BIO PLASTICS

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INTESA SANPAOLO INNOVATION CENTER

MATERIAS
ideas come to life for a sustainable world

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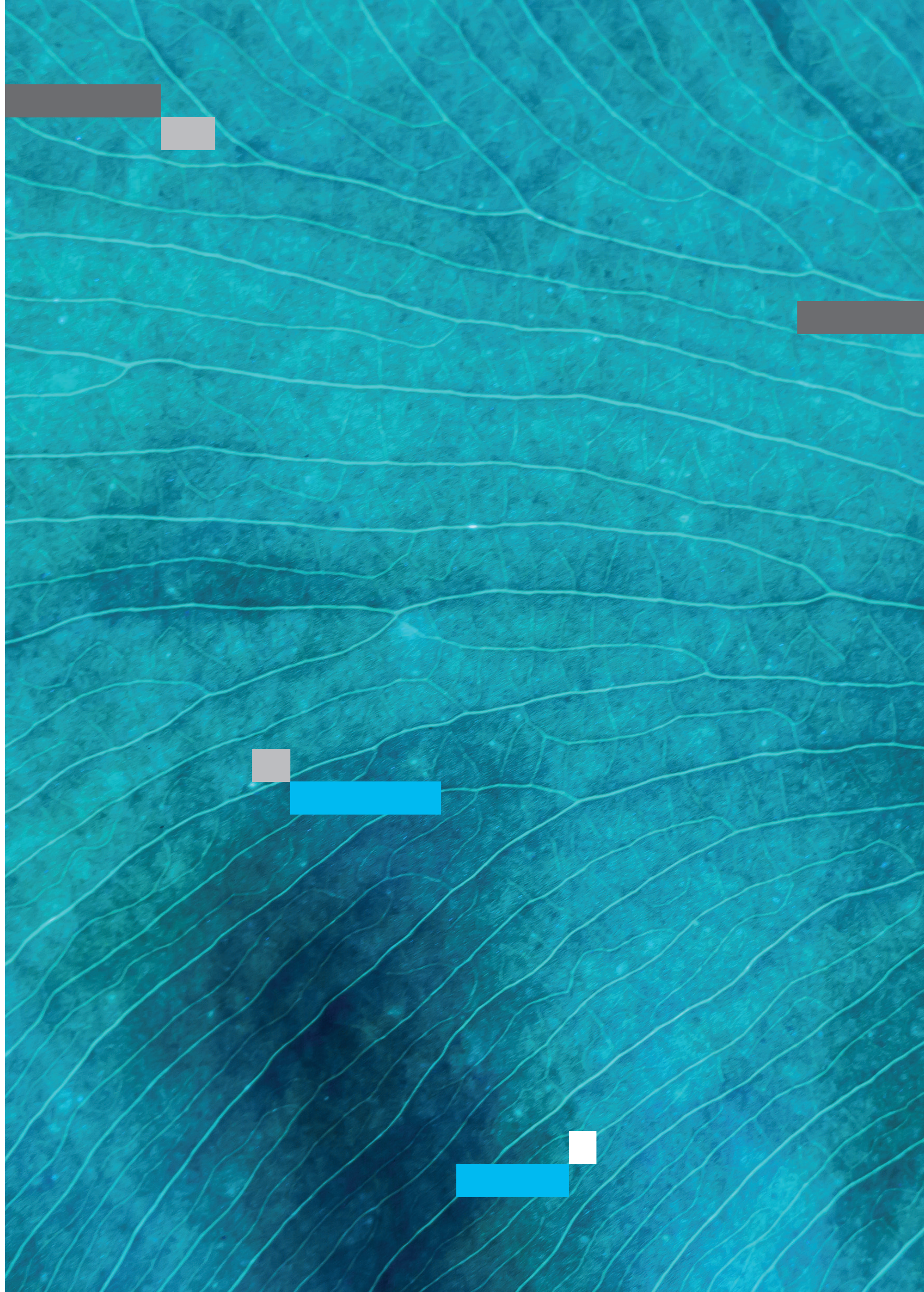

Humanity is facing significant challenges in achieving climate neutrality, circularity, healthy food systems, and sustainability while transitioning to renewable energy sources.

Although there is still little public awareness, Advanced Materials are considered a Key Enabling Technology to support this transition and are also essential for achieving Europe's technological sovereignty.

Among these, Bioplastics can truly represent a turning point in the transition to a world of circular economy, since biodegradable ones in particular allow innovative uses and technological advances in potentially every field, with consumer goods, mobility and the food industry being the most interesting ones.

This report investigates all different types of bioplastics, their characteristics, advantages and disadvantages of their adoption and what's new in the research field.

Enjoy the reading.

Intesa Sanpaolo Innovation Center

Preface

This editorial initiative highlights the positive impact that advanced materials have on sustainable development, playing a crucial role in protecting the environment and reducing waste. It emphasizes the importance of European policies, technological innovation, and collaboration in achieving these goals.

The work is structured as follows: first, it provides an overview of the European strategy and its focus on sustainable and advanced materials as a catalyst for innovation and competitiveness. The next section delves into sustainable materials and their innovative platforms through a circularity approach. Then this work focuses on the advantages and characteristics of bioplastics, one type of advanced and sustainable material, in supporting the transition towards a green economy.

In conclusion, it features case studies and offers insight into the future regarding the significance of bioplastic applications. This publication underscores the pivotal role of advanced materials in attaining sustainable development objectives and stresses the importance of sustained investment and cooperation in this field.

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Innovative and sustainable materials

1.1 Introduction

Humanity is facing significant challenges in achieving climate neutrality, circularity, healthy food systems, and sustainability while transitioning to renewable energy sources. The European Commission's launch of the Green Deal and Digital strategy addresses these challenges at a political level, leading to significant changes in materials development and use.

Advanced materials, which are engineered to exhibit novel or outstanding properties, play a critical and enabling role in the green and digital transition

Sustainable advanced materials drive innovation, creating new opportunities in multiple sectors. Scientific evidence indicates that action on climate change requires a systemic approach interconnecting research, industry, institutions, and society, and advanced materials can deliver solutions. However, despite Europe's status as a global leader in this field, there is no common framework for stakeholders to work together.

Initiatives, platforms, research, and industry organizations operate in silos, preventing collaboration and inhibiting progress towards more sustainable materials-based technologies and products. To address this lack of collaboration, the Advanced Materials Initiative 2030 (AMI2030) has introduced a common **framework called the 'Materials Commons'**. This framework aims to create a platform that fosters collaboration between all stakeholders involved in the development, production, and use of advanced materials, including researchers, developers, manufacturers, up takers, and end-users. By doing so, the initiative aims to promote the creation of sustainable materials-based technologies and products that serve the interests of both people and the planet, while also offering the potential for societal and economic growth.

The **Materials 2030 Manifesto**, published in February 2022, emphasizes the need for a systemic approach to developing the next generation of advanced materials that are solution-oriented, scalable, and efficient in responding to challenges, meeting the demand for high-performance sustainable products and services that benefit society, the economy, and the environment today and in the future. The Manifesto recognizes that both "blue sky" and applied research play an integral part in this approach. The vision of the Materials 2030 Manifesto is to enable the EU's twin green and digital transition, anchored in proper design principles combined with synergies between advanced materials, circularity, digital, and industrial technologies.

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1.2 The European strategy

The European strategy on advanced materials aims to foster the development of sustainable materials, and to promote their use in a range of sectors, including energy, transport, construction, and healthcare. The strategy also aims to address challenges related to the availability and sustainability of critical raw materials, and to promote resource efficiency and circularity throughout the materials value chain.

To achieve these goals, the European Commission has established several programs, which brings together stakeholders from across the materials value chain to promote innovation and sustainability. The strategy not only seeks to maintain Europe's strong position in advanced materials but also tackles challenges related to the availability and sustainability of critical raw materials, promoting resource efficiency and circularity across the entire materials value chain.

The inclusion of critical raw materials on the political agenda has received positive reception. These materials, play a vital role in driving the green and digital transitions by enabling the deployment of essential technologies as crucial components in various applications. For instance, rare earths are indispensable to produce permanent magnets used in wind turbines, while lithium and cobalt are essential in the manufacturing of batteries. Additionally, polysilicon is a critical ingredient in the production of semiconductors.

Acknowledging the crucial role of these materials, on March 16th, 2023, the European Union (EU) introduced the **Critical Raw Materials Act** as part of its efforts to secure resources crucial for technologies like renewable energy and battery power.

European Critical Raw Materials Act

The act aims to enhance the EU's self-sufficiency in mining, processing, and recycling a specified list of 34 critical metals and minerals, safeguarding the region from the impact of growing international competition for these resources. By 2030, the act calls for an increase in domestic production and a reduction in the reliance on third countries as sources of critical minerals. However, meeting the targets outlined in the act poses challenges for the EU, and its implementation may not significantly enhance supply-chain resilience in the region.

The legislation mandates that a minimum of 10% of the EU's annual consumption of strategic minerals must come from domestic sources

Additionally, 40% of processed strategic materials and 15% of recycled strategic materials should be domestically produced. The EU also aims to diversify its global supply of minerals, ensuring that no more than 65% of its annual consumption of each strategic raw material, at any stage of processing, is dependent on a single third country. To facilitate exploration of geological resources, EU member states are expected to develop national programs. Projects categorized as "strategic" will receive benefits such as access to financing opportunities and expedited permit approval timelines, with a two-year wait for mining projects and one year for processing and recycling projects. The EU also seeks to strengthen its negotiating position by forming partnerships or "Critical Raw Materials Clubs" with countries that maintain positive relations, such as Canada and Australia.

Moreover, the European strategy for advanced materials development and sustainability has been reinforced by two key documents: the **Materials 2030 Manifesto** and the **Materials 2030 Roadmap**. These initiatives serve as guiding frameworks for research and innovation, with a focus on discovering new materials and processes that can effectively address the challenges associated with transitioning to a sustainable, low-carbon economy.

The Manifesto serves as a comprehensive framework that not only identifies the Research and Innovation (R&I) areas crucial for achieving the European green deal and climate neutrality by 2050 but also emphasizes the importance of responsible development practices for these materials.

Materials 2030 Manifesto

Consequently, a transformation is necessary for the future of European R&I in advanced materials. This transformation emphasizes enhanced circularity and responsible practices as integral components of sustainable and safe advanced materials development. Furthermore, the integration of digital technologies such as artificial intelligence, robotization, high throughput analytics, and modelling will play a pivotal role in expediting the development process. The Manifesto marks the initial step in raising awareness and catalysing the expansion of funding capacities dedicated to advanced materials. It aims to align funding agendas and priorities across the EU, different Member States, and industry, fostering collective progress.

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Additionally, it seeks to establish a robust network of capacities and competences for advanced materials development within the EU and has promoted a strategic R&I Materials Roadmap with key priorities. This document begins with an assessment of the current materials landscape, evaluating the properties, applications, limitations, and areas for improvement of existing materials. Identifying key challenges is a crucial step in the roadmap. It highlights the major obstacles and gaps in materials science that need to be addressed.

Materials 2030 Roadmap

These challenges could involve developing materials with specific properties, improving manufacturing techniques, or discovering new materials altogether. To prioritize research efforts, the roadmap sets specific goals and research priorities. Collaboration and partnerships play a vital role in the roadmap. It emphasizes the importance of fostering collaboration among academia, industry, and government agencies. This document outlines strategies for building partnerships, sharing resources, promoting interdisciplinary research and considers the funding and resource allocation necessary to implement the outlined priorities.

A timeline and monitoring mechanism are integrated into the document to track progress and ensure accountability with regular assessments and evaluations to adapt the roadmap to emerging technologies and scientific advancements. Overall, the Materials Roadmap serves as a strategic tool to guide the materials community towards technological advancements, innovation, and the development of new materials with desired properties, fostering collaboration, research efforts, and driving progress in materials science and engineering.

In conclusion, the European Commission is actively driving the advancement of sustainable materials through the establishment of standards and regulations across different sectors.

One notable example is the implementation of regulations and the policy framework promoted by the European Commission to **encourage the adoption of bioplastics** in specific applications, as well as restrictions on the usage of hazardous chemicals in products and manufacturing processes. This policy framework aligns with the European Green Deal, Circular Economy Action Plan, and Plastics Strategy, aiming to contribute to the establishment of a sustainable plastics economy. A key objective is to enhance the understanding of bioplastics and their potential environmental benefits.

The framework provides clarity on the conditions and applications where these innovative materials can deliver positive environmental outcomes while adhering to stringent standards similar to other materials. At present, there is no specific EU legislation dedicated solely to bioplastics. However, certain existing legislations, including the EU Taxonomy, the Single Use Plastics Directive, the Plastic Carrier Bags Directive, the Packaging and Packaging Waste Directive, and the Waste Framework Directive, address certain aspects and applications of bio-based, biodegradable, and compostable plastics. Although the Commission's Communication for the EU policy framework is non-legislative and not legally binding, it represents the Commission's perspectives and intentions regarding these materials. It will serve as a guiding document for future EU policy-making endeavors, such as initiatives related to green claims, ecodesign for sustainable products, carbon removal, and microplastics. These measures are designed to foster a European economy that is simultaneously sustainable and competitive, while also contributing significantly to global initiatives aimed at addressing climate change and promoting sustainable development.

Relevant EU policies, regulatory frameworks and standards for bioplastics

European to-level strategies supporting bioplastics	EU Plastics Strategy (2018)
	EU Bioeconomy Strategy (2018)
	EU Green Deal (2019)
	New EU Circular Economy Action Plan (2020)
	EU Taxonomy (2020) & Climate Law (2021)
	Packaging & Packaging Waste Regulation (PPWR) (review 2022)
	Waste Framework Directive (review 2023)
Other important policy initiatives	Single-Use Plastics Directive (2019) incl. restriction on oxo-degradable plastics
	Sustainable Carbon Cycles (2021)
	EU rules on recycled plastics for food-contact materials (2022)
	Substantiating claims on environmental performance (2022)
	Sustainable Products Initiative (2022) /Proposal on ecodesign for sustainable products Regulation
	Policy Framework for bio-based, biodegradable and compostable plastics (2022)

1.3 Sustainable development goals

In the "Earth Summit" held in Rio De Janeiro in 1992, the international community became aware, in all its evidence, of the fact that sustainable development is a shared responsibility, to which governments, industrial and organizations can no longer pull back.

Sustainable development cannot be achieved only through the action of public authorities, but through the resources and capabilities of the research world and the business sector. By leveraging their resources and capabilities, businesses can drive innovation, implement sustainable practices, and develop solutions that address environmental and social challenges.

Embracing sustainable practices not only helps businesses mitigate risks associated with resource scarcity and regulatory compliance but also opens up avenues for growth and market differentiation. With an increasing sense of urgency to optimize resource utilization, there has been a growing recognition of the need to transition **from linear**, wasteful models **to circular** systems that promote resource efficiency and minimize waste.

Researchers and innovators have been actively exploring "disruptive" technologies and approaches to enhance the environmental sustainability of industrial systems and processes. This ongoing pursuit of knowledge and breakthroughs has yielded significant progress in integrating circularity principles into various sectors.

However, to achieve widespread transformative impact, it is crucial to go beyond isolated efforts and embed innovation as a regular practice in daily lives. This means fostering a culture of continuous improvement and embracing sustainable practices across industries, businesses, and households.

Central to this paradigm, The United Nations' "Sustainable Development Goals" (SDGs) Agenda, includes global and universal indicators for cross-border cooperation and for cooperation of civil society, governments, multilateral institutions, and the private sector, which are contributing to the increased attention given to the issue of sustainability.

The SDGs are a set of 17 goals and 169 targets adopted by the UN in 2015 as a blueprint for sustainable development, aiming to end poverty, protect the planet, and ensure prosperity for all.

Advanced materials can play a critical role in addressing some of the most pressing global challenges identified by the SDGs, including climate change, energy access, food security, water scarcity, and health (see table on next page).

To realize this potential, it is essential to prioritize sustainability in materials science and engineering research and development, promoting interdisciplinary collaboration, and engaging stakeholders throughout the materials lifecycle.

SDG	Advanced Materials Role
7: Affordable and Clean Energy	Photovoltaic cells, solar collectors, and energy storage devices can contribute to the transition towards a low-carbon economy and enable affordable and clean energy access, especially in remote and underdeveloped areas
9: Industry, Innovation, and Infrastructure	Essential for the development of new technologies and innovations that can improve industrial efficiency and productivity, reduce waste and emissions, and support sustainable infrastructure development
11: Sustainable Cities and Communities	AM can contribute to sustainable urban development by enabling the construction of energy-efficient buildings, smart and resilient infrastructure, and low-carbon transportation systems
12: Responsible Consumption and Production	AM can help to reduce the environmental impact of production and consumption by enabling the development of more efficient and sustainable products, recycling and waste management technologies, and eco-friendly packaging
13: Climate Action	Play a crucial role in mitigating and adapting to the impacts of climate change by enabling the development of renewable energy systems, energy-efficient technologies, and carbon capture and storage solutions
14: Life Below Water	Contribute to the protection and restoration of marine ecosystems by enabling the development of sustainable fishing gear, underwater monitoring devices, and biodegradable materials
15: Life on Land	Support the conservation and sustainable use of terrestrial ecosystems by enabling the development of eco-friendly agriculture and forestry practices, biodegradable materials, and sensors for environmental monitoring
17: Partnerships for the Goals	The development and deployment of advanced materials require collaboration and partnerships between academia, industry, government, and civil society. By promoting knowledge-sharing, capacity-building, and technology transfer, advanced materials can contribute to the achievement of all SDGs

#Advanced Materials as Key Enabling Technology

Advanced Materials are considered a Key Enabling Technology (KET) because they play a crucial role in many sectors such as health, energy, mobility, and housing, among others.

They are one of the six KETs prioritized by Europe for research and innovation support, along with advanced manufacturing, life-science technologies, micro/nano-electronics and photonics, artificial intelligence, and security and connectivity. **Advanced materials are essential for achieving technological sovereignty**, which is at the heart of recent political debate in the EU, and for creating advanced and sustainable economies.

Key enabling technologies for Europe's technological sovereignty

This topic is discussed in the document developed by European Commission "Strategic sectors and technologies value chains analysis and CRM demand". This report describes the critical raw materials grouped in nine strategic sectors (aerospace, defense, energy, electronics, health, mobility, information and communication technologies, sustainable construction materials, and water technologies) and it analyses their role in four key technologies: batteries, fuel cells, permanent magnets, and semiconductors.

