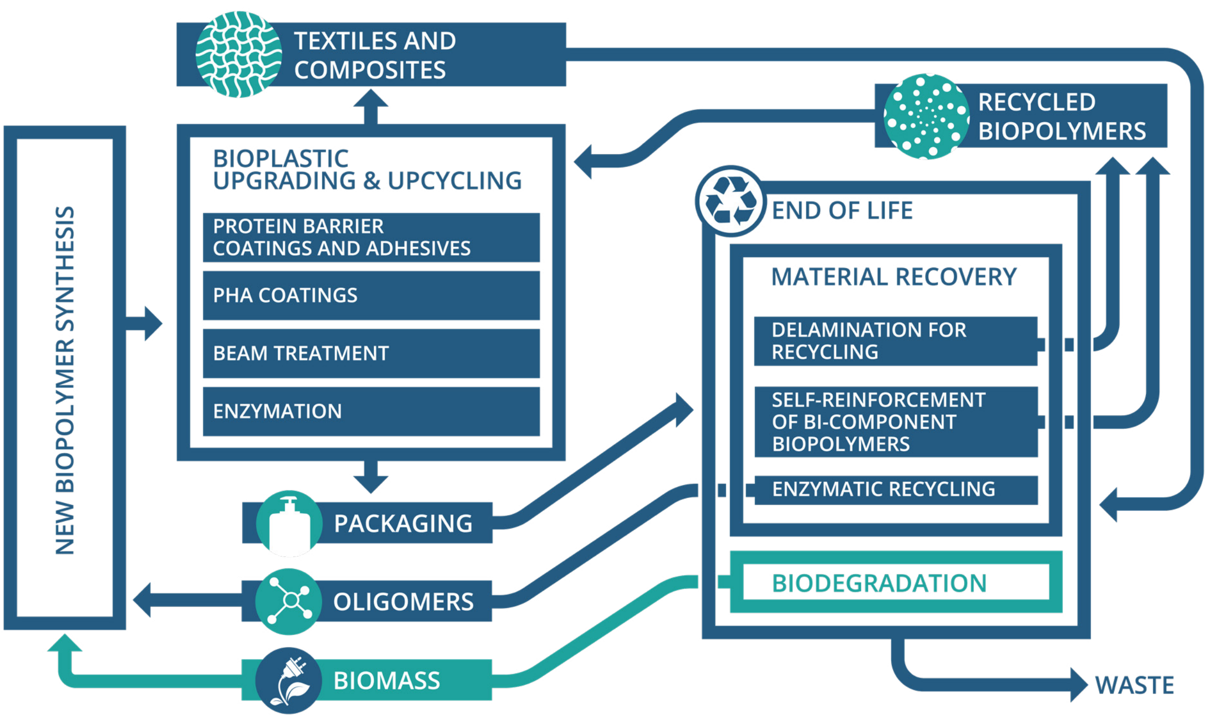
Many food and drink packaging solutions rely on multilayer structures to provide the mechanical strength -the ability of a material to withstand an applied force or load-, and barrier properties -the ability to resist the passage of substances such as gas, moisture, light and chemicals- needed to protect products and extend their shelf life. However, these multilayer materials pose

[9] European Environment Agency (2024/09), Circular by design Products in the circular economy, European Environment Agency (EEA) report, Nov. 2017. https://www.eea.europa.eu/publications/circular-by-design

significant challenges for economic recycling. Issues such as the complexity of separating individual layers and the lack of a level playing field with fossil-based materials hinder their recyclability and upcyclability. The ever-evolving regulatory framework also poses significant challenges to ensure compliance. To answer all these questions and dilemmas, EU research and innovation efforts are currently focused on developing alternative solutions based on high-performing monomaterial packaging suitable for mechanical recycling, alternative feedstock, new materials, and new processes. For these solutions to be viable alternatives to conventional plastics, they must meet critical technical requirements, including barrier, mechanical and sealing properties, among others. They also need to meet key sustainability requirements, not only regarding their end-of-life, but also during production: minimising or eliminating the negative environmental impacts of the manufacturing process while conserving energy and natural resources.