For example, aluminum is used in 15 strategic sectors of the EU economy referred to renewables, e-mobility, energy industry, ICT, and aerospace & defense. On the other hand, cobalt, that is essential for EV batteries that are themselves crucial for the energy transition, is identified as a critical raw material to achieve climate neutrality. In 2050 the demand for cobalt is expected to increase up to 350%, mainly driven by the uptake of electric mobility. Currently the EU imports most of the refined cobalt needed for batteries from third countries such as China and countries like the Democratic Republic of the Congo (DRC) for raw materials. The Commission itself recognizes that to achieve strategic autonomy it will need to increase the amount of cobalt processing in the EU, as well as boosting the amount of cobalt coming from the recycling industry.

1.4 Advanced and sustainable materials

Advanced materials are enabling new technologies and applications, and changing the way we interact with the world around us.

For example, our Bronze Age ancestors experimented with alloys to improve base metals, which opened up new opportunities and design challenges and fueled further technical development. This curiosity about manipulating the properties of materials has been a driving force in human development for thousands of years. Indeed, advanced materials not only provide solution to different technical challenge, but at the nano level advanced materials exhibit new properties, which offer the possibility of new devices, applications, and technologies which can be applied in different application sectors.

The key feature of advanced materials is the transversality

The transversality of advanced materials can play a role in improving sustainability. Advanced materials are often developed with specific properties that enable them to be used in multiple applications across different fields. This versatility can lead to reduced waste and increased efficiency, which can in turn contribute to more sustainable practices. Advanced materials (e.g. polymers, metals and alloys, glass, ceramics, composites, etc.) can facilitate the transition to more sustainable technologies with improved characteristics and enhanced performance. This is strongly aligned with Europe's goals in the context of the European Green Deal and industrial strategy.

In recent years, material science and engineering have seen significant advances in the development of new materials, especially those that are sustainable and eco-friendly. With the increasing demand for products that have minimal impact on the environment, **it has become necessary to develop materials that can replace traditional ones**, which often have harmful effects on the planet.

The development of advanced and sustainable materials has pushed the boundaries of traditional materials and opened up new opportunities in various fields such as energy, medicine, aerospace, electronics, construction and agri-food. **Sustainable materials are typically produced from renewable resources, and/or designed to be recycled, reused or biodegraded at the end of their life cycle.**

These materials are at the heart of circular economy concept; by incorporating recycled content or bio-based materials, products can be **manufactured with reduced reliance on virgin resources**.

An example are the biocomposites, innovative materials that combine natural fibers derived from renewable resources with a bio-based polymer matrix. The natural fibers are sourced from fast-growing plants like hemp or flax, which are abundant and renewable. These plants require fewer resources and have a lower carbon footprint. Biocomposites are fully recyclable at the end of their product life cycle. The material can be mechanically or chemically recycled, depending on the desired properties for the subsequent application.

Main uses of biocomposites also in terms of market shares are:

- automotive interior components (thanks to their lightness and sound insulation properties) like door panels, dashboard trims, and seat backs
- single-use packaging materials
- casings for electronic devices like smartphones, tablets, or laptops (thanks to their excellent strength, impact resistance, and aesthetic appeal)
- sporting goods as rackets, helmets and surfing boards
- panels for the constructions (door panels, window frames, furniture…)

Advanced materials offer also enhanced durability, corrosion resistance, and fatigue performance, which contribute to **longer product lifecycles**.
An example are the corrosion-resistant alloys that are engineered to have specific properties that make them resistant to corrosion in harsh environments, such as marine or industrial settings. Its unique composition and surface treatment prevent the material from deteriorating due to exposure to moisture, chemicals, or corrosive gases. This corrosion resistance significantly extends the lifespan of products, reducing the need for frequent repairs or replacements.

These alloys can be mainly used in

- the construction of offshore platforms, where exposure to saltwater and harsh weather conditions can lead to accelerated corrosion
- in bridge construction for critical structural elements like beams, columns, and cables
- in industrial equipment, such as chemical processing vessels, pumps, or pipelines, where resistance to corrosion and fatigue are crucial.

Self-healing materials possesses the ability to autonomously repair minor damages and regain their original functionality

Some advanced materials enable **repairability and reusability**. An example are polymers with self-healing properties that possesses the ability to autonomously repair minor damages and regain their original functionality, reducing the need for costly repairs or replacement of the entire component. For example, polymers can incorporate microcapsules or vascular networks containing a healing agent within its matrix. When the material experiences small-scale damage, such as microcracks or scratches, these capsules rupture or the vascular network is breached, releasing the healing agent. The agent then reacts with a catalyst present in the material, initiating a chemical reaction that repairs the damage by filling the void and restoring the material's integrity. These polymers can be used in the manufacturing of electronic devices, can be incorporated into automotive parts (like bumpers, body panels, or interior trims), can be utilized in construction materials such as concrete or asphalt.

Advanced materials can also be engineered to be **more easily recyclable** or compatible with existing recycling technologies. This, in turn, reduces the demand for virgin materials and the energy-intensive processes associated with their extraction and production. Advanced materials also enable the development of **innovative recycling methods**. Technologies such as chemical recycling, which can break down complex materials into their constituent monomers or valuable chemical feedstocks, offer new avenues for material recovery. By utilizing advanced materials that are compatible with these recycling processes, the circularity of materials can be further enhanced.

The integration of advanced materials with **digital technologies** presents exciting opportunities for the circular economy. Through the use of sensors and data analytics, advanced materials can be monitored throughout their lifecycle, enabling **predictive maintenance**, optimizing performance, and facilitating material tracking and traceability. This integration enhances the efficiency of resource utilization, extends product lifecycles, and improves material recovery processes.

1.5 Technological trends on advanced circular materials

In recent years, the development of sustainable renewable and recyclable materials has gained significant attention as a promising solution to mitigate environmental impacts and promote a more sustainable future.

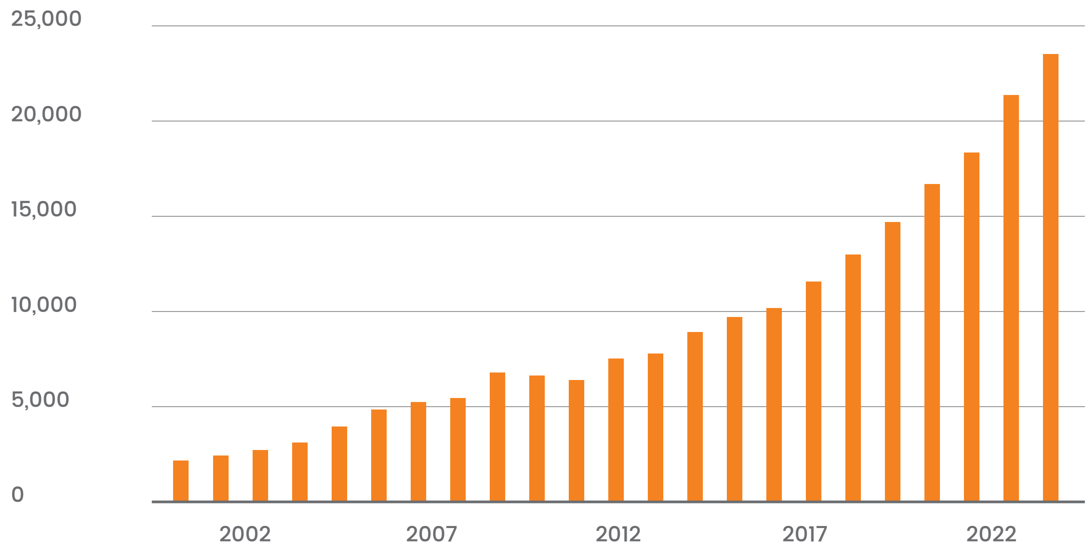
To investigate key advancements, challenges, and potential applications of such materials, showcasing their potential to revolutionize various industries, we applied a **bibliometric analysis** on Scopus database by examining publication patterns, citation networks, and keywords.

Our analysis was based on a total of 210,516 articles related to advanced renewable or recyclable materials from 2000 to 2022, retrieved from Scopus.

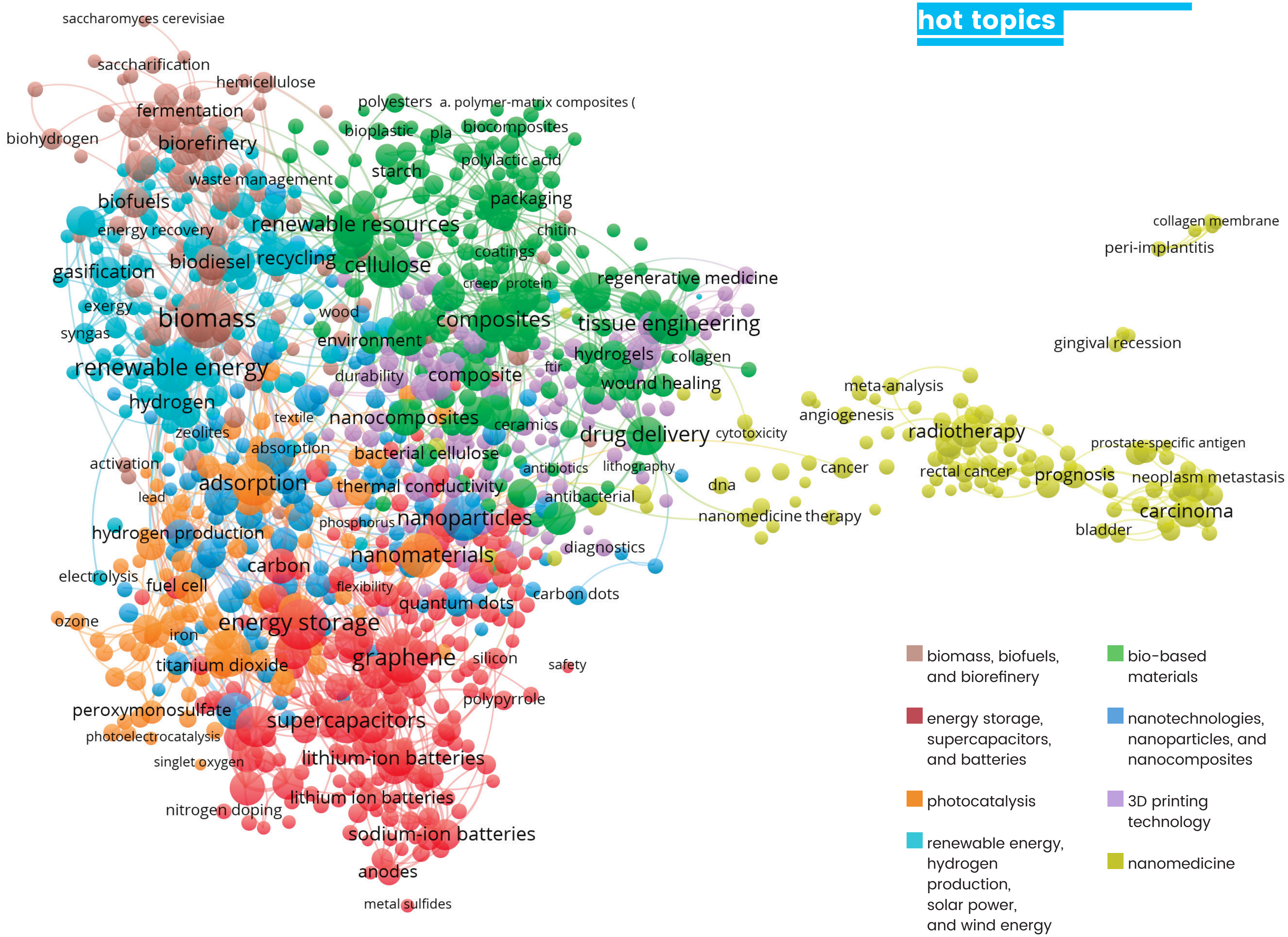
The annual global publications increased from 2,033 in 2000 to 23,453 in 2022, with an average annual growth rate of 10%. The main subject areas derived from the bibliographic analysis (i.e. Engineering, Material Science, Chemistry, Physics, Biology) correspond to the issue of research activities performed on this field. In fact, advanced materials are a multidisciplinary theme working at the crossroads of physics, chemistry, biology, engineering, and information technology. Collaboration and integration of knowledge from different fields are often required to develop new materials with enhanced properties for specific applications.

Annual global pubblications on advanced renewable and recyclable materials

Source: Processing by Materias on Scopus data



The co-occurrence cluster analysis of top keywords in advanced renewable and recyclable materials
Source: Processing by Materias on Scopus data



Using a co-occurrence analysis to identify hot topics

Co-occurrence of keywords analysis was performed to identify the main themes and investigate hotspots in literature. This kind of analysis uses the frequency of multiple words to identify how close they are, thereby demonstrating hot topics and trends in the discipline. In this study, the top high-frequency keywords appearing in the retrieved publications were analysed to explore the research hotspots of advanced renewable and recyclable materials.

In the following map, **larger circles indicate the higher frequency** in the co-occurrence analysis; the colour of each circle is determined by the cluster they belong to. Minor keywords are not displayed to avoid overlapping. The length of links between nodes represents the strength and the relevance of the connection between corresponding nodes. The closer two keywords are located to each other, the stronger their relatedness.

For example, the network analysis shows that the yellow cluster (related to nanomedicine) is separated from other clusters. This separation may be due to the fact that the keywords used in the nanomedicine do not co-occur frequently with keywords used in renewable energy, biomass, batteries, bio-based polymers etc.

The **brown** cluster encompasses technologies related to **biomass, biofuels, and biorefinery** processes. Researchers have made remarkable progress in developing advanced biofuels derived from a variety of biomass feedstocks, such as agricultural waste, dedicated energy crops, and algae. These biofuels, including cellulosic ethanol and biodiesel, hold promise as cleaner alternatives to conventional fossil fuels. Furthermore, biorefinery processes have gained attention for their ability to convert biomass into multiple valuable products, such as biofuels, biochemicals, and bioplastics, thereby maximizing resource utilization and reducing waste.

The **red** cluster focuses on technologies related to **energy storage, supercapacitors, and batteries**. With the growing need for efficient energy storage solutions, researchers have made significant strides in improving lithium-ion battery technology. This includes the development of high-capacity electrodes, solid-state electrolytes, and longer-lasting batteries. Furthermore, next-generation batteries, such as sodium-ion, magnesium-ion, and solid-state batteries, have emerged as potential alternatives with improved energy density and safety. Supercapacitors, known for their high-power energy storage capabilities and rapid charging characteristics, have also witnessed advancements.

The **orange** cluster revolves around the field of **photocatalysis**. Researchers are actively exploring the development of efficient photocatalysts that harness solar energy for various applications. One prominent area of focus is water splitting, which involves using photocatalysts to generate hydrogen fuel from water. This process holds significant promise for sustainable energy production. Additionally, photocatalysis is being applied to organic pollutant degradation and wastewater treatment, offering a potential solution for environmental remediation challenges.

The **blue sky** cluster encompasses technologies related to **renewable energy, hydrogen production, solar power, and wind energy**. As the world strives to transition to a low-carbon energy system, renewable energy sources have gained considerable traction. Solar power and wind energy, in particular, have experienced significant growth in deployment, driven by advancements in photovoltaic technologies and turbine efficiency. Additionally, researchers are actively working on improving hydrogen production methods using renewable energy sources, aiming to leverage hydrogen as a clean and versatile energy carrier.

The **green** cluster highlights advancements in the field of **bio-based materials**, with a particular focus on **cellulose** and **biopolymers**. Researchers have been exploring renewable feedstocks to develop biodegradable and biocompatible materials that can serve as sustainable alternatives to conventional plastics and materials derived from fossil fuels. Cellulose-based materials, including nanocellulose and cellulose nanofibrils, have gained attention for their exceptional mechanical properties and potential applications in various industries.

The **blue** cluster centers around **nanotechnologies, nanoparticles, and nanocomposites**. Nanotechnology offers tremendous opportunities for enhancing material properties and enabling novel applications. Researchers are actively developing nanomaterials with unique properties, such as nanoparticles and nanocomposites, for applications ranging from electronics to energy and medicine. Nanoparticles are being explored for targeted drug delivery, improved catalysis, and enhanced performance in solar cells. Nanocomposites, which combine nanomaterials with polymers or metals, are being investigated to create high-performance materials with a wide range of applications. Moreover, nanotechnology is being leveraged for water purification, environmental remediation, and energy storage, showcasing its potential for sustainable solutions.

The **purple** cluster highlights the advancements in **3D printing technology**. 3D printing, also known as additive manufacturing, has revolutionized manufacturing processes by enabling the creation of complex structures with high precision and customization. In recent years, the focus has shifted towards utilizing recyclable and sustainable materials in 3D printing. Researchers are exploring the use of biodegradable and bio-based materials as printing feedstocks, reducing the reliance on traditional plastics and contributing to a more sustainable manufacturing ecosystem. Large-scale 3D printers are being developed for construction applications, offering the potential for efficient and eco-friendly building practices. The integration of digital design tools and artificial intelligence further enhances the optimization and sustainability of 3D printing processes.

The **yellow** cluster encompasses the exciting field of **nanomedicine**, which combines nanotechnology with **medical applications**. Researchers are focusing on the development of nanoparticles and nanoscale delivery systems for targeted drug delivery, particularly in the field of cancer treatment. Nanoparticles can be engineered to specifically target cancer cells, improving the efficacy of therapies while minimizing side effects. Furthermore, nanotechnology is being employed in advanced imaging techniques, enabling precise diagnostics and monitoring of diseases. In radiotherapy, nanoparticles are utilized for targeted tumor treatments, enhancing the effectiveness of radiation therapy while reducing damage to healthy tissues. Nanomedicine holds great promise for personalized medicine, offering tailored treatments and improved patient outcomes.

This analysis, using cluster to identify scientific and technological trends and their relationships, can provide valuable insights to researchers, companies, decision-makers, science managers, and innovators. By examining clusters of co-occurrence keywords, this approach can reveal patterns and trends within the research literature, enabling the identification of active areas of research and potential collaboration opportunities.

This information can be valuable for innovators looking to stay up-to-date with the latest advancements or organizations seeking to invest in promising research areas. Moreover, cluster analysis can assist decision-makers and science managers in prioritizing research projects or technologies. By examining the clusters' characteristics, such as their size, growth rate, and connectivity, it is possible to optimize resource allocation, allowing organizations to focus their efforts on high-potential projects or technologies while avoiding less promising areas.

In summary, cluster analysis can save time and resources by providing a data-driven approach to decision-making and can be a powerful tool for identifying scientific and technological trends, understanding their relationships.

02/ Bioplastics

2.1 Bioplastic Materials

Bioplastics come from renewable sources and/or are biodegradable. Due to high costs and poor mechanical properties, bioplastics made up a small portion of plastics production until a few decades ago. To overcome these limitations, several companies and laboratories are researching ways to make bioplastics manufacturing more efficient and cheaper.

Nearly every conventional plastic material and corresponding application has a bioplastic alternative today. A bioplastic has the same properties as conventional fossil-based plastics and, in some cases, offers even greater benefits. Reducing carbon footprints and composting are two options to achieve this goal.

In the evolution of plastics, bioplastics play an important role and contribute to a more sustainable society. Since fossil-based plastic was introduced, there has been a revolution in everyday life all over the globe; today, we cannot imagine living without it; in fact, any other material that performs like plastic is unimaginable. As one of the most important qualities of plastics, it is a durable material; however, it is very hard to decompose, so it is usually not biodegradable. Several nations throughout the world started World Environment Day on 2018 by emphasizing the need to "Beat Plastic Pollution" to create public awareness of the problem of overusing fossil-based plastics.

Overview of relevant EU legislation for bioplastics

Bioplastics have the potential to play a crucial role in developing a truly circular bioeconomy, enabling innovation, and attracting new investments as a result of several policy processes, many of which are related to the European Green Deal. As part of a circular economy, it is important that legislation acknowledges the significant role bioplastics play within a circular economy so that we can contribute to the ambitious climate goals of the European Union. Several policies, regulatory frameworks, and standards have been introduced or adapted by the European Union in recent years to strengthen and implement the bioeconomy and circular economy in Europe, all of which have an impact on bioplastics.

2.1.1 Bioplastics History

As history has shown, bioplastics from bio-based materials have been used since ancient times. It has been observed that the **Egyptians** were already empirically producing sticking agents in 15th century BC by using gelatin or albumin, both of which are proteins derived from renewable resources (animal and vegetable). Natural rubber was already being used by **Mesoamericans** for making religious statuettes, extracted from the rubber tree. During the **Middle Ages**, certain lantern parts were produced by treating bovine horns with a strong base.

As the use of renewable resources for the production of plastic materials has been going on for centuries, Charles Goodyear's discoveries will mark the turning point in polymeric materials chemistry. By accident, this American chemist invented in 1839 the process of vulcanization, which cross-links liquid natural rubber to create a solid and stable plastic material called **Caoutchouc**. With this invention, it becomes possible to manufacture materials that are stable over time, functional, and have improved properties.

A man-made plastic was first manufactured by treating cellulose with nitric acid and a solvent in 1862. It was discovered by Alexander Parkes and named **Parkesine**. Parkes formed the Parkesine Company in 1866 to mass produce the material.
The synthetic substitute for ivory was developed by John Wesley Hyatt by combining nitrocellulose and camphor with alcohol. In 1869, this modified and stabilized cellulose was marketed under the name **Celluloid**, marking the first industrial production of plastics.

Viscose, another polymeric material still used in the textile industry today, is also derived from cellulose, alongside celluloid. Developed by Hilaire de Chardonnet in 1884, this material was intended to replace natural silk at a lower cost. The popularity of viscose boomed during World War II, and it is still widely used today. As a result of the production of viscose, Tongass National Forest in Alaska was deforested and heavy metals, dioxins, and polychlorinated biphenyls were released into the environment.

Alfred Trillat, a self-taught French chemist, discovered that formaldehyde hardens albuminoids and makes them insoluble in 1893. As a result of the reaction between formaldehyde and casein, a protein obtained from milk, **Galalith** transformed the world of button manufacturing.

Bakelite was the first fossil-based plastic to be mass produced

Before there was a well-defined word for these plastics, chemists and industrialists had already synthesized bioplastics, i.e., plastics derived from renewable vegetable (or animal) materials. We owe the transition from bioplastics obtained from renewable sources to plastics to a more industrial and controlled era to a Belgian chemist, Leo Baekeland. Baekeland invented **Bakelite** in 1907 by combining phenols and formaldehyde to create a moldable plastic that can be controlled in pressure and temperature in a press. During the post-World War II economic recovery, petroleum-based plastics experienced a boom.

Jacques Edwin Brandenberger invented **Cellophane** in 1908, a transparent material made with wood, cotton, or hemp cellulose. In addition to being a trademark, cellophane is a generic term.

Maurice Lemoigne, a French scientist, discovered **polyhydroxybutyrate (PHB)** in 1926, considered **the first known bioplastic made from bacteria**. Since petroleum was abundant and cheap at the time, his discovery was neglected for several decades and the pollution was not yet considered a problem.

The **principle of biodegradable** plastics was discovered in 1975 when Japanese scientists discovered a bacterium that could break down nylon (Flavobacterium). As a result of a joint venture between Imperial Chemical Industries (UK) and Marlborough Teeside Management (a venture capital firm), the first bioplastics company, Marlborough Biopolymers, was formed, in 1983. Known as **Biopol**, their bioplastics were made by bacteria. The bacteria-based Biopol could be processed into strips, filaments, chips, panels and powders.
In 1990, the Italian company Novamont was founded. In terms of bioplastic production, they are the market leader. One of the company's flagship products is **Mater-Bi**, which is a biodegradable and compostable bioplastic.

Novamont Mater-Bi

In 1996, Monsanto acquires the Biopol business from Zeneca. Plants are used instead of bacteria and microbes to produce bioplastics.

Dow Chemicals and Cargill established a joint venture in 1997 to produce bioplastics from corn. The joint venture starts producing PLA in 2001. The company was rebranded NatureWorks in 2005 and became the global leader in the production of **polylactic acid (PLA)**.

The first bioplastics company based on seawood is founded by Rémy Lucas in 2010. Seaweed plantations do not require pesticides, fertilizers, or land, which is a big step forward. In addition to being rigid, durable, and compostable, the bioplastic also becomes a natural fertilizer at the end of its life cycle. Seaweed bioplastics degrade in soil within 12 weeks and in water within 5 hours.

#video
How to make Algae Seaweed Bioplastic

Nowadays, companies and laboratories of all sizes keep researching the field. Many of them are already producing biodegradable and compostable alternatives to petroleum-based plastics. Consumers and even companies prefer to purchase safer and more environmentally friendly products as the public environmental conscience is increasing.

02 / Bioplastics

Timeline in bioplastic discovery and product development
Source: data elaborated by Materias

2010 ALGOPACK
Rémy Lycas

2005 NATUREWORKS
become leader in PLA production

1996 MONSANTO
starts using plants to produce bioplastics

1990 NOVAMONT
was founded in Italy

1983 MARLBOROUGH BIOPOLYMERS
the first bioplastics company was founded

1975 PRINCIPLE OF BIODEGRADATION
was discovered by japanese scientists

1970 PETROLEUM CRISIS

1930 SOYABEAN CAR
Ford

1926 PHB
Lemoigne

1908 CELLOPHANE
Brandenberger

1907 BAKÉLITE
Beakeland

1893 GALALITH
Trillat

1884 VISCOSE
de Chardonnet

1869 CELLULOID
Hyatt

1862 PARKESINE
Parkes

1839 CAOUTCHOUC
Goodyear

2.2 What are bioplastics?

Currently, bioplastics are being promoted as a sustainable alternative to fossil-based plastics that can often take hundreds of years before they begin to decompose, with a tendency to be more environmentally friendly.

The term "bioplastic" refers to a plastic material that is either bio-based, biodegradable, or features both properties

Bio-based: materials derived from a biological source (e.g. biomass) rather than from fossil sources (such as coal or oil). By combining renewable energy sources with these natural materials, we can further reduce our carbon footprint, since these materials come from a renewable source, such as plants, cornstarch, sugarcane, potato starch, and other natural sources.

Biodegradable: materials that can be broken down into water, carbon dioxide, and biomass by microbial action naturally occurring in the environment. Biodegradation is a biochemical process in which microorganisms, such as bacteria and fungi, commonly present in certain environments, digest macromolecules through enzymatic processes. The rate of biodegradation depends on several factors, including the surrounding environment (e.g., temperature, inoculum, humidity) and the material itself.

Biodegradability is determined only by the chemical structure of a bioplastic, and not by its underlying resource. It is important to note that some fully bio-based plastics are not biodegradable and those made of fossil fuels can biodegrade when certain environmental conditions are met.

The term **compostability** is sometimes used interchangeably with biodegradability, but there is a huge difference between these two concepts. Those materials that biodegrade within a timeframe and conditions defined by European standards for industrial composting, EN 13432, can be certified and labeled as industrially compostable.

Main differences between biodegradable and non-biodegradable plastics

Biodegradable		Non-Biodegradable	
Biodegradable	Decompose in the environment naturally, helping reduce plastic pollution.	**Non-biodegradable**	Unless properly disposed of, remain in the environment for a long time, contributing to plastic pollution.
Versatile	Used for a variety of applications, such as packaging, consumer goods, and even medical equipment.	**Durable**	Supposed to be more durable than biodegradable bioplastics, allowing them to withstand harsh environments and everyday use.
Limited shelf-life	Limited shelf-life because moisture and heat may break them down.	**Recyclable**	Some non-biodegradable bioplastics can be recycled, reducing plastic waste.

Main differences between biodegradability and compostability

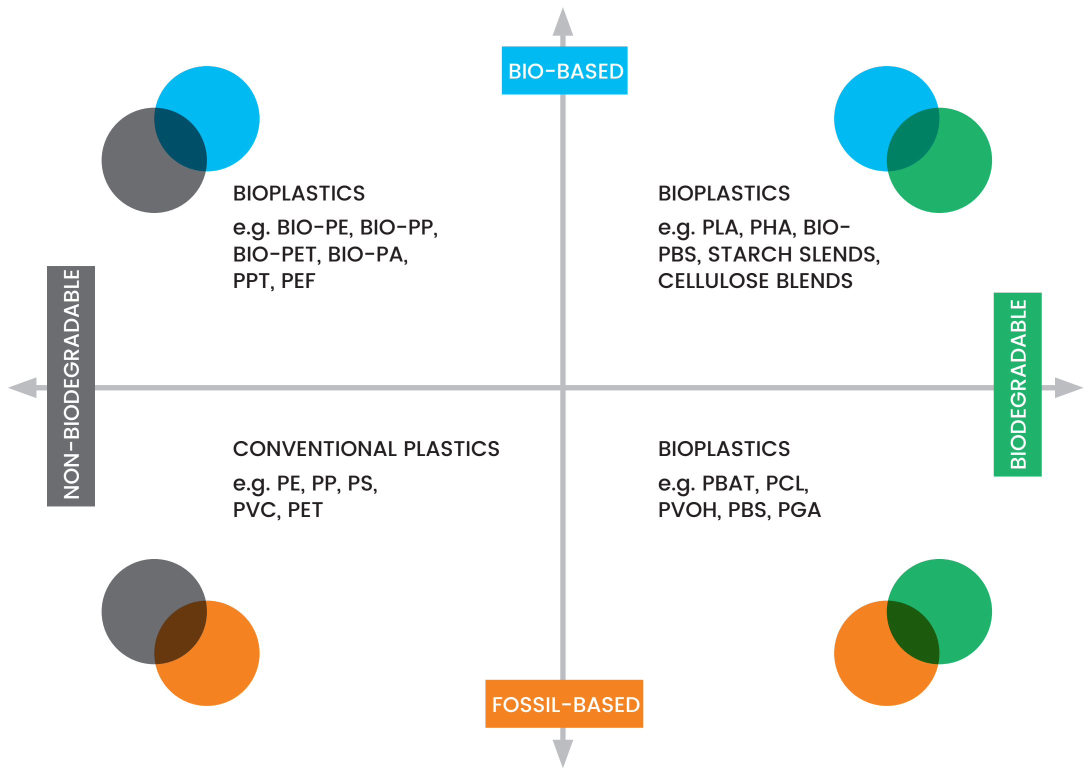
Biodegradable	Compostable
Breaks down into smaller compounds with the help of biological organisms, such as fungi and bacteria. In aerobic conditions, biodegradable products will break down to produce carbon dioxide, water and biomass. In anaerobic conditions, they produce carbon dioxide, methane, water and biomass	Breaks down into smaller compounds with the help of biological organisms, but it does so in specific conditions to a defined outcome. In general, a compostable product breaks down in a specific timeframe in a controlled moist, warm, aerobic environment to produce compost that is no toxic and can enhance soil and support plant life

2.2.1 Types of bioplastics and their characteristics

The family of bioplastics can be divided into three main groups according to their biodegradability and/or bio-based content.

Bio-based & non-biodegradable bioplastics
Since it is possible to make traditional plastics like polyetheylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) from renewable resources as well, such as sugarcane or plant oil waste, this group include bio-based PE (Bio-PE), bio-based PP (Bio-PP), bio-based PET (Bio-PET) and technical performance polymers, such as numerous bio-based polyamides (Bio-PA), bio-based polyurethanes (PUR), polytrimethylene terephthalate (PTT) or totally new polymers, such as polyethylene furanoate (PEF).

Material coordinate system of bioplastics



Some of these polymers, such as Bio-PA, PTT, PUR or some bio-based polyepoxides have some typical technical applications such as textile fibers (seat covers, carpets), automotive foams for seating, casings, cables, hoses, and covers. For these applications the property of biodegradability is not sought after in durable bioplastics. Compared to conventional options, they often perform better.

The market will soon be introduced to a new fully bio-based polyester, PEF. It shows good barrier mechanical and thermal properties making it suitable for packaging. Having a lower melting point and a higher glass transition temperature, PEF is recyclable, reducing its carbon footprint. Furthermore, PEF is cost-competitive on an industrial scale and will replace PET containers.

Bio-based & biodegradable bioplastics
This group includes starch blends made of thermoplastic starch (TPS), cellulose blends and other biodegradable polymers as well as innovative polyesters, such as PLA, bio-based polybutylene succinate (Bio-PBS) and polyhydroxyalkanoates (PHAs).

These materials are now receiving a lot of attention and technical development due to their renewable content. As a result of this dynamic development, bioplastics have a great deal of potential to shape the plastics industry and to lead to the development of new innovative and competitive materials since the technology, equipment, and machinery are the same as conventional plastics.

The majority of their applications are for short-lived products, such as packaging, but they have been used for long-term applications as well. It is most likely that some of these materials will biodegrade in composting conditions, but some will also degrade in less controlled environments.

Biodegradable & fossil-based bioplastics
This group includes polybutylene adipate terephthalate (PBAT), PBS, poly caprolactone (PCL), polyglycolic acid (PGA), polyvinyl alcohol (PVOH) and polyethylene vinyl alcohol (EVOH) that may well be produced at least partly from bio-based feedstock.
This group of plastics is relatively small, and they are often used in combination with PLA or other biodegradable plastics to enhance application-specific performance. Rather than the origin of the raw materials, polymer degradation studies suggest that chain characteristics such as hydrophilicity, reactivity, functional group stability, and mechanical properties such as molecular weight and elasticity determine biodegradability. In reality, these biodegradable plastics are still mainly manufactured using fossil fuels. A partially biodegradable version of these materials has already been developed and will soon be available.

What are bioplastics?

Following table shows the main bioplastics, their fields of application, properties, main manufacturers and cost to 2022 (USD/kg).

Commercial applications of bio-based polymers and their properties (2022 data)

BIOPLASTICS	APPLICATIONS	PROPERTIES	MANUFACTURER	COST USD/kg
PLA	Bottles, cups, transparent films, containers, dishes, fruit nets, top-covering films, trays, tea bags, ice cream cups, carrier bags.	Approved for direct contact, transparent, sealable, durable, barrier for water and oxygen.	Nature Works(USA) Biofoam (Netherlands) Ingeo (USA) Hisun (China) Biofront(Japan)	4.0-6.0
Starch	Translucent film, net packaging, bags, containers, egg boxes, sandwich bags, capsules, carrier bags, drinking straws, drug-release films.	Sealable, durable, fine finishing, barrier for water.	Novamont (Italy) Livan (Canada) Ever Corn (Japan) Plastra rch (USA)	0.5-2.0
PBAT	Compostable organic waste bags, agricultural mulch films, packaging (wrapping) films, disposable tableware.	Excellent toughness, improved wear and fracture resistance, good chemical resistance to water and oils, high strain at break.	BASF (Germany) Bio-Fed (Germany) Jinhui Zhaolong (China) Eastman (USA)	3.8-5.8
PHA	Disposable cups, plates and cultery, Tetra Pak covers, tubes to produce vegetable seedlings, agrochemical packaging, textile fibers, electronic equipment components.	Physical properties like conventional plastics, insoluble in water, no toxic and biocompatible, present piezoelectric properties, some PHA films exhibit gas-barrier properties.	Minerv (Italy) Biogreen (Japan) Biocycle (Brazil) Breen Bio (China)	2.4-5.5
Cellulose	Packaging films, films, transparent films, barrier films, cups for cold drinks, plates and dishes, cups for hot drinks, labels.	Sealable, barrier for water, transparent, approved for direct food contact.	Natural flrx (UK) Tenite (USA) Biograde (Germany) Sateri (China)	1.8-4.0
PBS	Biopackaging, tissue-engineering, and medical materials, agricultural mulch film, plant pots, hygiene products.	High processability, good mechanical properties, thermal properties.	PTT MCC Biochem (Thailand) Anhui Sealong (China) Biotechnology Co., Ltd. (China) Vizag Chemicals (India)	4.0-10.0
PCL	Drug delivery systems and tissue-engineering scaffolds.	High toughness and flexibility, biocompatibility and slow degradation in vivo conditions.	Perstop Holding AB (Sweden) BASF (Germany) Diacel Corporation (Japan) Merck (Germany)	4.5-10.0
Bio-PE	Food packaging, cosmetics, personal care, automotive and toy applications.	Equal in its chemical, physical and mechanical properties to fossil-based PE.	Dow (USA) LyondellBasell (Netherlands) Exxon Mobile Corporation (USA)	2.3

2.2.2 Bioplastic feedstock 1st, 2nd and 3rd generations

It is common for such plastics to be made from renewable, bio-based feedstocks and retain the beneficial material properties of petrochemical plastics, while reducing fossil resource extraction and reducing end-of-life burdens as a result of their compostable nature, allowing for a transition towards a circular economy. It may also be possible to reduce the global carbon footprint of plastics through this displacement of petrochemical plastics with bioplastics.