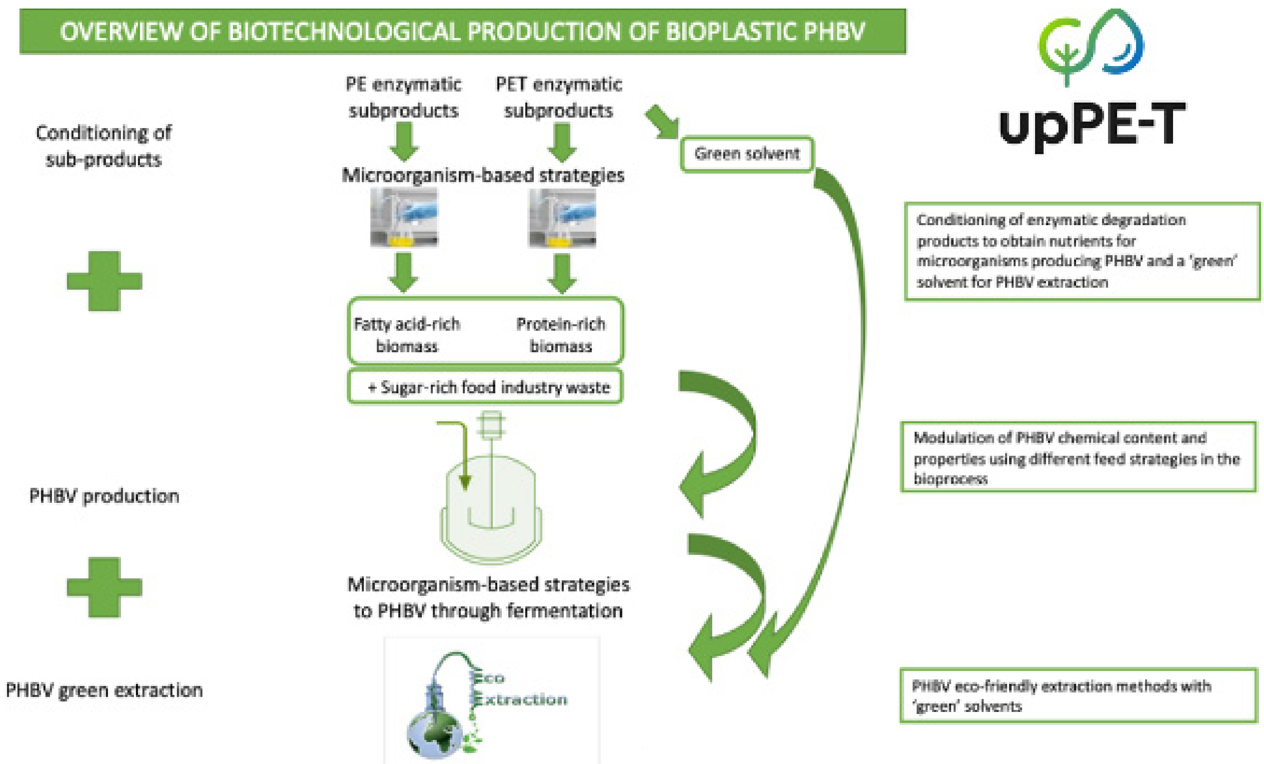
The innovation

PRESERVE: The PRESERVE project aims to enhance packaging design through cutting-edge biopolymer synthesis. One of the project's key designs and developments is a whey protein-based coating that enhances oxygen barrier properties. Since large amounts of the annual European production of whey protein are discarded, it is considered a non-direct food competing source.

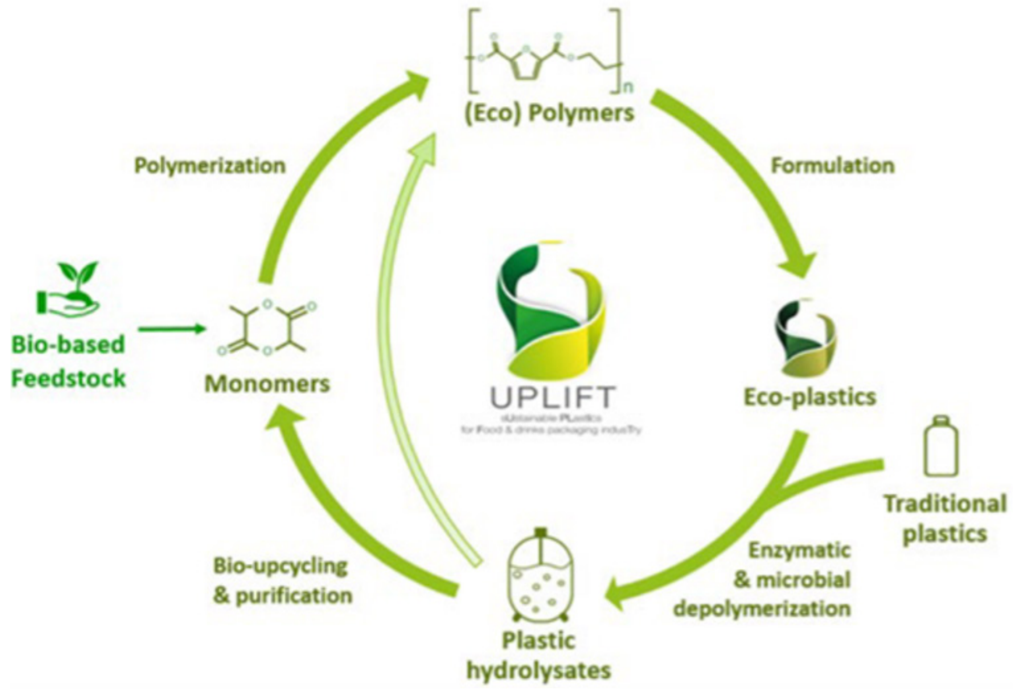


The use of a whey protein-based interlayer in multilayer structures has the added benefit of facilitating enzymatic delamination. This enables easy material separation of the multilayer structure, allowing for efficient and subsequent re- or upcycling of the recovered materials. PHA is also another material of interest due to its exceptional biodegradability and good film-forming properties. They have been shown to be good candidates to provide water-vapour barrier properties when they have been manufactured by extrusion processes. The end result of PRESERVE is packaging applications prototypes for food and drink packaging and for second high performance applications such as flow packs, trays, pouches, beverage bricks, injected jars, bottle, carrier boxes and bags.

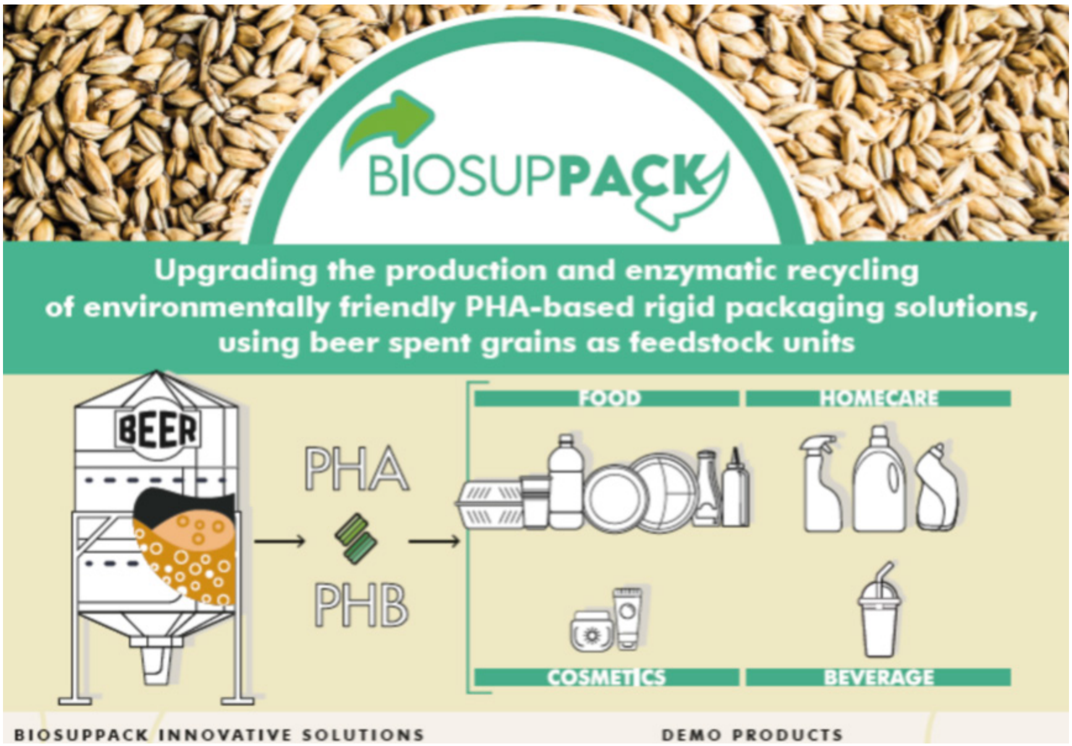
upPE-T: upPE-T is working on developing more sustainable packaging for food contact applications. Achieving gas and water barrier properties is a challenge when it comes to biodegradable packaging. By developing PHBV-based composites, using silica and cellulose modified nanoparticles, barrier and mechanical properties can be obtained while maintaining biodegradability and biobased origin and subsequent recyclability. The upPE-T project is developing a bioprocess in which the content of hydroxy valerate monomer in the PHBV polymer composition is modulated to improve its mechanical properties and thus increase the content of PHBV in the final composite formulations which will enhance the biodegradability and biobased origin of the flexible packaging prototypes.