First generation feedstock

First generation feedstocks include **crops** and **plants** that are used to produce bioplastics. They are carbohydrate-rich and can be consumed by humans and animals. The first generation of feedstock is the most efficient when it comes to producing bioplastics, since it requires less land to grow and has a higher yield and "efficiency" than subsequent generations.

The relationship between crops and bioplastics was measured using two indices: the annual carbohydrate yield per hectare and the acreage used per ton of bioplastics. It is possible that future crop efficiency will be improved by R&D and new production processes.

There are many types of first generation feedstocks, including **corn**, **wheat**, **sugarcane**, **potato**, **sugarbeet**, **rice** and **plant oil**.

First-generation feedstock has been criticized for its potential **to compete with food and animal feed**. In other words, they take food that will be consumed by humans or animals. Bio-fuels were criticized more than bioplastics, but there seems to be an assumptive link between the two. Nevertheless, the evolution of the biofuel sector inspired and drove the segmentation of feedstock into the first, second, and third generations in the bioplastics sector. This polemic was resolved by the second generation feedstock.

Second generation feedstock

The term "second generation feedstock" refers to crops and plants that are not suitable for human consumption (food) or animal consumption (feed). In addition to **non-food crops** (cellulosic feedstock), second generation feedstocks can also be **waste materials** from the first generation of feedstocks (e.g. waste vegetable oil).

Second-generation feedstocks include **wood**, **short-rotation crops** like poplar, **willow**, and **miscanthus** (elephant grass), **wheat straw**, **bagasse**, **corncobs**, **palm fruit bunches**, and **switch grass**.

If non-food crops are grown on land intended for food production, the "Food vs Fuel" polemic continues. If they're residues from the first generation feedstock, agricultural waste or residues won't directly conflict with food. There is a possibility that straw could eventually be used as animal feed and as a component of the food chain.

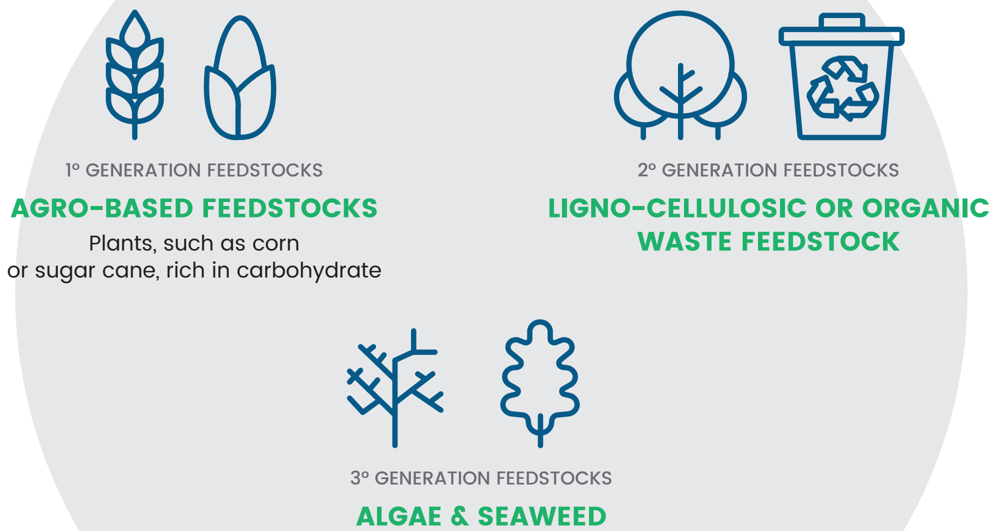
Third generation feedstock

Third-generation feedstocks are **algae-derived biomasses**. Seaweed differs from algae in the following ways:

- As algae contain chlorophyll, they are commonly found in aquatic environments such as marine bodies, seas, and even freshwater bodies, whereas seaweed is a plant-like organism that attaches itself to rocks and other hard surfaces
- Algae can be unicellular and multi-cellular, whereas seaweeds are only multi-cellular
- Algae usually rely on external sources of food, while seaweed is an autotroph
- There are algae in both freshwater and marine waters, whereas there are only seaweeds in seawater
- It is possible for marine algae to live in shallow and deep waters, while seaweeds are mostly found in shallow waters

In comparison to 1st and 2nd generation feedstock, algae have a higher yield or efficiency. There is no need for fertilisers, pesticides, herbicides, or land to grow them. The biodegradability of seaweed bioplastics is 12 weeks in soil and 5 hours in water. The bioplastics industry may be disrupted by algae bioplastics. Compared to traditional plastics, algae bioplastics are more expensive.

Bioplastic feedstock 1st, 2nd and 3rd generations
Source: Materias



2.2.3 Bioplastic market & application

Overall, Frost & Sullivan estimates that the global bioplastic market was valued at $19.7b in 2022 will grow at a CAGR of 10.3% to reach $35.4b in 2028.
This equates to 3,853 thousand tons (kT) in 2022.

Expansion is being driven by mandatory Life Cycle Assessments which propel demand whilst restricting the opportunity for conventional solutions.

However, the cost of bio-based monomers for bioplastics remains quite prohibitive and materially higher than that of their petrol-based equivalents.

Price remains a barrier to adoption, especially in markets where cost is a significant competitive differentiator. Most drop-in bioplastics are more expensive than their fossil fuel-based counterparts which restrains their penetration across applications.

Large-scale manufacturing has the potential to reduce costs but requires investments in monomer and polymer production capacities as well as time to build the corresponding infrastructure. New facilities across the supply chain are under construction but the share of bioplastics as a percentage of total plastic production is still minimal globally.

Even if fossil fuel prices stay high, the costs for shifting to bioplastics must be amortized by the benefits of using it. Against this background, the price of bioplastics, whether they are entirely bio-based or biodegradable or drop-in alternatives to non-biodegradable polymers, is expected to stay higher than petroleum-based alternatives in the foreseeable future.

Bioplastic: Growth Metrics, Global, 2022-2028
Source: Frost & Sullivan

Life Cycle Stage	Revenue	Demand	Revenue Forecast
Growth	$19.71 B 2022 ↑	3,852.7 kTon 2022 ↑	$35.43 B 2028 ↑

Base Year Growth Rate	Compound Annual Growth Rate	Degree of Technical Change	Number of Competitors
9.2% 2022 ↑	10.3% 2022-2028	8 scale 1 [low] to 10 [high] ↑	>50 active competitors in 2022 –

From a penetration point of view, bioplastics represent just 1% of the total

By 2028, this percentage is expected to increase to 1.7% in volume terms as production of bioplastics grows by 13.8% CAGR versus 3.8% for the total market.

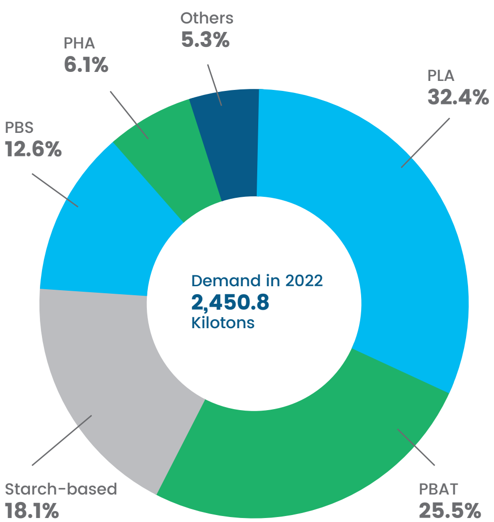
Within this, biodegradables and in particular polylactic acid is widely used.

PLA represents 32.4% of global demand and is followed by PBAT with 25.5% and starch-based solutions with 18.1%. Behind this PBS and PHA have low double and high single digit shares.

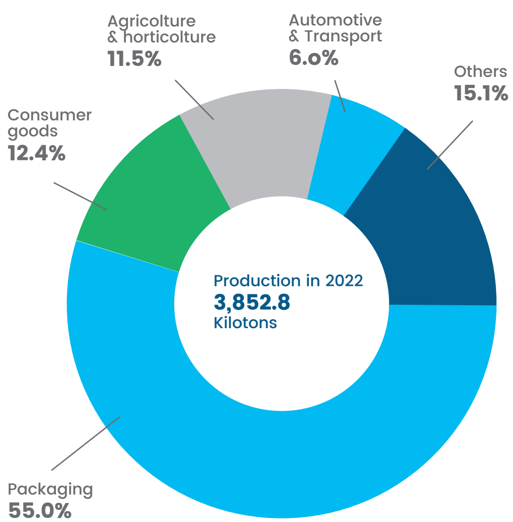
The use of bioplastics can be applied to almost every conventional plastic material and its corresponding application. It is predicted that within the next 5 years, the production capacity will continue to grow gradually and diversify due to a strong growth in polymers, such as PHA, PLA, and PA, as well as a steady growth in PP.

In addition to packaging, catering products, consumer electronics, automotive, agriculture/horticulture, toys, and textiles, bioplastics are used in a growing number of market segments. Packaging is expected to account for 55% of the total bioplastics market in 2022. As a result, the portfolio of applications continues to grow. With growing capacities of functional polymers, segments such as automotives & transport or building & construction remain on the rise.

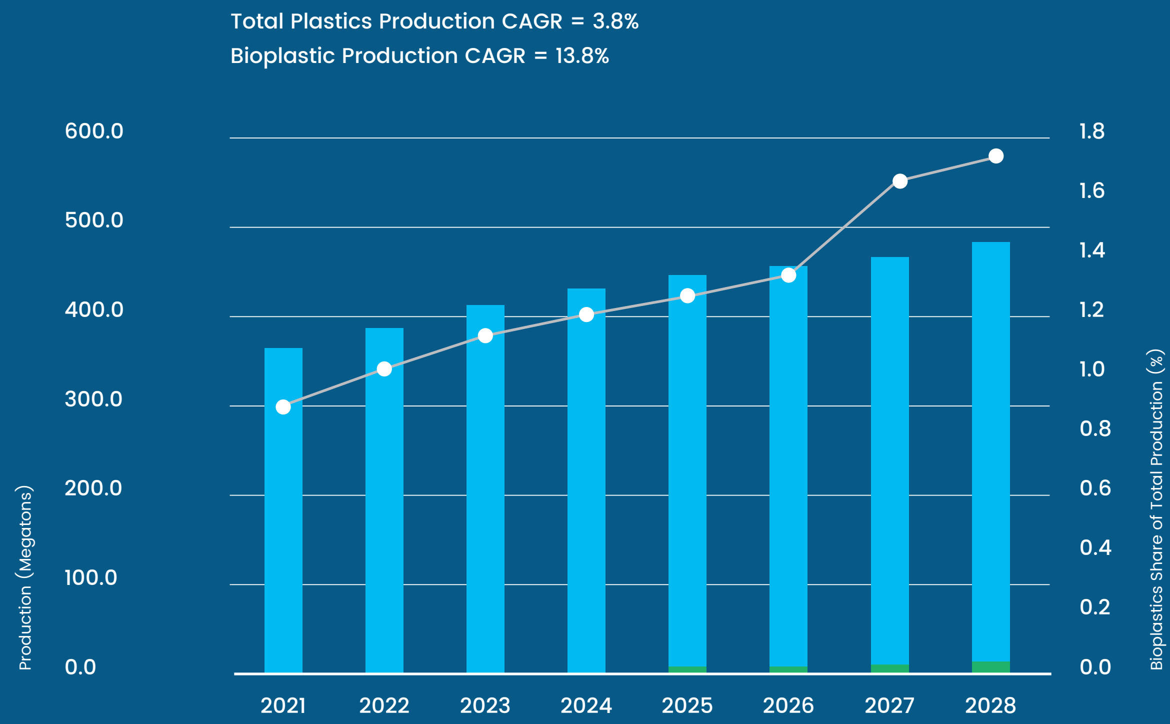
Biodegradable Bioplastic: Demand Share by Type of Bioplastic, Global, 2022
Source: Frost & Sullivan



Global production capacities of bioplastics 2022 (by market segment)
Source: Frost & Sullivan



Total Plastic Production and Bioplastic Share Forecast, Global, 2021-2028
Source: Frost & Sullivan



	2021	2022	2023	2024	2025	2026	2027	2028
Total Plastics	380.0	395.0	409.9	425.4	441.4	458.1	475.4	493.3
Bioplastics	3.4	3.9	4,3	4.9	5.6	6.4	7.4	8.4
Bioplastics Share	0.9	1.0	1.1	1.2	1.3	1.4	1.6	1.7

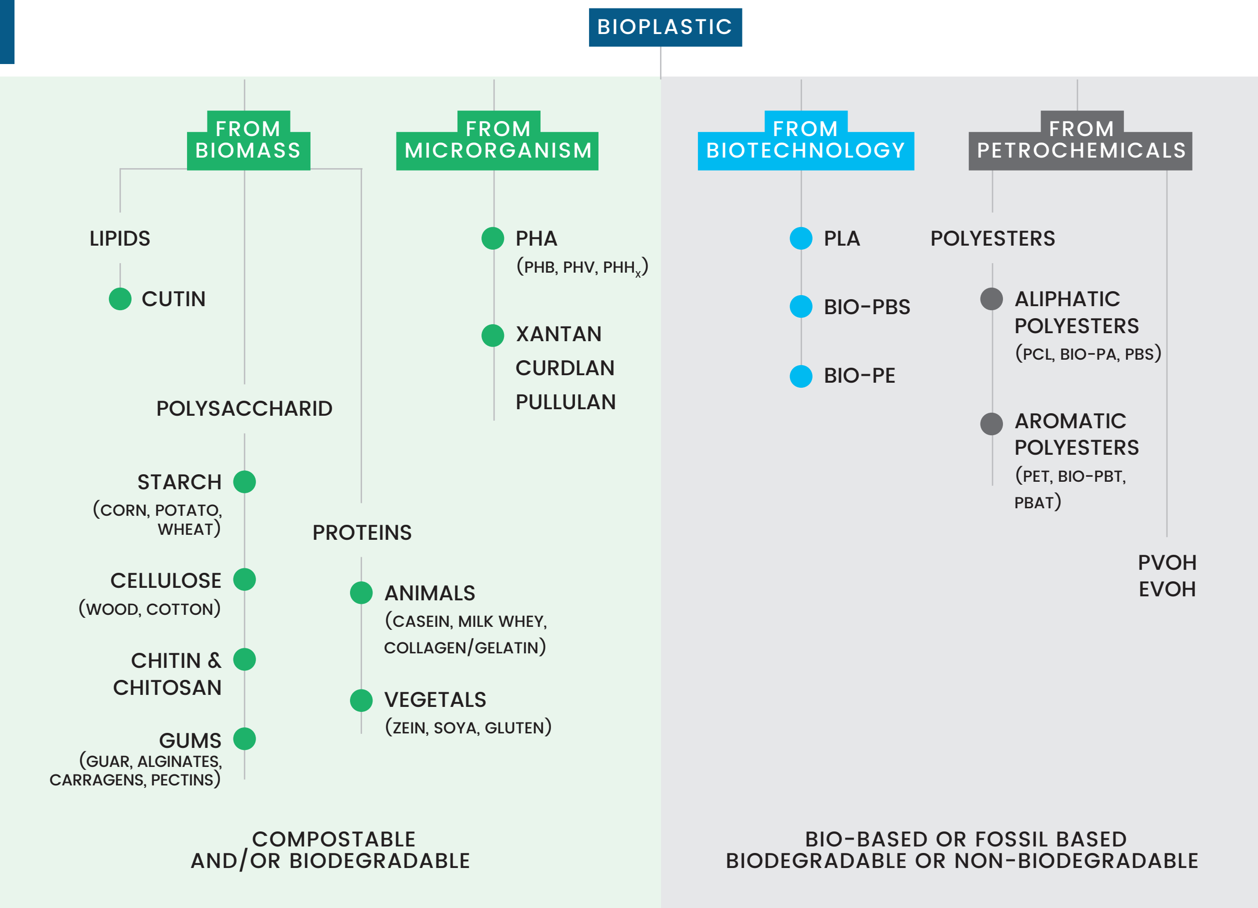
2.3 Classification and synthesis of bioplastics

Bioplastics can be classified into two main groups according to their source (bioplastics derived from biomass or petrochemicals) and method of manufacture (bioplastic produced by microorganisms or biotechnology).

2.3.1 Bioplastics from biomass (Agro-biopolymers)

There are many sources of biomass that can be used to make bioplastics, including **polysaccharides** (starch, cellulose, lignin, chitin, chitosan), **proteins** (collagen wool, soy, gluten) and **lipid** (cutin).
The most important biomasses differ in their types and properties.

Classification of bioplastics based on sources and method of manufacture
Source: Materias



List of main biomass-derived bioplastics

BIOMASS	SOURCES	PROPERTIES
Starch	Starch is the polymerized form of D-glucose which is mainly available in many plants (e.g. rice, wheat, corn, potato).	Starch is a very abundant natural polymer and starch-based bioplastics are quite cheap. One of the most important products under this category are TPS based bioplastics. Starch-based bioplastics biodegrade easily and show good oxygen barrier properties.
Cellulose	Natural sources of cellulose are cotton, bamboo, mulberry branches, wheat straw, flax.	Cellulose-based bioplastic are quite cheap due to their abundance.
Lignocelluloses	The main sources of lignocelluloses are agricultural wastes and byproducts (e.g. rice and wheat straw and husks, wood flour, palm fiber).	Lignocellulose based bioplastics have good mechanical properties.
Chitin	Commercial sources of chitin are mainly marine objects like shellfish (construction elements) or many fungal species (cell walls).	Chitin-based bioplastics show high barrier properties, flame retardancy, high-temperature resistance, mechanical properties and soil degradation properties.
Chitosan	Chitosan can easily be produced from chitin by deacetylisation.	Chitosan-based bioplastics show water soluble and bio-adhesive properties.
Protein: **1. Animal Protein (Collagen)**	**1.** Animal tissues (e.g. bones, tendons and skins).	**1.** Collagen-based bioplastics have biological compatibility and good mechanical properties.
2. Plant Based Protein	**2.** Wheat gluten, soy protein.	**2.** Gluten-based bioplastics are transparent, flexible and completely biodegradable. Soy protein-based bioplastics are biodegradable polymers and with such modifications can improve mechanical and functional properties.
Lipid: Cutin	Cutin is the main component of plant cuticles constituting the framework that supports the rest of the cuticle components. This biopolymer is composed of esterified bi- and trifunctional fatty acids.	Despite its ubiquity in terrestrial plants, it has been underutilized as raw material due to its insolubility and lack of melting point. In recent years, a few technologies have been developed to obtain cutin monomers from several agro-wastes at an industrial scale.