UPLIFT: UPLIFT is using a design for recyclability approach, for instance by incorporating bio-based aromatic compounds, produced by newly engineered microorganisms, together with aliphatic polyesters such as PLA and PHA. This allows to modulate the properties of the new copolymers and obtain tuneable degradability. Tailor-made formulations have been made from recycled monomers to obtain rigid and flexible packaging with applications for the Food and Drinks sector. Furan-based polymers will be used to produce bottles with improved barrier properties.



BioSupPack: BioSupPack aims to deliver versatile and competitive biobased packaging solutions based on PHA suitable for food, cosmetics, homecare and beverage sectors uses. Innovative biopolymers such as polyhydroxyalkanoates (PHAs) are very promising to produce biobased packaging materials. PHA can be obtained from second and third-generation feedstocks and can be used to craft high-performance rigid packaging with properties similar to those of conventional petrochemical plastics. For instance, brew spent grains can be used to produce PHB-based polymers. Brew spent grains are by-products of the brewery industry: they are available at low or no cost and are produced in large quantities in many European countries. Environmentally safe packaging solutions based on the new PHB polymer will be developed at pilot scale. As an additional innovation, plasma technology will be used to pre-treat brew spent grains and facilitate their conversion into PHB polymer, increasing yields for a more economically viable process. The PHB-based packaging materials feature not only unique functionalities (e.g. microwaving, squeezability), but also compatibility with optimal end-of-life options, including mechanical and enzymatic recycling processes to reintroduce materials in the production step.



II. Upcycling strategies and technologies

The challenge

Transforming by-products, waste or waste materials, and useless, used, or unwanted products into new, higher-quality materials is essential for preserving natural resources, reducing plastic packaging and lowering greenhouse gas emissions from fossil-based production. Biotechnology plays a critical role in this process, and it must advance quickly to allow the transformation of these novel feedstocks into quality packaging materials, making them economically feasible.

Recycling and upcycling: what's the difference?

Recycling is the process of recovering materials that would otherwise be discarded. This can include for instance waste paper, plastic, glass, and metal, which are collected, sorted and reprocessed into materials and products that can be used for the same or new purposes.

Upcycling, on the other hand, is the process of taking discarded materials and using them to create something new that is of higher quality or value than the original item. This can be done by repurposing the material in a way to add new functionalities and/or improved properties. Upcycling allows us to valorise resources that would otherwise be thrown away.

State of the art

So far, efforts have primarily focused on the mechanical recycling of plastic food and beverage packaging. However, the recycled materials are often used for lower-value applications like garbage bags, insulation materials, or pallets and other industrial packaging. While this reduces environmental impact, it has limitations and does not encourage large scale recycling. To address this, chemical, biological and enzymatic upcycling strategies have emerged as a complementary alternative solution to conventional mechanical recycling strategies. These strategies can process highly degraded and complex wastes which cannot be valorised mechanically. Currently, biological and chemical recycling, especially biological recycling, is at a low degree of progress in the market, with lower Technology Readiness Level (TRL) at pilot scale but with great potential.

The innovation

PRESERVE: PRESERVE has developed an advanced "bioplastic upgrading and upcycling toolbox". This toolbox includes whey-protein barrier coatings and adhesives, biobased PHA coatings, enzymatic processes, micro-fibrillation approaches for mechanical reprocessing of biopolymers, optimised extrusion processes and electron beam (eBeam) irradiation treatment. By combining these tools, packaging solutions for food and drink are developed, with several end-of-life routes depending on the material used for the packaging:

1. biodegradation, allowing for the creation of biomass that is used again for the creation of biopolymers.
2. material recovery, which includes:
   a. enzymatic recycling, allowing for the development of oligomers that are used again for the synthesis of new biopolymers.
   b. delamination for recycling: PRESERVE has also established a delamination pilot plant for the delamination of multilayers for recycling, with an initial sorting via advanced photonic and artificial intelligence approaches. Following the delamination process, the separated multilayers can be sorted and recycled in accordance with the respective material cycles. The result is recycled polymers upon which the bioplastic upgrading and upcycling toolbox is again applied for the creation of personal care and transportation applications.
   c. self-reinforcement of bio-component biopolymers: allowing the (re-)processing of composites to mechanically enhanced recycled composites.

The latter two result in turn in recycled biopolymers that are upcycled for second high performance applications for personal care and transport packaging. All these technologies and processes have allowed for the upcycling of different combinations of materials together into new materials with improved properties. They also aim to prevent the release of microplastics to the environment.

upPE-T: the upPE-T project aims to develop an innovative circular solution for the upcycling of PET and PE packaging waste based on the enzymatic depolymerisation of the plastics into valuable monomers/oligomers that can be used as secondary raw materials for the production and extraction of PHBV bioplastic.