POLYSACCHARIDE-BASED BIOPLASTIC

Polysaccharides are reported to play a role in bioplastic production. A polysaccharide is a long chain of carbohydrate molecules linked together by glycosidic bonds. A wide range of polysaccharides have unique properties, which is why they are used in bioplastic manufacturing.

1. Starch-based bioplastic

Amylose and amylopectin are the components of starch, one of the most recognized polysaccharides. Its unique physiochemical properties are derived from the specific ratio of these two glucose-based polymers. Polymers with high amylose content will have high film strength, while films with branched amylopectin will have low strength. Plasticizers such as glycerol and sorbitol can improve this low mechanical property of polymer. In addition to increasing film strength, permeability, and water absorption, biopolymers manufactured by blending conventional polymers with starch will also reduce the cost of production.
By adding the ester group, starch molecules are modified for their physiochemical characteristics. Through this manipulation, thermal stability, moisture absorption, and water vapor transmission rates are improved, as well as barrier properties for different gases. In conventional polymers, starch molecules are used to increase biodegradability.

2. Cellulose-based bioplastic

Cellulose is a naturally occurring polysaccharide found in plant cells that is biodegradable. As a chemically synthesized biodegradable material, cellophane is made by dissolving cellulose in a mixture of carbon disulfide and sodium hydroxide. This resulted in cellulose xanthate, which was then dipped in acidic solution (H_2SO_4), resulting in cellophane film.
It is also possible to obtain cellulose derivatives by esterifying and etherifying the hydroxyl groups. In order to manufacture bioplastic materials from cellulose, additional additives such as cellulose diacetate and cellulose triacetate must be added. In addition, these chemicals enhance the extrusion molding and lamination process, which result in good film properties for cellophane.

3. Pectin-based bioplastic

Pectin is a linear biomacromolecule which is based upon the linear configuration of α-(1-4)-linked D-galacturonic acid. Pectin undergoes many chemical changes by partial replacement of monomer units like α-(1-2)-L-rhamnose, resulting in rhamnogalacturonan I. However, rhamnogalacturonan II is highly branched and complex polysaccharide structure. Methanol is used to esterify the galacturonic acid carboxyl group in nature; the percentage of extraction determines where the esterification occurs. In food applications, pectin behaves differently based on how much galacturonic acid is esterified and how much is not esterified. The esterification of pectin determines its classification.

4. Chitin and Chitosan-based bioplastic

In nature, chitin is one of the most familiar agro-polymers after cellulose, which is abundant. In nature, it exists primarily as an orderly crystalline microfibril structure. Many arthropods, as well as fungi and yeast, contain chitin in their exoskeletons. These polysaccharides are biodegradable, nontoxic, and biocompatible. A study by Flieger et al. found that natural chitin is extracted from crab crumb during pretreatment; a dilute solution of sodium hydroxide (pH 13.5) is often used to prevent microbial infections of crab flesh and shell degradation. In the rector, isolated crushed shells are treated with hydrochloric acid (HCL) to gasify them. The third step of the process involves washing the produced chitin and liquefied proteins a bit higher in temperature before adding them to another NaOH solution. Crushed crab crumbs yield 12% chitin after the whole process is completed. Various chemical processes use chitin to produce chitosan. Chitin is washed and boiled until acetate is removed from the molecules. The resulted material, chitosan, is washed, dried, ground, weighed, and packed for sale after hydrolysis.

PROTEIN-BASED BIOPLASTIC

For the production of bioplastics, proteins play a crucial role. The main source of protein for bioplastics is plants and animals. The denaturation ability of proteins plays a crucial role in thermosetting modifications of plastics. They are also known for their high degradability, which makes them fast-degrading polymers. Biodegradable polymers have gained maximum attention due to their biodegradable properties, but only a few of them have an impact due to their high assembly costs, definite industrial scale-up, and low performance. A major source of plant proteins is com protein (zein), soy protein, and wheat protein (gluten). Proteins from animals such as gelatin, collagen, and casein can also serve as biodegradable polymers. Lactate dehydrogenase, fumarase, and chymotrypsin are also enzymatically active proteins inside bacteria.

1. Wheat gluten protein-based bioplastic

A protein called wheat gluten is a by-product of the bio-ethanol industry that is also used in the baking industry for packaging. There are many advantages to wheat gluten over other proteins, such as its abundant availability, relatively low cost, and mechanical and biodegradability. Wheat gluten also has unique properties such as gas barrier, film formation, and biodegradability. Two types of proteins are involved in the development of polymers from wheat gluten: gliadins and glutenins. In recent years, wheat gluten has been used for the manufacture of bio-composites and bio-films based on natural fibers (Muneer et al. 2014).

2. Cottonseed protein-based bioplastic

A significant source of plant protein is cottonseed. There is a unique combination of amino acids in it that enhances its nutritional value, and it is commonly used in cattle feeds, but not as much in non-food industries. The mechanical properties of protein-based bioplastics are lower than those of synthetic polymers. Its poor mechanical properties are a result of its hydrophilic nature, complex composition, and sensitivity to the environment. Different modifications are needed to overcome these issues, such as plasticization, denaturation, and cross-linking. In particular, cottonseed protein, modified by denaturation and cross-linking with aldehyde and urea can be used to produce bioplastics.

LIPID-BASED BIOPLASTIC

Lipids offer excellent possibilities for the production of biopolymers. In addition to some additives, they may be polymerized directly through free-radical and cationic processes. Due to the reactivity of many triglycerides (hydroxyl groups, double bonds), they can readily be modified for polymerization with whatever functional group is desired.

1. Cutin-based bioplastic

Plant cuticles are composed primarily of cutin, which provides the framework for other cuticle components. It has long been the interest of researchers to create synthetic replicas of plant cuticles for a variety of applications, such as packaging materials, membranes, and UV filters, because of their protective properties against the environment, such as water loss, gas exchange, humidity, temperature oscillations, and pathogen attacks.
Compared to other traditional biopolymers like cellulose and lignin, cutin is an abundant biopolyester with a complex chemical composition. Various cutin monomers could cause problems in the production of bioplastics. The chemical profile of monomers can, however, be reproduced by focusing on specific agro-waste rich in defined fatty acids. It is also possible to increase cutin and control monomer composition by using plant breeding strategies.

2.3.2 Bioplastics from microorganisms (obtained by extraction)

Under different nutritional and environmental conditions, microbes can produce biopolymers, which are usually polyester in nature. The majority of polyesters are produced inside the microbes when some nutrients are lacking, under stress, as storage materials. Physicochemical properties and number of granules vary from species to species.

PHA

PHA is a biopolymer that is well-known for its biodegradability, usually present inside microorganisms as a source of energy. PHAs are water-insoluble inclusions synthesized and stored by bacteria and archaea in their cytoplasm. PHAs are usually produced when microbes are cultured with nutrient-limiting concentrations of nitrogen, phosphorus, sulfur, or oxygen, along with excess carbon sources. In order to reduce the cost of commercially produced PHAs, industry has optimized fermentation conditions.
Crystallinity can also be manipulated to improve its functionality to some extent, even it can be used in some cases as a substitute for engineered thermoplastics.
A complex extraction process is involved in the production of PHAs from wild-type microorganisms. Therefore, genetically engineered microorganisms have been studied for their potential to produce PHA. Using genetically engineered bacteria, bio-production costs can be reduced, growth can be accelerated, cell density can be increased, separation can be simplified, and cost can be reduced.

2.3.3 Bioplastics from biotechnology (conventional synthesis from bio-derived monomers)

Biotechnology has played an important role in creating methods for obtaining bulk quantities of products within a short period of time. Biotechnology can be used to alter products according to our needs and improve their quality. Several biotechnological methods can be used to obtain our desired product.
The biotechnology industry converts plant sugar into bioplastic, grows bioplastic in a variety of crops, and produces bioplastic inside microorganisms. Compared to conventional plastic, bioplastics are more useful and environmentally friendly thanks to biotechnology.

PLA

PLA is an aliphatic biodegradable polymer derived from hydroxyl acids, principally polyglycolic acid. Among the most important renewable monomers of bioplastics, polylactic acid comes from the fermentation of starch-rich agricultural byproducts such as sugar or wheat and corn starch. During the fermentation process, corn and another carbohydrate are converted into dextrose and then lactic acid. There are two methods for obtaining PLA from lactic acid. Using the first method, cyclic lactic acid dimer lactide produced by the lactic acid cycle is converted into PLA with large molar masses by converting it into cyclic lactic acid dimers. The second method involves direct polymerization of lactic acid, usually condensation polymerization, resulting in PLA polymer with a low molar mass. Lactic acid comes in two stereo-regular forms: L-lactic acid and D-lactic acid. Petro-chemicals produce D-lactic acid, whereas starch fermentation produces L-lactic acid.

Bio-PBS

A bio-based PBS that includes succinic acid derived from natural resources and 1,4-butandiol is produced and sold by PTT MCC Biochem since 2017. A marine-biodegradable form of Bio-PBS was later developed to increase revenue and product portfolio for the company. The PTT MCC Biochem company also develops, produces, and sells the compound that gives Bio-PBS a new function by improving its biodegradability and compatibility.
Bio-PBS is a biodegradable plastic that breaks down into water and carbon dioxide under the soil when microorganisms consume it. In comparison with general biodegradability resins, Bio-PBS has high heat resistance and fiber compatibility. Through this goodness, it is possible to achieve performance that cannot be shown alone as a compound with other resins and materials.

BioPBS

Bio-PE

In addition to being a bioplastic material, Bio-PE can also eliminate greenhouse gas emissions. Bio-PE is mainly composed of ethylene. The source of ethylene is ethanol, and it has many similar properties. From agricultural feedstocks like corn or sugar cane, Bio-PE is primarily synthesized by fermentation. Despite being bio-derived, Bio-PE is not biodegradable, but it has chemical and physical similarities to traditional PE.

2.3.4 Bioplastics from petrochemical (conventional synthesis from synthetic monomers)

A number of polymers, including aliphatic polyesters, aromatic co-polyesters, and PVOH, can be synthesized from fossil-based extracts, and enzymes are generally responsible for their biodegradation.

ALIPHATIC POLYESTERS

One of the most important conventional methods for the synthesis of polymers is the chemical method, since it produces large quantities of "biopolyesters." A fermentation process is used to produce all kinds of classical packaging materials derived from mineral oil-based renewable resources.

1. PCL

Polycaprolactone is a crude oil-based bioplastic material that is chemically synthesized using thermoplastic polymer methods. Polycaprolactones are resistant to oils, solvents, water, and chlorine due to their composition. Due to its adhesive nature, polycaprolactones are used for thermoplastic polyurethanes, resins for the synthesis of leather, fabrics, and surface coatings.

2. PA

Aliphatic PA, also known as nylons, are among the most important product polymers. In recent years, researchers have been concentrating on bio-based polyamide thermoplastics, which are partly or entirely manufactured from renewable resources at a low cost. In the fabrication of bio-based PA thermoplastics, castor oil is used as a bio-based monomer and is also mass-produced through fermentation. Both bio-based and synthetic polyamides are synthesized the same way.

PA11 is a biopolymer derived from natural oil. It is a technical polymer that does not biodegrade. While PA11 is produced, greenhouse gas emissions and nonrenewable assets are depleted. PA11 has a good thermal resistance and as a result of its extraordinary properties, this material is most commonly used for pneumatic air brake tubing, automotive fuel lines, flexible oil and gas pipes, electric cable anti-termite sheathing, sports shoes, and electric device components.

3. PBS

PBS is an aliphatic polyester with similar properties to PP. PBS is typically produced from succinic acid (SA) and 1,4-butanediol (BDO), both derived from petroleum. It is possible to divide the synthesis into two stages: the first is the esterification of SA and BDO to obtain oligomers. To achieve high-molecular-weight PBS, oligomers are polycondensed. A significant novelty was the production of PBS from renewable resources, such as sugarcane, cassava, and corn. PBS has become a viable sustainable, bio-based, and biodegradable plastic alternative in the last ten years.

AROMATIC POLYESTERS

Aliphatic diols and aromatic dicarboxylic acids, through intra-condensation, produce PET and PBT. Because of the presence of aromatic rings, they are very much resistant to attack by the chemical agents and enzymes, which make them very difficult to biodegrade.

1. Bio-PET

In addition to its colorlessness, transparency, and hygroscopic characteristics, Bio-PET is a semicrystalline resin with exceptional physical and chemical properties. Among the most significant bioplastics, Bio-PET is partially made from renewable resources. The applications of Bio-PET vary from packaging to textile manufacturing.
The Bio-PET is produced by fermenting ethanol sugars or starches, which are then transformed into a variety of metabolites and converted to monoethylene glycol (MEG), which is combined with fossil-derived terephthalic acid (TPA) by conventional transesterification to produce partly Bio-PET (23% bio-based). PET is made up of TPA and MEG monomers. Water is produced by the polycondensation of the two monomers. In order to create a Bio-PET made entirely from renewable materials, both precursors must be derived from renewable resources. Currently, only MEG, which accounts for 30% of all biomass content, is available on a large scale. Approximately 70% of Bio-PET is still derived from fossil fuels.

2. PBT

PBT is a thermoplastic semi-crystalline engineering polyester commonly used in electrical and electronics applications. Among its advantages are its solvent resistance, low shrinkage during forming, good mechanical properties, heat resistance up to 150 °C (or 200 °C with glass-fiber reinforcement), and flame-retardant properties.
PBT is slightly weaker, more rigid, and more impact resistant than PET, as well as having a lower glass transition temperature. PET and PBT are sensitive to hot water above 60 °C. The polyesters PBT and PET need UV protection if they are to be used outdoors, and most grades are flammable. However, additives can help improve both UV and flammability properties.

PVOH & EVOH

PVOH is a hydrophilic polymer, prepared by polymerizing vinyl acetate to polyvinyl acetate (PVAC) and then hydrolyzing it. According to the extent of hydrolysis, PVAC is converted into PVOH at a faster rate, and glass transition and melting temperatures (T_g and T_m respectively) depend on the degree of hydrolysis.
EVOH is a hydrophilic, highly crystalline polymer made up of ethylene and vinyl alcohol. This material has anti-static properties and a high level of permeability. In addition, it has a high resistance to organic solvents. It is also weather-resistant. It has special properties that make it an ideal packaging material. Because of its excessive cost, it is less popular in the industrial sector than PVOH.

2.4 Biodegradation processes of bioplastics and environmental impact

There are benefits and problems associated with everything in the environment, and these fall into the white or black areas, but bioplastics fall into the grey area due to many issues related to their benefits and problems. As bioplastics degrade in different environmental media based on their chemical and physical structure, they play a unique role in biodegradation. Different factors impact bioplastic biodegradation, such as accumulation in various environmental conditions and the amount of degradation by microorganisms.

A wide variety of bacteria and fungi species participate in biodegrading bioplastics

Biodegradation is basically the breakdown of complex compounds by microorganisms. There are two types of biodegradations which include aerobic and anaerobic biodegradation.

Aerobic biodegradation of polymers takes place when oxygen is available to the microorganisms capable of breaking down the polymers. This process is carried out by aerobic bacteria whose metabolism is oxygen-dependent. Degradation occurs completely without producing pungent odors.

Anaerobic biodegradation occurs when anaerobic bacteria break down polymers without oxygen. The polymers first broke down into small molecules, making them available to other bacteria. Several bacteria are involved in anaerobic biodegradation, including acetogenic bacteria that convert polymers into sugars, amino acids, hydrogen and organic acids, and methanogen bacteria that convert them into methane and carbon dioxide.

The most important method of degradation of bioplastics is by releasing enzymes from microorganisms like bacteria, fungi, and yeast. The process consists of three steps:
1. Bio-Fragmentation: the first step is of fragmentation which mostly occurs outside of the organism and depends on the size of the polymer.
2. Biodegradation or Bio-mineralization: the second step involves biodegradation or mineralization by microbes.
3. Bio-assimilation: the third step is of assimilation of biodegraded polymers.

BIO-FRAGMENTATION

Fragmentation is generally the first step in decomposition. When a polymer is exposed to living or non-living factors, it undergoes chemical decomposition, resulting in mechanical decomposition. Thermal oxidation, ultraviolet (UV) radiation, and microbial activity all contribute to fragmentation. In the presence of UV radiation, the surface cracks and fragments, resulting in microplastics. Thus, UV radiation along with high oxygen levels and high temperatures will cause higher fragmentation when exposed to UV radiations. In the process of fragmentation, sediments cover the area so that fragmentation decreases rapidly. Fragmentation can be stopped by adding thermal and UV stabilizers.

BIO-MINERALIZATION

Compounds such as polymers are broken down into smaller inorganic substances, such as carbon dioxide, by decomposition. In this way, plastics can be converted into natural materials.

BIO-ASSIMILATION

The process of bio-assimilation involves two steps that provide nutrients to animal cells. The first step is absorbing vitamins, chemicals, and minerals from food which has been reduced to simple forms like carbon dioxide and sugar, while the second step is chemically altering substances in the bloodstream.

Polymer structure greatly influences the biodegradability of materials. Polymer structures usually have either a hetero-chain or a carbon backbone. There are several hetero-chain polymers, including polysaccharides, proteins, polymers derived from plants like PLA and PBS, and polymers synthesized by microbes like PHA. Among the factors that influence the degradation of hetero-chain polymers are thickness, chemical bonds, co-polymer type, water uptake, and morphology. The biodegradation of polymers with carbon backbones, like natural rubber and lignin, may take years and be slower than that of hetero-chain polymers. To enhance their biodegradability, most biodegradable materials are composed of other biodegradable materials like potato peel waste fermentation residue, empty fruit branch fibers. As a result, adding such eco-friendly composites does not guarantee enhanced biodegradation, because temperature variations and other factors in real-world field conditions are difficult to predict.