The starting point is the development and scaling up of technological processes for the enzymatic degradation of post-consumer food and beverage PET and PE waste. Using innovative solutions, the resulting products are then transformed into biodegradable and recyclable PHBV-based bioplastics, that is again used for food and beverage packaging. The upPE-T solution is presented as an alternative to mechanical and chemical recycling. Sugar-rich organic waste from the candy industry has also been tested as a carbon source to produce PHBV polymer.

UPLIFT: UPLIFT is leading a revolutionary shift in recycling, converting complex mixed plastic waste (currently incinerated) into more circular and renewable polymers, to mitigate global pollution. The main approach is to develop a so-called "Plastic Biorefinery", in which monomers from plastic waste with biobased/fermented building blocks, to reduce dependency on fossil resources. Plastic monomers from real plastic waste are obtained by novel chemo-enzymatic processes that allow for environmentally friendly and infinite recycling, without the need of previous sorting of the different plastic waste fractions.

BioSupPack: BioSupPack is working on the production of PHB polymer from brew spent grains, optimising the yields of the processes involved and the final polymer quality. The material obtained is compounded to produce tailor-made formulations suitable for their processing by different processing technologies for rigid packaging production, such as injection moulding and extrusion blow moulding. In addition, PHB is formulated into coatings for their application in fibre-based packaging. In both cases, compounds and coatings have been specifically formulated to improve the gas barrier, hydrophobic and squeezable properties of PHB-based packaging, making them suitable for the food, beverages, but also for cosmetics and homecare products. The novel PHB-derived packaging solutions will be scaled up from pilot to large scale and will prove to be also suitable for being recycled, both mechanically and enzymatically, making them optimal for the re-entering the production flow, according to a circular model.

III. Upcycling Packaging and End-of-life options

The challenge

Upcycled packaging involves creatively reusing discarded or waste materials in their existing form to create new and valuable packaging solutions. This approach helps to reduce the demand for new raw materials, lowers energy consumption and minimises environmental impact. As consumers become more conscious of their choices, researchers are exploring upcycled packaging solutions.

However, several challenges are to be addressed: a) material availability of suitable waste materials for upcycling packaging, reliable, steady and involve large quantities; b) end-of-life of upcycled packaging materials also poses challenges, as not all materials may be easily recyclable or compostable; c) not all upcycled materials can be easily transformed into high-quality packaging because there are strict regulatory standards and certifications for upcycled packaging materials. Antimicrobial requirements for instance need to be considered for food-contact materials; d) closing the loop and achieving the zero-waste goal requires a development of more sustainable options for the management of plastic packaging waste. Particularly important are technological innovations, that would provide solutions for the use of plastic packaging that cannot be recycled at scale using the currently available processes.

State of the art

Presently only around 40% of plastic packaging waste in the EU is recycled. The remainder is for the most part incinerated, thus contributing to GHG emissions, while around 20% is landfilled or leaked into the environment.[10] In 2021, packaging recycling rates varied between 38-80 % in the EU, with an average of 64%. This includes plastic, fibre-based, glass, metal packaging. When looking at plastic packaging the figure is even lower 40%.[11]

The innovation

PRESERVE: PRESERVE is developing materials for future demonstrators for food and drink packaging: to-go pocket for liquid product, snack pack, pouch, beverage brick and pulp moulded packaging. These five packaging applications made with improved biobased materials would then be treated with our upcycling toolbox to create 5 upcycled demonstrators for personal care and transport packaging: personal care flow pack, personal care injected jar, small bottles, packaging textile, and composite carrier box. All the final developed demonstrator will have a biobased content of at least 85%. PRESERVE is also assessing multiple end-of-life options for all demonstrators, depending on the used material.

UpPE-T: it is estimated that the industrial application of innovative technological solutions developed within upPE-T would contribute to the upcycling of 60% of total food and beverage plastic packaging waste 2030. In other words, 60% of food and beverage packaging would be produced from renewable sources, which would be a step forward towards replacing fossil fuels in the plastic production. In this way, the use of renewable sources is expected to lead to an 85,6% decrease in CO2 emissions compared to conventional production of plastic from fossil fuels. upPE-T is assessing the recyclability and biodegradability of the biodegradable packaging prototypes, as a tool to improve their formulations and design to ensure these two end-of life options. The upPE-T consortium includes end-user representatives who are validating the biodegradable packaging prototypes in real industrial environment to bring the product closer to the market and facilitate the definition of strategies in the exploitation plan of the results.

UPLIFT: UPLIFT is upcycling end-of-life plastic waste (after chemo-enzymatic treatment) into novel polymers that are easier to recycle. The UPLIFT new technology allows to produce build-

[10] Eurostat (2024/09), Online database. https://ec.europa.eu/eurostat/databrowser/view/env_waspac/default/table

[11] Eurostat (2023/10), EU packaging waste generation with record increase, Eurostat Statistics explained. https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20231019-1

ing blocks such as FDCA or bioplastics such as PHAs from PET or PBAT waste, thanks to newly engineered microorganisms. Moreover, PE and PP pyrolysis wax from chemical recycling can be upcycled into PHAs as well, thanks to adapted microbial consortia. Last but not least, non-toxic guanidine metal catalysts are used to selectively break down specific polyesters, such as PLA.

BioSupPack: BioSupPack is crafting highly performing PHA-based rigid packaging with properties similar to those of conventional petrochemical plastics present in the market. The project is developing demo products for food, beverage, homecare and cosmetic applications: dressings plastic containers/bottle, services packaging bowls, prepared food trays, beer glass bottles, fabric wash liquids, sunscreens and body peeling. Technology plays a major role in the identification and sorting of PHB-based waste from novel biobased packaging materials, and in ensuring that this new type of waste can enter the recycling system. New technology approaches are also being tested and integrated to ensure that packaging waste materials are pre-treated before entering enzymatic recycling processes. Plasma technology has also proven to be valuable throughout the value chain for the pre-treatment of packaging waste: it allows easier enzymes attack and consequently, increases efficiency of the enzymatic recycling process for a re-introduction of materials in the production, but also the recovery of carbon sources for further fermentation process.