Abiotic and biotic factors affect the rate and degree of biodegradation, in addition to polymer properties. There is a higher rate of biodegradation in compost and soil at higher temperatures. Soil and compost support higher rates of biodegradation due to their higher microbial community concentrations and diversity.

Details on test conditions

MARINE ENVIRONMENT	FRESH WATER	SOIL	HOME COMPOSTING	LANDFILL	ANAEROBIC DIGESTION	INDUSTRIAL COMPOSTING
Temperature 30°C, 90% biodegradation within a maximum of 6 months (Certification: TÜV AUSTRIA OK biodegradable MARINE (ISO under preparation))	Temperature 21°C, 90% biodegradation within a maximum of 56 days (Certification: TÜV AUSTRIA OK biodegradable WATER)	Temperature 25°C, 90% biodegradation within a maximum of 2 years (Certification: TÜV AUSTRIA OK biodegradable SOIL; DIN Certco DIN-Geprüft biodegradable in soil)	Temperature 28°C, 90% biodegradation within a maximum of 12 months (Certification: TÜV AUSTRIA OK compost HOME; DIN Certco DIN-Geprüft Home Compostable)	No standard specifications or certification scheme available, since this is not a preferred end-of-life option	Termophilic 52°C / mesophilic 37°C; standard specification not yet available, but 90% generally considered as completely biodegradable	Temperature 58°C, 90% biodegradation within a maximum of 6 months (Standard: EN 13432)

Biodegradation of bioplastics in various environments

	Marine environment	Fresh water	Soil	Home composting	Landfill	Anaerobic digestion	Industrial composting
PBS							🟢
PLA[1]						🟠	🟢
PBAT[2]			🟠	🟠			🟢
PBSA			🟢	🟢			🟢
Lignin Wood[3]	🟠	🟠	🟠	🟠	🟠	🟠	🟠
Cellulose acetate[4] (and other derivatives)	🟠	🟠	🟠	🟠	🟠	🟠	🟠
Cellulose (Lignin <5%)	🟢	🟢	🟢	🟢	🟢	🟢	🟢
PHB[5] (and copolymers)	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Starch (and other natural polymers)	🟢	🟢	🟢	🟢	🟢	🟢	🟢

🟢 proven biodegradability 🟠 proven biodegradability under certain conditions or certain grades

1 PLA is only likely to be biodegradable in thermophilic anaerobic digestion at temperatures of 52°C.
2 Biodegradability in home composting and in soil of PBAT is only proven for certain polymer grades.
3 Complete biodegradation of materials with a high lignin content is not easily measurable with standard biodegradation tests, but does take place (slowly). Instead of CO_2, especially humus is produced by the biodegradation of lignin-rich materials.
4 The biodegradation of CA in all environments is only proven for certain polymer grades.
5 incl. P3HB, P4HB, P3HB4HB, P3HB3HV, P3HB3HV4HV, P3HB3Hx, P3HB3HO, P3HB3HD

Degradation of biodegradable plastics in aquatic systems is profoundly affected by microenvironments. In order to capture aquatic environment complexity efficiently, **test methodology must consider all habitats** (supralittoral, eulittoral, sublittoral benthic, deep-sea benthic, pelagic, sedimentary) as well as abiotic stressors (pH, salinity, temperature, UV, etc.) and microbial communities that influence degradation. The presence of oxygen, pH, salinity, humidity, and UV radiation are other factors affecting the biodegradation of materials.

Environments include marine environment, fresh water, soil, home composting, landfill, anaerobic digestion, and industrial composting.

Biodegradation of main bioplastics in various environments is reported in the side table.
Green circle on the table indicates "proven biodegradability"; orange circle indicates "proven biodegradability under certain conditions or for certain grades". Where the circle is missing means "biodegradability is not proven". Three of the 9 biodegradable polymers on the table — cellulose (lignin <5%), PHB (and copolymers), and starch and other natural polymers — have a proven biodegradability in all environments.

Biodegradable Polymers in Various Environments

2.4.1 Environmental impact of bioplastics

Synthetic plastics have caused environmental problems that have led to the search for alternatives. Several new materials, belonging to the bioplastic category, have emerged to address these concerns which are functionally similar to synthetic plastics and environmentally friendly.
In addition to their composition, degree of crystallinity, and environmental factors, bioplastics are also susceptible to degradation over time.
It is possible to categorize biodegradable bioplastics into two main categories, namely oxo-biodegradable and hydro-biodegradable.

Oxo-biodegradable

Several pro-oxidant additives are used in the manufacture of oxo-biodegradable plastics, including fossil-based polymers like PE. This additive catalyzes the degradation process of the plastic. In general, transition metals, including iron, manganese, cobalt, and nickel, are used as additives. As a result of the abiotic degradation process, large molecular polymer chains are broken down into smaller fragments that microorganisms can process and convert into biomass and carbon dioxide. Oil or natural gas by-product naphtha is currently used to produce oxo-biodegradable plastics. As with methane or nitrous oxide industrial processes, biodegradable oxo products can be programmed to degrade over time. It usually takes months or years for oxo-biodegradable plastics to degrade.

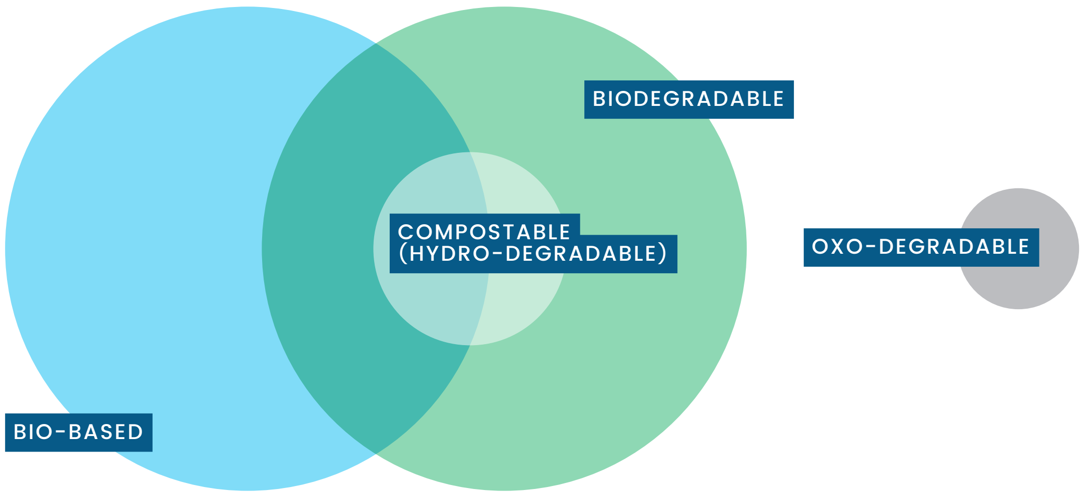
Hydro-biodegradable

Hydro-biodegradable plastics, on the other hand, decompose hydrolytically faster than oxo-degradable plastics. It is possible to convert these plastics into synthetic fertilizers. The PLA and bioplastics produced from plants (such as starch) are examples.

It is becoming increasingly difficult to determine the environmental impact of bioplastics

Despite being touted as a good alternative to conventional plastics, bioplastics have some disadvantages as well. By breaking down through microbial mechanisms, biodegradable plastics can blend harmlessly into soil. Water and oxygen are needed for this decomposition process. In composting, cornstarch-derived bioplastics, for example, swell up when water is absorbed by the cornstarch molecules. As a result, the starch bioplastic breaks apart into smaller fragments that bacteria can easily digest. Low-degradable or nondegradable bioplastics, however, only degrade at high temperatures or in municipal composters. Furthermore, some biodegradable plastics can only degrade at specific active landfill sites under definite and tested conditions. **The decomposition of organic matter during composting produces methane gas**, a potent greenhouse gas. As a result, this greenhouse gas contributes to global warming.

Biodegradable is not always compostable
Source: Materias



It also requires repurposing land for producing plastic rather than meeting food needs to produce bioplastics from plants such as corn and maize. Biofuels and bioplastics are produced on almost a quarter of agricultural land that produces grains. A significant rise in food prices may result from the conversion of agricultural land to biofuels and bioplastics, affecting the economically weaker sections of society.

But bioplastics are also eco-friendly.

The production of PLA, for example, saves two-thirds of the energy required for traditional plastics. Scientific studies confirm that there is no net increase in carbon dioxide gas during the biodegradation of PLA bioplastics. The plants from which they were produced absorbed as much carbon dioxide during their cultivation as they released during their decomposition. When PLA degrades in landfills, it emits 70% fewer greenhouse gases. A 25% reduction in greenhouse gas emissions can also be achieved by substituting traditional plastic with corn-based PLA bioplastics. By using renewable energy and reducing greenhouse gas emissions, new bioplastics can be produced in the future.

Environmental Benefits

The needs and demands of humans have also increased. As a result, it is necessary to run numerous industries in order to meet all their needs, resulting in increased waste production and accumulation. Plastics are the most widely used and important of these industries, which creates many environmental problems.

Since the 1960s, scientists and researchers have hardly tried to find solutions for maintaining the environment. They are now moving toward greener environments. By forming plastic from renewable resources, they find new techniques and methods that are environmentally friendly.

Microorganisms are used to produce naturally occurring PHA and PHB plastics. Environmentally friendly plastics are widely used in our everyday lives. With the help of microorganisms, these plastics are completely biodegradable in one year, converting to carbon dioxide and water.

Social Benefits

Because bioplastics have applications in all aspects of daily life, from automobiles and medicine to food packaging, bioplastics play a significant role in society. Unlike traditional plastics that accumulate in the environment posing a growing hazard to both human health and natural ecosystems, biodegradable plastics are a possible solution to this problem as they can be decomposed by micro-organisms without producing harmful or noxious residue during decomposition. Digestion and inhalation of micro and nano-plastics have a serious toxic effect on human health. On the other hand, EN 13432 certified compostable bioplastics fully biodegrade during industrial composting process and do not create microplastic.

Economic Benefits

In addition to being economically beneficial, bioplastics are used in many different applications. We can get fibers, bags, shampoo bottles, medical and surgical instruments, home instruments, and fertilizer bags from them. They provide a green economy. When we see bioplastics as environmentally friendly, we see them as cost-effective. They help us save money in this way, by reducing the amount of money we spend on climate-related issues. In other ways, however, it is more expensive than standard plastics. Substituting the annual global demand for fossil-based PE with bio-based PE would safe more than 73 million tonnes of CO_2. This equals the CO_2 emissions of 20 million flights around the world per year.

2.4.2 Standards, certifications, and labels

As bioplastics have evolved over the last few decades, their regulation has become increasingly important. Using specific techniques and conditions that can be replicated, experts from various fields have provided standards for analyzing the properties, composition, and compostability of various bioplastics.

The major organizations creating these standards are the **International Organization for Standardization** (ISO), the **European Committee for Standardization** (CEN), and the **American Society for Testing and Materials** (ASTM).

A number of national standardization organizations, such as the **Australian Standard** (AS), the **German Institute for Standardization** (DIN) and the **Japan Bioplastic Association** (JBPA), have incorporated extra testing procedures in order to improve regulation.

By introducing benchmarks, standardization encourages desirable product quality and prevents fraudulent market behavior. For example, the European Bioplastic Association describes two methods for evaluating products:
1) Using test methods that include procedures that must be followed based on the described methodology.
2) Using a pass-fail criteria will help ensure that a product or material meets the standard's requirements for compliance.

Harmonised standards for bioplastics

Standards are not mandatory, but instead are a set of guidelines and tests to determine whether the bioplastic is biodegradable.

When customers prefer brands with sustainable commitments, the part of the industry sector that analyzes bioplastic is motivated to obtain certification for customer approval. As part of the certification process, an independent certification laboratory evaluates the product to determine if it complies with the standards and is worthy of certification. Several organizations and associations offer these services and guide businesses in obtaining certifications recognized by governments and society as a whole. There are many organizations offering this service, but the most in-demand are **Biodegradable Product Institute**, **Tüv Austria** (formerly **Vinçotte**), **DIN Certco**, **Australasian Bioplastics Association** and the **Japan BioPlastics Association**.

Bioplastic certification world map

DIN Certco (based on EN 14995 or ISO 17088) and **Vinçotte** (based on EN 13432) issue independent certificates for biodegradable plastics in **Europe**, as well as products that degrade in soil and water in home composting. By successfully meeting the harmonized European standard EN 13432:2000 or EN 14995:2006, which defines the **technical specification for compostability of bioplastics products**, the plastic used in packaging can prove its compostability.

Material characterization

European standard CEN/TS 16137:2011 "Plastics—Determination of bio-based carbon content specifies the calculation method for determining the bio-based carbon content in monomers, polymers and plastic materials and products", based on the 14C content measurement (described in EN 15440 and ASTM D6866). It is currently the most important guideline for substantiating marketing claims regarding a material's or product's bio-based carbon (total and organic) content. Additionally, EN 16640:2017 and EN 16785:2018 contain methods to determine bio-based content using elemental analysis and material balance method.

Biodegradability

Any packaging product or biodegradable plastic, regardless of the polymer, must be able to degrade at least 90% in less than 6 months. In EN 17033, "*Biodegradable mulch films for use in agriculture and horticulture- Requirements and test methods*", requirements are specified for biodegradable films made from thermoplastic materials for mulching applications in agriculture and horticulture that are not intended to be removed. Ideally, it should degrade by 90% in two years at 25°C.

Disintegration

The original dry mass of material should not be more than 10% after 84 days in a controlled composting test.

Ecotoxicity

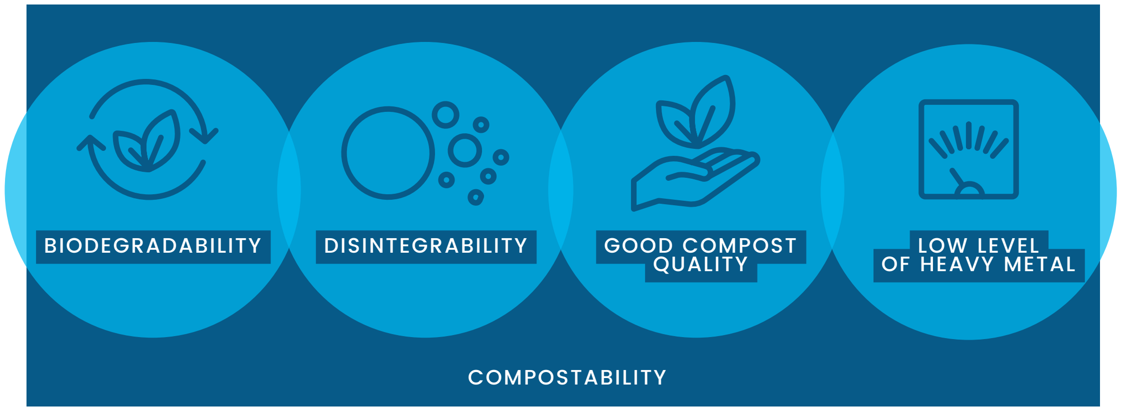
The seedling growth test follows OECD Chemical Guidelines 208 (OECD, 2003) which compares two higher plants (from Dicotyledonae and Monocotyledonae families), with one plant adding biodegraded plastics and the other not. Plant germination and plant growth are affected by the effect. As a minimum, the germination rate and plant biomass of both species should be 90% the same. In addition to volumetric weight, total dry solids, volatile solids, salt content, nitrogen, ammonium, phosphorus, magnesium, and potassium, compost must not be negatively affected by control waste treatment processes.

In **Europe**, **Tüv Austria** group offers diverse certification logos, which include the **Seedling logo**, **OK compost INDUSTRIAL**, and **OK compost HOME**, all of which are related to the compostability of organic material. When products comply with EN 13432, they are granted the first two logos, whereas the latter was developed by the Tüv Austria group without reference to a specific standard, but it outlines all of the technical requirements that a product must meet, thereby serving as the basis for other standards in Europe and Australia. **OK biodegradable MARINE**, **OK biodegradable SOIL**, and **OK biodegradable WATER** logos are also available from Tüv Austria that describe how plastic materials biodegrade in various environments. The aim of all of these programs is to stop littering and provide information on the conditions for the biodegradation of particular materials.

Companies that manufacture products with an alternative to fossil-based raw materials are rewarded with **OK biobased**. As a result of this certification, the product can be rated up to four stars based on its biobased percentage of renewable raw materials used as a base. Last but not least, the logo **NEN BIO-BASED CONTENT** refers to the amount of biomass in materials and products in general; this certification is based on the European standard EN 16785-1 and was recently added to the TÜV AUSTRIA database.

Often, plastic products are labelled to indicate whether they can be recycled, bio-based, biodegraded, and under what conditions. A variety of bioplastic labels are currently available to consumers and converters based on different industrial testing standards, some of which are cited by major governments, such as the United Nations, the European Union (EU) or the US. With the aim of revising and harmonizing these standards, especially those certifying biodegradation, which were established around 2000, some of these standards are currently being examined. It is important to understand the basis for these certifications as well as who is behind them.

Four criteria of compostability according to EN1342
Source: Materias



Identification labels

Most plastic products are labeled with plastic resin identification codes, which identify the polymer, but do not provide recyclability information (**panel a**).

In general, bioplastics such as polylactic acid are not recycled and are currently labelled as '7' (**OTHER**).

Recycling-oriented labels

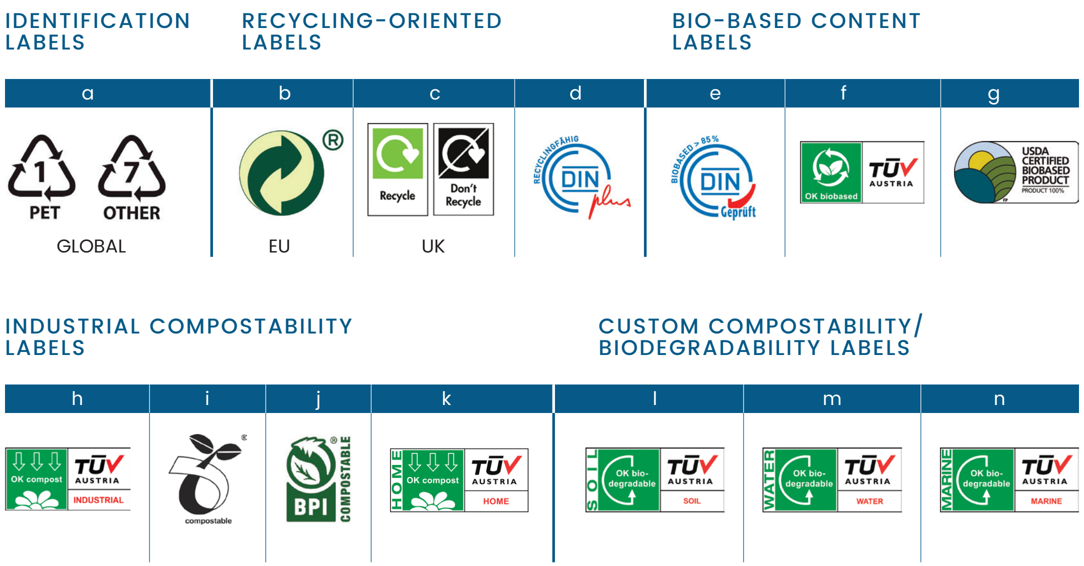
According to the EU, the "**green dot**" symbol (**panel b**) indicates that the producer has paid an extended producer responsibility (EPR) fee intended to fund collection and recycling programs, but not that the product can be recycled. Based on the nationwide probability of the component being collected, sorted, and reprocessed into a new product with a viable market, the on-pack recycling label ("**OPRL**") in the UK (**panel c**) recommends whether consumers should place individual plastic packaging components in the trash or recycling bin. The German certification body **DIN CERTCO** has developed new labels to certify the recyclability of plastic products based on the polymer and existing recycling infrastructure (**panel d**).

Bio-based content labels

Using the labels shown in panels e–g of the table, plastic products are certified to contain bio-based carbon. There are two types of bio-based labels: **DIN biobased** (**panel e**), and **OK biobased** (**panel f**) issued by DIN CERTCO and TÜV Austria, respectively. The US Department of Agriculture's Bio-Preferred program issues labels based on third-party analysis (**panel g**). These labels follow European and international standards like EN 16640 and ISO 16620.

Labelling bioplastics

Source: Materias



Industrial compostability labels

Recent years have seen the popularity of labels such as "**OK compost**" (**panel h**) and "**seedling**" (**panel i**) in Europe and "**BPI compostable**" (**panel j**) in the USA due to consumers awareness to understand the need for industrial biodegradability. Under the EN 13432 and ASTM D6400 standards, four tests are specified for the "industrial" sub-label: biodegradation (90% of the inoculum is converted into CO_2 after 6 months at 58 °C), disintegration (90% of the material is smaller than 2 mm after 3 months at 40–70 °C, depending on the standard), ecotoxicity (90% of regular plant growth in soil containing plastic) and a certain level of heavy metal content.

'Custom' compostability/ biodegradability labels

The "**home compost**" label (**panel k**) has seen an increase in use, but is not governed by any legislation. This label was proposed by TÜV Austria as a modification of EN 13432, with tests conducted at 20–30 °C over time periods twice as long as those in EN 13432. Further labels and certification procedures have been developed by TÜV Austria for the different environments where plastics may end up (**panels l–n**). The CEN is currently reviewing new standards for bioplastic testing, including EN 17427 (2020), which examines the compostability of plastic bags at home.

2.4.3 LCA of bioplastics

It is crucial to evaluate bioplastics' environmental impact from the initial production to the end of their life cycle in order to compare them comprehensively with conventional plastics. **Life Cycle Assessment (LCA)** or cradle-to-grave analysis is the most important tool for evaluating the environmental impact of bioplastics and conventional plastics. It enables a bioplastic's overall impact on the environment to be determined at different stages of its life cycle. As a result, the whole life cycle of this industrial product is evaluated, from raw material extraction to its various stages of processing, manufacturing, distribution, and use. In addition, when conducting an LCA, it is necessary to consider Land Use Change (LUC)-related emissions, as well as cost and benefits of bioplastic disposal. LUC is a guide for considering when land is converted for composting or biofuel production.

Bioplastic production in terms of life cycle assessment: A state-of-the-art review

The production of bioplastics might appear to be a better alternative to conventional plastics in terms of greenhouse gas emissions and energy demand, however the presence of non-biodegradable polymers in drop-ins significantly increases the energy requirement and CO_2 emissions as compared to biodegradable plastics. Due to their low calorific value when compared to fossil-based plastics, bioplastics also have low energy recovery by incineration.
The bioplastic material landscape is constantly evolving as a result of ever-evolving

LCA of bioplastics is based on characterizing and comparing following environmental impacts:

Abiotic depletion	The abiotic depletion potential associated with mining and extraction of the minerals and fossil fuels is expressed in kg of antimony per kilogram of extracted material
Global warming	It represents the potential for global warming caused by greenhouse gases released into the air during the manufacturing of a material, expressed as a kilogram of carbon dioxide equivalent per kilogram of carbon dioxide released
Human toxicity	As a measure of the human toxicity of each substance released into the air, water, or soil, it is calculated as a kilogram of 1,4-dichlorobenzene equivalent per kilogram of emission
Freshwater/marine aquatic ecotoxicology	As a measure of the aquatic toxicity of each substance released into the air, water, or soil, it is expressed as 1,4-dichlorobenzene equivalent per kilogram of emission
Terrestrial ecotoxicology	As a measure of the terrestrial toxicity of each substance released into the air, water, or soil, it is expressed as 1,4-dichlorobenzene equivalent per kilogram of emission
Photochemical oxidation	It is expressed in kg of ethylene equivalents per kg of emissions for each substance released into the air
Acidification	Amount of sulfur dioxide equivalent per kilogram of acidifying emissions to the air
Eutrophication	Each eutrophication potential is expressed as kg of phosphate ion equivalent per kg of eutrophication emission to air, water, and soil

socioeconomic and material-level inventions. Since sustainability and circular economy are influencing the bioplastics industry, many innovative bioplastics are entering the market. In spite of the relatively low land use for feedstock production for bioplastics, the expected increase in demand can certainly place additional stress on limited resources such as land and water, thereby affecting food security and climate change.

As a result, it is important to find a way to produce bioplastics in large quantities in order to support a sustainable plastic supply. Both micro and macroalgal biomass can be used directly as a source of bioplastics, as well as as a feedstock in secondary processes. Bioplastics derived from microalgae offer ecological alternatives as they are biodegradable and resemble petroleum-based plastics.
The LCA method can also be used to identify the best disposal method for bioplastic waste. For instance, it has shown that incinerating and landfilling bioplastics is not an effective alternative. A plausible solution to the bioplastic waste management problem was confirmed by adhering to the LUC emissions principle, which established bioplastics as an excellent substitute for petroleum-based plastics. As compared to conventional petroleum-derived plastics, PLA and TPS significantly reduce carbon dioxide emissions, in the case of the former by 50–70%.

The greenhouse gas emissions of Bio-PU and PTT are 36% and 44% lower respectively than those from petroleum-derived sources

2.4.4 End of Life of bioplastics

It is widely accepted that recycling bioplastics is the most environmentally friendly End of Life (EoL) option and better than simple composting. The issue of plastic leakage into the environment is a central issue of inappropriate EoL management. Despite this, bioplastics recycling streams are less established than those for traditional plastics.

It is generally difficult to recycle plastic and bioplastics due to the presence of additives in most finished plastics. It is also important to consider recyclability and simplicity in product design in order to greatly increase recycling rates because plastic products are usually complex and multimaterial, making them difficult to recycle. Incentives such as higher fees for less recyclable plastics would help promote the design of products that are easy to recycle.

A European strategy for plastics in a Circular Economy

Mechanical recycling

Plastic waste is usually sorted by polymer type, label removed, washed, mechanically shrunk, melted and remoulded into new shapes during mechanical recycling, the simplest, most cost-effective and most common form of recycling. There has been some literature on re-extrusion of bioplastics, but mechanical recycling of bioplastics is not yet available commercially. When PLA and PHA are mechanically recycled, their quality is usually reduced, such as their tensile strength and molecular weight. Due to the inability of mechanical recycling to effectively remove contaminants and additives from polymer wastes, as well as the inherent thermal and mechanical stresses, the products are usually “downcycled” into inferior goods. The environmental impact of mechanically recycled plastic is typically lower than that of virgin plastic. Virgin polymers are often mixed with recycled plastics to improve the quality of the recycled ones. **The environmental impact of recycled PET (rPET) is two times lower than that of virgin PET** (GHG emissions from transport and process energy use). For recycled PE and PP (rPE and rPP, respectively), the impact is three times higher than that of virgin materials. However, this recycling method has a very limited capacity: globally, 10% of PET and high-density PE are recycled, while PSe and PP are virtually nonexistent.

Chemical recycling

Unlike mechanical recycling, chemical recycling allows for the manufacture of high-quality polymers from waste - referred to as “upcycling”.

Using controlled polymerization mechanisms, plastic products can be depolymerized to their monomeric subunits, which can then be repolymerized into polymers with desired properties (such as a controlled molecular weight). Low-molecular-weight fiber polyesters, for example, can be depolymerized into monomers, which can then be polymerized into longer-chain polyesters needed for bottles. In addition to removing impurities, color can also be removed. Solvolysis and thermolysis are the most common methods of chemical recycling.

As a result of solvolysis, polymers with cleavable groups along their backbones, such as ester bonds in PET and PEF, can be depolymerized using solvent-based methods such as hydrolysis, glycolysis, and methanolysis. With a four-fold lower energy demand than virgin lactic acid production, PLA can be hydrolyzed to 95% lactic acid at (160–180)°C for 2 hours without a catalyst, or depolymerized back into 90% cyclic lactide monomers after 6 h using Zn transesterification catalysts. High-quality plastics are produced using the monomers produced by the process. Currently, chemical recycling is less economically competitive than mechanical recycling due to the need for chemicals and complex separation units. A significant number of large chemical companies are developing processes to make chemcycled products more cost-effective than virgin polymers. Chemical recycling accounts for 1% of all recycled plastics. The use of chemically recyclable polymers in plastic applications can solve persisting EOL issues and support a circular materials economy because they provide monomers suitable for repolymerization into high-quality condensation polymers, such as polyesters and polyamides.

The thermolytic process involves pyrolyzing polyolefins, which lack hydrolysable functional groups, at temperatures between 200 and 800 °C (depending on the polymer and the catalyst) in the absence of O_2. This condition causes the polymer to break down, converting it into feedstock, such as hydrocarbon oil or gas or olefin monomers. In the end, the feedstock can be fed into refineries and polymerization factories. PS, Bio-PE, and Bio-PP are hydrocarbon polyolefin materials that are best suited to thermolysis. It is important to capture potentially toxic gases generated by (often unknown) additives during this process.

Biodegradation and composting

The process of biodegradation and composting involves various known species digesting polymeric materials and converting them into CO_2, H_2O and other inorganic compounds.

Typically, physical processes are used to facilitate this process, particularly those that reduce particle size and fragmentation. For example, amorphization of crystalline structures in typically semi-crystalline plastics through micronization or extrusion can make them more susceptible to enzymatic degradation. An amorphous region of a polymer, typically aliphatic esters, can be hydrolyzed by microbial enzymes, acids and bases. In photodegradation using UV light, tertiary and aromatic C–C bonds are broken, leaving brittle and discoloured materials. Metallic catalysts can be embedded in the polymer to accelerate this process. The process of oxo-degradation (i.e. decomposition through oxidation) can be triggered by metals, but it can fragment into microplastics and result in insufficient digestion. Therefore, oxo-degradation is restricted in the EU and Switzerland.

The rate of biodegradation depends very heavily on the chemical structure and stabilizing additives of a polymer, the surrounding conditions (such as H_2O and O_2), and any microorganisms used.

The conditions are often not met in home composting, open water composting, or even industrial composting. Due to the long decomposition times required by biodegradable plastics, such as PLA shopping bags and utensils, composters often reject them.

A great variety of certifications and labels are used to identify biodegradable materials; there is indeed a need for revision and global harmonization of these guidelines, since the conditions in these standards may not necessarily be met in local disposal settings and, therefore, may cause confusion among consumers and converters.

Biological recycling

It is possible to depolymerize condensation polymers into monomers, rather than CO_2, with microorganisms and their hydrolysing enzymes, similar to chemical recycling, rather than complete biodegradation (composting). While biological processes hold promise as a cleaner alternative to chemical processes, they are still underexplored. Aromatic polyesters are typically resistant to enzymatic hydrolysis, whereas aliphatic esters can be readily hydrolyzed.

A bacterium discovered in a Japanese recycling plant, Ideonella sakaiensis, can depolymerize PET within 40 days at ambient temperatures. A leaf compost cutinase enzyme that is specific to aromatic polyester degradation but ineffective for aliphatic polyesters can be genetically modified to increase substrate specificity and thermal stability. Micronized, amorphous PET can be depolymerized into monomers by the optimized enzyme in 10 hours at temperatures close to PET's glass transition (75°C). It is at this temperature that the amorphous chain mobility increases, which makes the polymer more susceptible to microorganism degradation. This technology was also used to depolymerize PEF, which is used to synthesize bottle-grade PET.

Incineration

By burning only C/H/O-containing renewable material, CO_2 emissions are net zero, and some of the thermal energy generated is available for energy use. The combustion of polymers containing N, S, and Cl produces toxic NO_x, SO_x and HCl, however. Polymer additives may also release toxic substances upon combustion, requiring potentially expensive treatment and capture. Furthermore, there are concerns of a “locking-in” effect, which may jeopardize the adoption of recycling technologies due to the high investment cost for incineration plants and the need for constant waste influx.

Landfill

Many countries still use landfills for waste disposal. Poorly maintained and leaky landfills are regarded as major environmental pollutants.

As biodegradable polymers can compost anaerobically to CH_4, they should also not go in landfills since they have a GHG impact that is 20 times higher than CO_2. Globally, only 10% of CH_4 produced in landfills was captured in 2006, which is an approach that has the potential to recover energy while also benefiting the climate and public health. Recyclability could become more cost-competitive through landfilling fees, according to the UN.

Anaerobic digestion

In a methanization “biogas” facility, controlled anaerobic digestion produces CH_4 from biodegradable polymer waste in the absence of O_2. Using this process, the bioplastic waste can be captured and burned, producing CO_2 and H_2O. Heat and energy can be recovered for use. This process also produces energy, producing a net carbon balance. Including elements such as a ‘bioreactor landfill’ can increase the efficiency of anaerobic digestion.

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2.5 Advantages and disadvantages of bioplastics

With the rising costs of fossil fuels in the coming decades, bio-based bioplastics are expected to help reduce dependence on limited petrochemical resources. Bio-based bioplastics gradually replace fossil resources used in the production of conventional plastics with renewable resources (currently primarily annual crops, such as corn and sugar beet, or perennial crops, such as cassava and sugar cane).

Plants absorb atmospheric carbon dioxide as they grow, making bio-based plastics the perfect solution for reducing greenhouse gas emissions or even becoming carbon neutral. As a result of using plants (i.e. biomass) to produce bio-based plastics, greenhouse gases (CO_2) are temporarily removed from the atmosphere. A period of time can be extended for carbon fixation by establishing a “use cascade”, that is, if the material is reused or recycled as much as possible before it is used for energy recovery. As a result of energy recovery, previously sequestered CO_2 is released and renewable energy is generated. It is important to note that bio-based bioplastics also have the potential to “close the cycle” and improve resource efficiency. Depending on the EoL option, this can mean:
1. In order to produce renewable energy, renewable resources are used to produce bio-based, durable products that can be recycled mechanically and eventually incinerated.
2. The use of renewable resources allows for the production of bio-based, biodegradable, and compostable products that can be organically recycled (industrial composting and anaerobic digestion) at the end of a product's life cycle (if certified accordingly) and produce valuable biomass (humus). Hence, the cycle can be closed by using the humus to grow new plants.
Also, compostable and biodegradable plastics can drastically reduce biowaste going to landfills throughout Europe and increase waste management efficiency.

A fast-growing, innovative industry that is enhancing the bioeconomy and reducing resource depletion and environmental impact, bioplastics are essential to the bioeconomy.

Bioplastics, PROs and CONs (as of June 2023)

PROs	CONs
Waste management	Production costs
Carbon Footprint	Weaker mechanical properties
Energy usage	Raw materials availability
Compostability	Unclear communication to consumers
Environmental and health protection	Specific recycling processes
Market attractiveness	
Reuse of standard production plants	

2.5.1 Advantages of using bioplastics

1. Benefits of using biodegradable bioplastics for waste management

Grocery chains, food service and agricultural companies have implemented bioplastic packaging successfully in order to reduce the amount of plastic trash produced by society. Biodegradable plastics simplify the handling of biological waste. For example, catering businesses, which dispose of a lot of garbage, including plastic tableware, have started using biodegradable flatware. The result has been an increase in composting and a reduction in rubbish being gathered and disposed of in landfills.

2. Possibility of a much smaller carbon footprint

The carbon footprint of a bioplastic can be significantly impacted by whether or not it permanently stores carbon taken from the air by the growing plant. The carbon dioxide taken by plants during photosynthesis is sequestered by a synthetic material derived from living organisms. When the bioplastic reverts to CO_2 and water, the sequestration is undone. A permanent bioplastic, however, can hold CO_2 indefinitely. No matter how many times plastic is recycled, CO_2 first removed from the atmosphere remains trapped within it.

3. Reduction in energy use (less petroleum dependence)

It is now a major concern that petroleum will be in short supply. Bioplastics require less fossil fuel to manufacture than conventional plastics. According to a life cycle assessment of polylactic acid films, their environmental impact is about half that of petroleum-based films.

4. A decrease in litter and an increase in compostability

The decrease in persistent litter is the most understood benefit of biodegradable bioplastics. One of the most prominent examples of how plastics damage our environment over time is the use of single use shopping bags. Disposable plastic bags make up a significant portion of our trash. Many cities and countries are fighting litter, sometimes by banning non-biodegradable plastic bags altogether.

5. Increased environmental and health protection

Starch-based bioplastics, PLA and PHB, are non-toxic and do not pose a health risk. They are thus useful for food packaging because they don't taint food with any taste, nor leech chemicals (e.g. bisphenol A), unlike oil-based plastics.

6. Greater market attractiveness

With a green marketing campaign, bioplastics may be used to increase the value-add of a product. In spite of the fact that studies have shown that 80% of Europeans prefer products that have a minimal impact on the environment, bioplastics are likely to be an effective argument.