Key Challenges Identified and Recommendations for the Future

Throughout the activities of our 4 projects, we have identified several key challenges that must be addressed to advance in the field and achieve our goal by 2030. We also lay down recommendations for the future addressed to policymakers, industry and innovation experts, research and academia, and civil society. We have identified four critical areas:

Technological and Logistical

KEY CHALLENGES

Collection, sorting and management of waste, including recycling streams: the current waste management infrastructure needs improvements, particularly in terms of collection, sorting, and recycling to effectively handle bioplastics. Currently, only a limited number of plastics are sorted for recycling, those are in general the plastics with the highest market shares, such as PET, PP, PE and, in specific cases, also PS. Examining the input streams of sorting facilities, it is clear that several other types of plastics are entering the facilities, which – due to low volumes – will not be recycled and have to be sorted out. Although biobased drop-in solutions such as biobased PET or biobased PE, are perfectly integrated in the recycling stream of their conventional counterpart, other types of bioplastics are separated from those streams and usually get incinerated.

Even though bioplastics are gaining popularity as environmentally friendly alternatives to traditional plastics, the systems for processing them — especially biodegradable plastic packaging — are severely underdeveloped. Integrating biodegradable materials into existing recycling streams and ensuring their viability beyond composting presents significant challenges. Biodegradable plastics are perfectly sortable with current NIR technology, but incentives are missing to do so.

This has important implications for achieving ambitious recycling targets and environmental goals, particularly within the EU's sustainability framework.

RECOMMENDATIONS FOR THE FUTURE

- **Investment in infrastructure:** provide incentives for the creation of networks and infrastructure for bioplastics collection and sorting that align with existing waste management infrastructure, including specialised recycling and composting facilities and bioprocessing plants. Incentives for industries that innovate in bioplastic collection and recycling and policies that promote sustainable practices could enhance the end-of-life of bioplastic products without placing direct accountability on manufacturers.

• **Promote clear standardisation and labelling:** a clear labelling bioplastic products with information about their disposal requirements (e.g., compostable, recyclable) is crucial.

• **Support innovation in recycling technologies and infrastructure:** incentives for research and development of advanced sorting technology and recycling methods, particularly for multilayer packaging and biobased materials, enzymatic delamination and mechanical recycling technologies are critical to improving material recovery. This must go hand in hand with the establishment of an infrastructure for mixed plastic waste management from post-consumer wastes, able to differentiate towards pure bioplastics or composites.

• **Incentivise political and economic support:** the EU and other governments could introduce regulations that mandate the use of bioplastics in specific industries, accompanied by economic incentives such as tax breaks or subsidies for companies that invest in bioplastic recycling and composting technologies.

Value Chain and Market integration

KEY CHALLENGES

Economic viability of upcycling processes: transforming waste into higher-value products through biotechnology is promising but faces economic barriers. For these processes to be adopted at scale, they must become cost-competitive with conventional recycling and fossil-based packaging production. Ensuring that innovations can be effectively scaled from pilot to industrial levels is very challenging. Price disparities and the lack of a level playing field with fossil-based solutions hinder the scaleup of biobased solutions.

RECOMMENDATIONS FOR THE FUTURE

Reinforce financing frameworks to support scaling up of novel technologies: institutions and public administration can provide financial incentives to companies investing in biotechnological upcycling and encourage their maturity with respect to market TRLs. Scaling up manufacturing processes to meet commercial demands can be technically challenging and will require a favourable financial environment for innovation to be able to grow at scale. Governments and private companies can collaborate on building the infrastructure needed to support biotechnological upcycling. Public-private partnerships could be used to fund pilot projects, scale up production, and ensure that biobased solutions have access to the necessary feedstock and supply chains.

KEY CHALLENGES

Defining value chains and stakeholder engagement: circular solutions require clearly defined value chains and the identification of key actors. This involves uniting diverse stakeholders with varying interests to achieve common goals – a complex and challenging task.

RECOMMENDATIONS FOR THE FUTURE

- **Promote strategic industry collaboration and stakeholder engagement in value chain definition:** incentivise partnerships between industries and packaging manufacturers, to integrate by-products into the value chain, i.e.: through tax incentives, the creation of multi-stakeholder platforms, collaborative business models, grants or subsidies that encourage companies to engage in joint ventures and collaborative projects. The integration of biobased innovations requires collaboration from all players in the value chain, including primary producers, processing industries, and consumer brands. Research organisations and academia must also be involved.

- **Encourage public-private partnerships:** foster collaboration between government, industry, and academia to accelerate the development and commercialisation of upcycling technologies to establish robust circular supply chains. This could involve incentivising partnerships between waste management companies, manufacturers, and sorting and recycling facilities. A great example is the CBE JU.

KEY CHALLENGES

Feedstock market impact: the production costs of bioplastics depend on the development of feedstock prices. The success of our solutions will be measured by their readiness for market exploitation.

RECOMMENDATIONS FOR THE FUTURE

- **Facilitate the development of logistics and management frameworks:** logistics supports the process of harvesting underutilised biomass for the manufacturing of biobased products. Life Cycle Assessments can also serve as a tool for identifying sustainability hiccups along the supply and logistics chain. Market readiness also depends on the development of infrastructure to handle bioplastics at the end of their lifecycle.

- **Leverage alternative feedstocks:** encourage the use of 2G and 3G bioplastics along with 1G to decrease environmental impacts. 2G bioplastics are produced from lignocellulosic biomass and non-food edible oils, while 3G bioplastics are obtained from sugars or oils produced by micro-organisms (microalgae, bacteria, mushrooms, yeasts and others) or from municipal waste material. Ad hoc marketplaces should be set up for matching offer and demand of 2G and 3G feedstock and mixes of plastics and facilitate the logistics of the supply chain.

- **Promote circular economy with feedstock valorisation:** support projects that use waste by-products (e.g., brew spent grains, organic waste) as feedstock for bioplastic production. Encouraging the use of second-generation feedstocks, along with first generation and third generation, contributes to resource efficiency and reduces dependence on fossil-based materials.

KEY CHALLENGES

Lack of market parity with fossil-based materials: despite the environ mental benefits of biobased packaging, fossil-based materials remain dominant due to cost-effectiveness, scale of production, supply chain infrastructure, policy and regulatory support and consumer preference and demand. Creating a level playing field for alternative materials is challenging.

RECOMMENDATIONS FOR THE FUTURE

Provide financial and policy incentives for biobased packaging: support the acceleration of the adoption of eco-friendly alternatives that help create a level playing field. Promote and standardise life cycle assessments for packaging materials, ensuring that environmental impacts are minimised not only in end-of-life processes but also during production and use.

Regulatory and Compliance

KEY CHALLENGES

Regulatory uncertainties, inconsistencies and disconnected EU regulatory framework: navigating a complex and evolving policy framework remains a significant hurdle. There are currently over 10 strategies, plans or initiatives and a dozen more legislations with significant overlaps and inconsistencies. Discrepancies between high-level political support, strategies and initiatives for the bioeconomy, the environment, industry and climate and current EU legislation are hampering investment and creating barriers to market entry and expansion. The lack of harmonised frameworks and uncertainties also constitute important challenges regarding the compliance with certain safety requirements, end of waste status of by products and food contact applications.

RECOMMENDATIONS FOR THE FUTURE

• **Harmonise policy frameworks:** a better integrated bioeconomy framework with stronger links between the circular economy, environment, climate and bioeconomy and industrial strategies are needed as often they are treated as separate concepts when in fact the bioeconomy is one half of the circular economy. Clear, streamlined strategies and unified regulations on the use and recycling of biobased and biodegradable packaging materials are essential. Regulatory frameworks should ensure these materials meet safety standards without stifling innovation and provide clear guidelines for compliance.

• **Establish solid legislative and regulatory frameworks that encourage the development of new technologies:** an example is regulation 2022/1616 concerning recycled plastic materials and articles intended to come into contact with food. It opens a window to new recycling technologies, considered as novel recycling technologies, allowing the evolution of recycling techniques still at low TRLs with respect to the market. Inconsistencies such as those in the Sustainable Taxonomy Climate Delegated Act and the Delegated Act on Environment and Circular Economy when it comes to the use of primary biomass for plastics production must be worked upon. Upcoming delegated acts deriving from the PPWR regulation should avoid stifling innovation.

• **Ensure participation of relevant experts in intra-department discussion at European Commission:** involve industry, academia, NGOs, civil society organisations as well as EU funded projects developing novel material, technologies and processes in the preparation of secondary regulation/delegated acts, such as the upcoming deriving from PPWR. EU projects often represent all key stakeholders and possess valuable insights on the development of the sector, its potential, the challenges to be overcome and the needs to overcome them.

• **Leverage the use of digital tools:** e.g. to design customised portals to communicate information or to collaborate with industry, research an innovation actors and EU projects in the development of delegated acts; to develop interactive tools to simplify compliance assessment or speed up administrative processing.

KEY CHALLENGES

Compliance and safety standards: ensuring compliance with safety standards for biobased materials—especially for food contact applications and their end-of-life —presents a complex set of challenges. Biobased materials, though promising in terms of sustainability, must meet stringent regulatory requirements to ensure consumer safety, environmental protection, and product performance. Achieving compliance while supporting the valorisation (commercialisation and utilisation) of new technologies through standardisation is often difficult due to a lack of clear links between research, policy, and regulatory frameworks. These challenges reflect the intricate relationships between innovation, regulatory compliance, and the development of standards that apply to biobased products throughout their lifecycle.

RECOMMENDATIONS FOR THE FUTURE

Early involvement of regulatory bodies and foster of industry and research collaboration: involving regulators and standardisation bodies early in the research process can help ensure that new materials are developed with compliance in mind. Collaborative efforts between researchers, industry, and regulators can lead to the co-development of materials that meet both technical performance requirements and regulatory standards. Standardisation helps bridge the gap between research and market, increasing the probability that technological innovations will be adopted by the market. Horizon EU research projects are melting pots of ideas between research organisations, academia, industry and civil society. EU projects also contribute to the development of informative or technical aspects such as new materials, processes or specifications, contributing notably to standardsation efforts at EU level.

• **Harmonization of standards:** the European Committee for Standardisation (CEN) plays a critical role in developing common frameworks for material safety, biodegradability, and food contact compliance. Harmonised standards would allow companies to meet one set of criteria for multiple markets, reducing the complexity and cost of compliance. The European Commission can steer this process by mandating CEN the development of specific standards.

What is the regulatory framework of our activities?

Below is a non exhaustive list of all the main EU strategies, initiatives, action plans and legislation in the field of work of these EU-funded projects. Changes to this framework are expected beginning in 2025 when the new European Commission is expected to launch new ones such as the European Biotech Act or review some such as the Circular Economy Action Plan.

EU Plastics Strategy (2018)
- Directive on single-use plastics (2019)
- Communication on a policy framework for biobased, biodegradable and compostable plastics (2022)
- EU Bioeconomy Strategy (2018)

European Green Deal (2019), from which almost other plans, initiatives, roadmaps and legislation derives from.
- Environmental Footprint Method (2021)
- Organisation Environmental Method (2021)

EU Circular Economy Action Plan (2020)
- EU strategy for sustainable and circular textiles (2022)
- Directive on Green Claims (2023)
- Directive on empowering consumers for the green transition (2024)
- Ecodesign for Sustainable Products Regulation (2024)
- Packaging and Packaging Waste Regulation (2024/2025)
- Proposal for a targeted revision of the Waste Framework Directive (2023)

Zero Pollution Action Plan (2020)
- REACH restriction addressing internationally added microplastics (2023)

Chemicals Strategy for sustainability (2020)
- Recommendations on framework for Safe and sustainable by design chemicals (2022)
- REACH restrictions Roadmap (2022)

European Industrial Strategy (2021)

Communication on Building the future with nature: Boosting biotechnology and biomanufacturing in the EU (2024)

Education, Awareness, and Cultural Shift

KEY CHALLENGES

Public awareness: substantial efforts from policymakers and market players are needed to raise citizen awareness and promote eco-friendly alternatives.

RECOMMENDATIONS FOR THE FUTURE

Educational, public awareness campaigns and harmonised labelling schemes: labelling of products, also for disposal, and certification schemes will play a critical role determining the willingness-to-pay of consumers, in combating greenwashing and building public trust in more sustainable practices. The development of labelling schemes, transparent and credible to the customers is key: these schemes will have to be tied to effective environmental standards and the compliance should be monitored by competent agencies on a regular basis. Education and public awareness campaigns are key for the proper disposal of bioplastics and biobased materials to avoid contaminating waste streams.

KEY CHALLENGES

Education and skill development: transitioning from a linear to a circular economy necessitates new knowledge and skills. Educational programmes must evolve to meet these demands, and corporate training must align with new policies and sustainable practices.

RECOMMENDATIONS FOR THE FUTURE

- **Invest in educational campaigns:** governments should invest in educational campaigns aimed at consumers and businesses to promote the benefits of sustainable packaging and circular economy practices and the national and EU level legal commitments. Public understanding and acceptance of biobased and biodegradable packaging and recycling options are crucial for widespread adoption.

- **Update educational curricula:** align corporate training and academic programs with new demands of the circular economy, ensuring businesses and workers are equipped for the shift.

MoeBIOS (2024-2028) will be improving the waste manage-ment of biobased plastics and focus on the upcycling in the packaging, textile and agricultural sector.

The MoeBIOS project aims to innovate and optimise recycling processes to mitigate plastic pollution, promote sustainable practices, and enhance waste management efficiency across Europe.

The novel recycling processes (e.g., biological, mechanical and chemical) for bioplastics will result in new upcycled and high-value-added products. This systemic innovation addresses hierarchical challenges from bioplastic waste collection to upcycling, aiming for holistic and coordinated solutions. The project covers sorting, conditioning, and valorising waste streams into end-products of equivalent quality and functionality.

MoeBIOS will help to bring recycling processes to industrial exploitation, resulting in important positive impacts for the environment and the economy: the goal is to process approximately 232,505 tonnes of mixed bioplastic waste per year and additionally reduce GHG emissions by 178 tonnes annually.

PRESERVE: High performance sustainable biobased packaging with tailored end-of-life and upcycled secondary use

The PRESERVE project is developing a set of innovative processes and materials such as coatings and adhesives, which will foster the circular use of biobased packaging, contributing to boost the European competitiveness of the sector. The project will enhance biomaterials to optimally preserve food and beverage products and upcycle the resulting end-of-life materials to supply high added value personal care and transport packaging. At least 10 bioplastic and fibre-based packaging items of at least 85 % biobased content and with minimal environmental impact will be delivered to validate the results on a circular economy perspective.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952983.

BioSupPack: Demonstrative process for the production and enzymatic recycling of environmentally safe, superior and versatile PHA-based rigid packaging solutions by plasma integration in the value chain

BioSupPack's purpose is to upscale new, economically convenient, and highly performing biobased rigid packaging solutions based on PHA, also suitable for being recycled and recovered. The project will explore, first at lab-scale and pilot level and then at large scale, the possibility to use beer-spent grains as a fermentation feedstock for PHB production. The partners will collaborate to demonstrate at least two new biobased materials and to create two new consumer products of commercial value after the end of the project that are also safe and in compliance with European regulatory standards in place.

This project has received funding from the Bio-based Industries Joint Undertaking (JU) under the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 101023685. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Bio-based Industries Consortium.

UPLIFT

UPLIFT: sustainable plastics for the Food and drink packaging industry

The core of UPLIFT has a dual strategy: on one hand, it seeks to develop industrial scalable enzymatic and microbial degradation processes to selectively depolymerize and upcycle plastic packaging waste materials, which are currently considered unrecyclable; on the other hand, the project will manufacture at pilot scale new renewable eco-polymers specifically designed to ensure easier end-of-life processing.

UPLIFT will contribute to putting the European plastic packaging industry at the forefront of innovation and sustainability worldwide, by keeping plastic waste in the loop and integrating biobased building blocks, instead of using virgin fossil-based monomers. This will result in a reduction of plastic waste generation and greenhouse gas emissions associated with its production. Finally, the project will look into social aspects, exploring the potential synergies between policymakers, industry, consumers, and recyclers, which are critical in order to change the plastic economy.

In summary, UPLIFT seeks to boost the development and validation of novel enzymatic and microbial processes for the sustainable use of plastics in food and drinks packaging applications, which will be tested and evaluated from a technical, environmental and socio-economical point of view, thereby contributing to the development of a more circular European plastic packaging industry.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 953073.

upPE-T: Upcycling of PE and PET wastes to generate biodegradable bioplastics for food and drink packaging

The upPE-T project addresses the challenges by proposing a circular solution with a holistic approach. The development of the technological solutions goes hand in hand with other important tasks that include assessing the social, environmental and economic impact of the processes and products developed, working on providing new standards and certifications schemes to help bring these new products to market and improve their acceptance by citizens and businesses. To this end, upPE-T has made a great effort to involve the key actors and stakeholders, encompassing the different expertise needed to understand the challenges and to successfully address and resolve them.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 953214.

MoeBIOS: improving the waste management of biobased plastics and focus on the upcycling in the packaging, textile and agricultural sector

MoeBIOS aims to innovate and optimise recycling processes within these value chains to mitigate plastic pollution, promote sustainable practices, and enhance waste management efficiency across Europe.

MoeBIOS project has received funding from the Circular Bio-based Joint Undertaking (JU) and its members under the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101157652.

Glossary

Adhesive: a coating or film applied to a surface to prevent or reduce its adhesion to another material.

Biobased[12]**:** the material or product is (partly) derived from biomass (plants). Biobased plastics are fully or partially made from biological resources, rather than fossil raw materials. Biomass used for bioplastics stems from e.g. corn, sugarcane, or cellulose.[13] Secondary biomass, such as organic waste and by-products (e.g. starch waste, beer spent grains, used cooking oils, etc.) can also be used as biomass for the development of bioplastics.

Biobased feedstock: raw material originating from nature that forms the basis for bioplastics. There is a wide range of biobased feedstock: agro-based (plants such as corn or sugar cane), ligno-cellulose (not eligible for food or feed production), organic waste, etc.[14]

Biodegradable: biodegradable plastics biodegrade in certain conditions at their end-of-life. Compostable plastics - a subset of biodegradable ones – typically decompose in industrial composting facilities, and first need to be collected. Biodegradable and compostable plastics may be made from biological resources or fossil raw materials.[15]

Biological/organic recycling: aerobic (composting) or anaerobic (biomethanization) treatment, under conditions and using micro-organisms, of the biodegradable parts of packaging waste.[16]

Bioplastics: bioplastics are not just one single material. They comprise of a whole family of materials with different properties and applications. According to European Bioplastics, a plastic material is defined as a bioplastic if it is either biobased, biodegradable, or features both properties.[17]

[12] European Commission (2024/09), Biobased, biodegradable and compostable plastics, Energy, Climate change, Environment. https://environment.ec.europa.eu/topics/plastics/biobased-biodegradable-and-compostable-plastics_en

[13] European Bioplastics (2024/09), What are Bioplastics?. https://www.european-bioplastics.org/bioplastics/

[14] Ibidem

[15] Ibidem

[16] Directive 1994/12. European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, Art. 2.9. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A01994L0062-20180704

[17] European Bioplastics (2024/09), What are Bioplastics?. https://www.european-bioplastics.org/bioplastics/

Coating: to apply a layer of a liquid substance to the surface of a material or object. The objective might be protective, decorative, a primer for subsequent coatings, improved barrier properties, waterproofing, antistatic and so on.

Cellulose: vital component of the plant cell wall derived from marine invertebrates, algae, fungus, and bacteria. It is one of the most common biomaterials on the planet.[18]

Chemical recycling: also known as feedstock or tertiary recycling, comprises different varying technologies that convert plastic waste into an upstream feedstock resulting in secondary raw materials that have the same quality as virgin materials.[19]

Delamination: separation process which consists of the dissolution of the inner layers (adhesives or metal) that join the polymers using a different solution.[20]

Electron irradiation/eBeam treatment: eBeam technology involves the use of accelerated electrons to treat various surfaces, such as polymer films. The basic principle revolves accelerating electrons to high velocities and directing them at selected items/surfaces. These accelerated electrons can penetrate polymer films, causing the formation of radicals. These radicals can either "travel" along the polymer chain resulting in chain scission or interact with radicals formed on the neighbour polymer molecules resulting in cross-linking. Both processes can be used to modify polymer films regarding mechanical and barrier properties, among others.[21]

Enzymatic recycling/Enzymation: a pioneering biological recycling process which uses naturally-occurring enzymes to transform plastic and textile waste into new products.[22]

Mechanical recycling: refers to operations that aim to recover plastics via mechanical process-

[18] Shivani Khopade, Shyam Sudhakar Gomte, Chetan Janrao, Akshay Bavaskar, Tejas Girish Agnihotri, Aakanchha Jain, Renuka Khatik, Chapter 4 - Peptide and protein delivery through cellulose, hyaluronic acid, and heparin, Editor(s): Aakanchha Jain, Sonia Malik, Peptide and Protein Drug Delivery Using Polysaccharides, Academic Press, 2024, Pages 75-113, ISBN 9780443189258, https://doi.org/10.1016/B978-0-443-18925-8.00003-9

[19] European Bioplastics (2024/09), Chemical recycling. https://www.european-bioplastics.org/chemical-recycling/

[20] Imene Berkane, Andrea Cabanes, Oksana Horodytska, Ignacio Aracil, Andrés Fullana, The delamination of metalized multilayer flexible packaging using a microperforation technique, Resources, Conservation and Recycling, Volume 189, 2023, 106744, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2022.106744.

[21] Zivanovic, S. Electron beam processing to improve the functionality of biodegradable food packaging. Electron Beam Pasteurization and Complementary Food Processing Technologies; Elsevier, 2015; pp 279–294, ISBN 9781782421009.

[22] European Climate (2024/09), New LIFE for waste plastic, Infrastructure and Environment Executive Agency. https://cinea.ec.europa.eu/news-events/news/new-life-waste-plastic-2023-08-03_en

es (grinding, washing, separating, drying, re-granulating and compounding), thus producing recyclates that can be converted into plastics products, substituting virgin plastics. It is also known as material recycling, material recovery or, related to plastics, back-to-plastics recycling.[23]

PLA: Polylactic acid (PLA), a biobased, recyclable, biodegradable and compostable material.

PHAs: Polyhydroxyalkanoate, a biobased, biodegradable and compostable materials´ family, produced in nature by various microorganisms.

PET: Polyethylene terephthalate: fossil based, non-biodegradable.

PBAT: Polybutylene Adipate Co-Terephthalate.

PP: Polypropylene.

PHBV: Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) is a promising biodegradable biobased material, which is designed for a vast range of applications, depending on its composite.[24]

Recycling: any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.[25]

Renewable material: material that is composed of biomass and that can be continually replenished.[26]

TRL: Technology readiness level.

[23] European Bioplastics (2024/09), Mechanical recycling. https://www.european-bioplastics.org/mechanical-recycling/

[24] Pavlo Lyshtva, Viktoria Voronova, Jelena Barbir, Walter Leal Filho, Silja Denise Kröger, Gesine Witt, Lukas Miksch, Reinhard Saborowski, Lars Gutow, Carina Frank, Anita Emmerstorfer-Augustin, Sarai Agustin-Salazar, Pierfrancesco Cerruti, Gabriella Santagata, Paola Stagnaro, Cristina D'Arrigo, Maurizio Vignolo, Anna-Sara Krång, Emma Strömberg, Liisa Lehtinen, Ville Annunen, Degradation of a poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) compound in different environments, Heliyon, Volume 10, Issue 3, 2024,e24770, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2024.e24770.

[25] Joint Research Centre (2024/09), Definition of recycling, EU Science Hub. https://joint-research-centre.ec.europa.eu/scientific-activities-z/less-waste-more-value/definition-recycling_en

[26] European Commission (2024/09), Renewable material - EN 16575:2014, European Committee for Standardisation, Technical Committee 411 (CEN TC/411), Bio-based products – Vocabulary, Mandate M/492, August 2014.), Knowledge for Policy. https://knowledge4policy. ec.europa.eu/glossary-item/renewable-material_en

Upcycling:

" Process that leads to improved value and/or properties of the new material."

Uplift, 2024/09