7. Workability in conventional plastic processing plants

There is a wide range of common bioplastics that can be molded and shaped in the same way as traditional thermoplastics like injection molded, extrusion, thermos-forming Indeed, the bioplastics are typically stronger, lighter, and can be used in more niche applications as well.

Processing possibilities of typical commercial bioplastics

	Injection moulding	Extrusion	Extrusion blow moulding	Cast film extrusion	Blow moulding	Fiber spinning	Thermo-forming
PLA	●	●		●	●	●	●
Starch	●	●	●	●			
Starch + PVA	●	●		●	●	●	
Starch + cellulose acetate	●	●	●		●		●
PBAT		●	●	●			
PHA	●	●	●	●	●	●	●
PHB	●	●	●	●	●		●
Cellulose	●	●			●		
PBS	●	●					
PCL	●	●	●		●	●	●
PBST	●	●		●			●
PTMAT		●	●	●		●	
PVA	●		●	●		●	●
Bio-PP, Bio-PE + additives	●	●		●	●	●	●

2.5.2 Disadvantages of using bioplastics

1. High production cost
In general, bioplastics are not cost-competitive with oil-based alternatives. They are generally two or three times more expensive than the major conventional plastics such as PE or PET, and their production is plagued by low yields and being expensive. As manufacturing plants grow and benefit from economies of scale, this disadvantage should decrease. In the case of Braskem, its 200,000 tonnes of Bio-PE plant (about 20% of world's bioplastic production) is an excellent example.

2. Bioplastics have weak mechanical properties
There are some bioplastics that have shorter lifetimes than oil-based plastics due to their weak mechanical properties, including greater water vapour permeability than standard plastics, ease of tear, or fragility. Algae-based bioplastics, for example, break down in an hour when in water – this makes them very biodegradable but also fragile.

3. Uncertainty among consumers
There is insufficient information provided by manufacturers in terms of labeling and identification of bioplastics, which creates uncertainty and makes it difficult to handle bioplastics correctly.

4. The stockpiles of raw materials used to make bioplastics can decline
Utilizing 2nd e 3rd generation feedstocks is also becoming increasingly popular in order to reduce energy consumption during the production of bioplastics, prevent potential competition with agricultural resources for food, and provide new raw materials.

5. Specificities of industrial plants for compostability
Even though bioplastics sound great, they need to follow a specific disposal procedure to avoid being incinerated or disposed of in landfills and require industrial composting. It is possible that 'green' bioplastics will end up being thrown away with regular trash if local authorities lack this facility, and when in landfills, they do not break down as easily as regular non-biodegradable plastics.

2.6 Future perspectives and development in the research of bioplastic field

Bioplastics derived from biomass are essential to achieve the goal of a sustainable low-carbon society. A great deal of research is going on in academia to move forward the frontier of knowledge, to improve the properties of these materials and make them more competitive, to discover new biomaterials and to develop new production processes with lower manufacturing cost.

Hereafter, some examples of current early stage studies in the field of bioplastics are reported:
I) PLA produced industrially directly by microbial fermentation;
II) PHA produced directly from microalgae;
III) synthesis of recyclable PE-like polymers;
IV) synthesis of recyclable poly(ethyl cyanoacrylate) (PECA).

These scientific research efforts have a relatively low Technology Readiness Level (TRL) ranging from 2 to 4. However, it is relevant to underline that some of the above-mentioned research have the potential to successfully scale up to industrialization in order to reach the market in the future.

I) PLA is a bioplastic widely used on the market in more demanding applications, such as packaging and consumers products. Today, lactic acid is also produced through the fermentation of genus Lactobacillus microorganisms. These bacteria have high resistance capabilities at low pH values and therefore lactic acid is produced in the form of lactate. This process represents one of the major problems when using this kind of micro-organisms. In fact, the lactic acid must be regenerated in a subsequent step of reaction using chemical acids. Even today, PLA is polymerized by an industrial chemical process of polycondensation of lactic acid and/or by the Ring-Opening Polymerization (ROP) of lactide. In the future, PLA will be produced industrially directly by microbial fermentation from agro-industrial waste and by-products. New molecular approaches will be adopted to a simple and direct production of D- and L-lactic acid isomers and their polymerization into pure poly-L-LA (PLLA) or poly-D-LA (PDLA) within the same microbial cell.

II) Microalgae can be used to treat food waste and extract different polymers as building blocks for bioplastics. As a potential feedstock during the bioplastic industry improvement process, microalgal biomass obtained through biorefining can be processed into bioplastic polymers such as PHA. As a result of their ability to fix CO_2, microalgae are particularly attractive to cultivate in tropical countries due to their suitable climatic conditions. In this context, microalgae can grow photoautotrophically, but at a faster rate, making them a valuable source of biomass showing a higher access to cellulose than plants do. Bioengineering can be used to optimize microalgae growth factors and peak biomass productivity for wild-type microalgae. Genetic engineering can modify an organism's genes directly, thanks to biotechnology tools, in order to increase biomass productivity by modifying photosynthesis, resistance, and metabolism genes.
Scholars have also conducted studies on producing PHA directly from microalgae, but there is a relevant research gap in this field. Moreover, some critical factors must be taken into account to ensure the success

of large-scale PHA synthesis with microalgal biomass i) identifying microalgae strains and determining optimal growth conditions will ensure maximum biomass production, ii) employing microalgae cultivation systems and microalgae harvesting techniques that are both economically feasible and require less management, and iii) choosing the right bacteria to work with microalgae biomass.

To sum up, it is crucial to identify bacteria that are capable of utilizing the most of the microalgal nutrients in order to maximize the use of the microalgal biomass. The general population of PHA-producing microorganisms are able to utilize simple sugars and some are able to consume triglycerides while hydrocarbon utilization for PHA synthesis is rare. In the future, PHA will certainly be produced from a third-generation feedstock, as this area is currently of interest to the scientific world.

III) Another research line is that of PE, a fascinating material with a wide range of applications. PE and its bio-based counterpart, Bio-PE, possess excellent properties such as high strength, durability, and chemical resistance. However, the inert nature of PE and Bio-PE, as thermoplastic polymers composed of long chains of hydrocarbon molecules, poses challenges when it comes to their recycling. These chains are highly stable and resistant to chemical reactions, making it difficult to break them down through conventional chemical recycling methods. Similarly, Bio-PE, which is derived from renewable resources such as sugarcane, shares similar chemical properties. When mechanical recycling is commonly used for PE and the material is melted and reshaped into new products, high-quality recycled PE is not guaranteed due to degradation and loss of mechanical properties. Chemical recycling of PE requires temperatures above 600°C and ethylene recovery with a yield of less than 10%. To overcome the drawback of the non-biodegradability of this plastic material, in a recent study (2021) entitled "Closed-loop recycling of polyethylene-like materials" Mecking et al. show how it is possible to create renewable polymer by inserting some functional groups into the chain as PE chain breakpoints. In this way, these PE-like polymers can be chemically recycled in a closed loop by solvolysis with a recovery rate of more than 96% by polycondensing long-chain building blocks derived from common vegetable oils or microalgae oils, using state-of-the-art catalytic schemes. Using chemical recycling, it is indeed possible to create high-quality polymers from waste, so-called 'upcycling'. To obtain polymers of the desired quality (e.g. polymers with a controlled molecular weight), plastic products must first be depolymerized into monomer subunits, which can then be re-polymerized through controlled polymerization mechanisms. Future perspective studies will be based on these PE-like polymers which represent a turning point in the world of bioplastics.

IV) Recycling and reusing fossil-based plastic are energy-intensive, time-consuming, and lead to pollution and accumulation of plastic waste in the environment. The possibility of developing a recyclable plastic based on PECA, which is prepared from the monomer ethyl cyanoacrylate (more commonly known by the trade names Super Glue and Krazy Glue), has been explored in 2023 in the research laboratory by Allison and Scott. This research has captured the media interest and has been published on informative websites such as Science Alert and Nature World News.

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Scientists Created a New Recyclable Plastic Not Made From Crude Oil

As a result of its non-petroleum starting materials, this PECA plastic could be scalable and economically competitive compared to fossil-based products (i.e., the monomer is readily available and cheaply priced), and its mechanical properties are comparable to commercial plastics in terms of strength and durability. A closed-loop recycling process can be also performed by thermally cracking polymers and distilling monomers. Ethyl cyanoacrylate is composed by methanol, chloroacetic acid, and sodium cyanide, which are derived from hydrogen, nitrogen, methane, carbon monoxide, chlorine, and sodium hydroxide (none of these elements are derived from petroleum).

The high glass transition temperature (Tg = 110°C), tensile strength, percent elongation when stressed, hardness, density, and amorphous morphology of PECA are similar to atactic poly(styrene) which is instead challenging to recycle. Replacing PS-based plastics with PECA plastics would increase the recyclability of at least 6% of plastic waste.

03/

Bioplastics for a circular economy

3.1 Introduction

In line with the principles of the circular economy, a fair and sustainable increase in bioplastics, particularly biodegradable ones at the expense of fossil-based plastics, can strengthen the biological value cycle of all those materials that can safely re-enter the natural ecosystem, the biosphere.

These materials, once they have gone through one or more cycles of use through the so-called 'cascade effect', tend to biodegrade in different forms over time, returning nutrients to the natural environment. This process ends at the last possible stage with energy recovery through compost, which represents the last option for making the best use of resources.

While maximising resources and thus also their economic value over several cycles of use, with a view to regenerating natural capital the ultimate goal is to reintegrate natural elements into the biosphere at the end of their useful life.

Apart from a few specific local situations, which, however, are not insignificant since they almost always concern fragile economies and populations with a high rate of poverty, only 0.7 million hectares, or 0.02% of the world's agricultural area, are currently used for the cultivation of raw materials for bioplastics. Therefore, the additional pressure on agricultural land is negligible and will remain so in the coming years, even if there are high growth rates in the production of plant-based bioplastics. However, it is important that experimentation is already moving towards solutions that overcome this potential threat upstream.

The bioplastic market has attracted more than 50 leading producers and is characterized by close collaboration

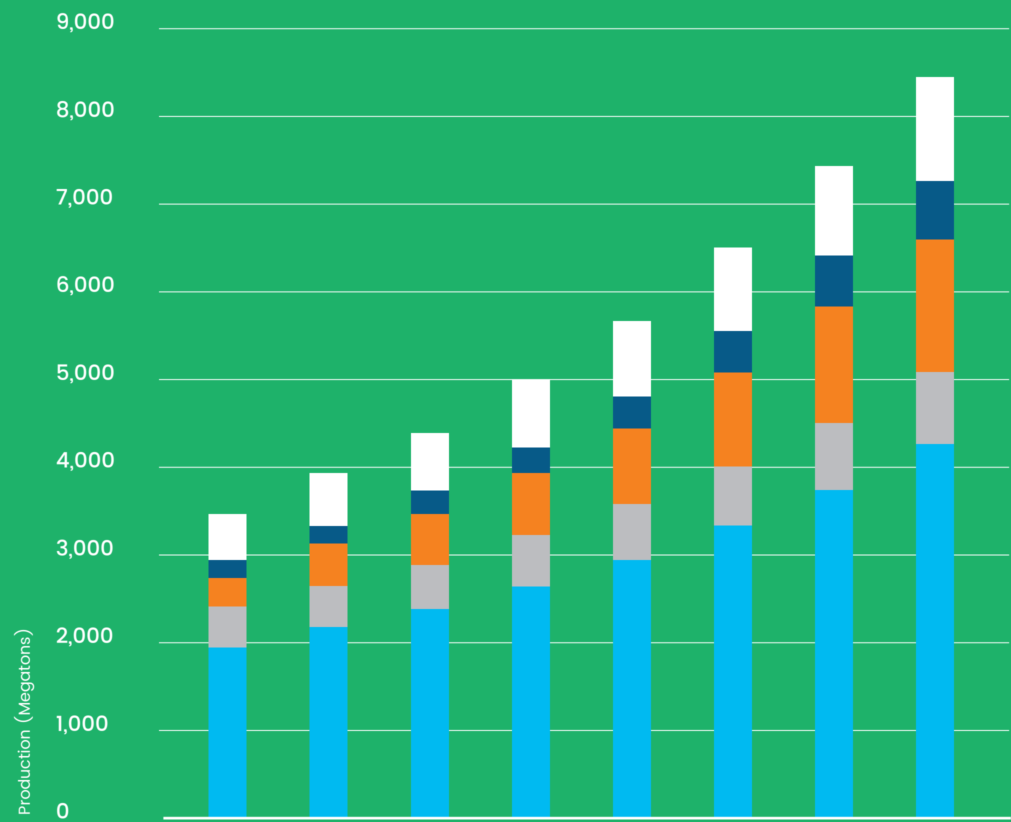
These players differentiate themselves according to the scale of their operations, their technology capabilities and their research and development (R&D) activities as well as cost.

Bioplastics find their applications across areas such as flexible and rigid packaging, consumer goods, agriculture and fishing, mobility, electronics, building and textiles. The space is currently characterized by mergers and acquisitions (M&A), notably including Advent and LANXESS' purchase of DSM's Engineering Materials (Netherlands) business, which was announced May 2022, and Huafon Group bid for DuPont's Biomaterials unit, from which it created Covation Biomaterials (USA) in the same month. More broadly, non-binding collaborations include TIPA and Aquapak Polymers' combined work on developing co-extruded films which began in August 2022.

Many of the main players are ramping up capacity with, for example, NatureWorks (USA) investing $600 million in a new 75,000-ton PLA plant in August 2021 and Avantium (Netherlands) beginning the construction of a commercial-scale furandicarboxylic acid (FDCA) facility last summer.

Bioplastic Demand Forecast by Industry, Global, 2021-2028, kT

Source: Frost & Sullivan



	2021	2022	2023	2024	2025	2026	2027	2028	CAGR 2022-2028
Others*	528.8	582.1	664.0	731.6	822.1	947.3	1,041.2	1,182.3	12.5%
Mobility	194.8	231.3	272.9	329.5	389.0	466.4	561.3	637.4	18.4%
Agriculture	349.9	443.3	561.3	698.1	854.5	1.056.3	1.325.9	1.504.1	22.6%
Consumer Goods	445.3	479.3	518.7	575.2	621.6	682.2	748.4	849.4	10.0%
Packaging	1,900.7	2,116.8	2,324.8	2,591.2	2,895.7	3,275.7	3,693.1	4,190.1	12.1%

* Others includes buildings, electronics and medical devices

Leading players include polymer manufacturers and compounders which typically still invest in other segments of the overall plastics market.
Indeed, many of the main market participants compete in several chemical industries, including BASF, Cargill and TotalEnergies. It is, as a result, challenging to extract segregated information from their financial statements (if available) on their bioplastic sales so the established competition is typically segregated into three tiers of players according to their estimated size.

Key market participants include:

- **Tier I** consist of TotalEnergies Corbion, NatureWorks, BASF, PTT MCC Biochem Co., Eastman, LANXESS, Novamont, Braskem, SABIC and Dow
- **Tier II** consists of Covation Bio, LyondellBasell, Toray Industries, Ineos, Avantium, Arkema, Danimer Scientific, Futerro, FKuR Kunststoff and Neste
- **Tier III** consists of Aquapak Polymers, Tianjin GreenBio Materials, Sinopec, Synbra Technology, Zhejiang Haizheng Biomaterials, Shenzhen eSun Industrial, Showa Denko and Kuraray Poval

The three industrial sectors with the highest penetration of bioplastics are Consumer Goods, Agriculture and Mobility.
However, by far the main area of application is packaging, regardless of the specific industrial sector.

Looking ahead, along a 7-year time frame with 2021 as the first year of observation, the highest growth rate is in the agricultural sector, followed by Mobility.
In absolute terms, however, the cross-industry area of packaging remains prevalent.

In the following chapters, we will therefore analyse how the adoption of bioplastics is taking place in the key sectors mentioned above, what their transformative potential is, who the key players and innovators are, and how much they can contribute to support the transition to a circular production model.

3.2 Agriculture, Food & Beverage

The agricultural and food industry sector, at all stages of the supply chain, is among those most involved in the search for innovative materials, whose most sought-after characteristics are biodegradability and compostability.

The agricultural sector has suffered a significant negative impact from climate change in recent decades, affected by groundwater pollution, rising global temperatures due to greenhouse gas emissions, and loss of biodiversity.

On the other hand, the agri-food industry is itself a major emitter of greenhouse gases, as well as being one of the largest generators of waste, in particular due to the extensive use of disposable containers and packaging, and so much so that in the distribution phase, packaging contributes more to global climate-changing emissions than does transport.

Last but not least, plastic packaging that is not properly recycled incurs environmental degradation, releasing contaminants such as microplastics and various additives, which are harmful both to the environment and to human health, in particular with direct long-term damage to the respiratory and digestive systems, as well as indirect consequences on the endocrine and reproductive systems.

In the agriculture, food & beverage space, the global market for bioplastics in *Agriculture* is valued at $2.4b and is growing at a CAGR of 18.5% to reach $6.7b in 2028
This equates to 443 kT in 2022.

Bioplastic in Agriculture: Growth Metrics, Global, 2022-2028
Source: Frost & Sullivan

Life Cycle Stage	Revenue	Demand
Growth	$2.41 B (2022) ↑	443.3 kTon (2022) ↑

Revenue Forecast	Base Year Growth Rate	Compound Annual Growth Rate
$6.69 B (2028) ↑	22.5% (2022) ↑	18.5% (2022-2028) ↑

Bioplastics offer technical and ecological advantages, reducing the contamination of soil and the sea by poorly performing non-biodegradable materials

Bioplastics are changing the paradigm of environmental protection for many primary economic activities, including agriculture and fishing. Demand in this segment is almost exclusively for biodegradable solutions.

In agriculture, bioplastics find their most significant application as mulch films. They serve as protection for crops and help to retain humidity in the soil; this results in a reduction in the need for pesticides and irrigation while improving the yield of the land. At the end of their useful lives, bioplastics can be composted in situ.
In the short and medium term, commodity food prices will continue to be high due to diminished production. Ukraine, a top producer of wheat, sunflower and corn, is at war with Russia, another significant agricultural producer. As a result, farmers' efforts are focused on efficiency rather than increasing arable land use.
Other trends are also gaining traction in the agricultural segment including the use of biodegradable plastic in pots, nets and pesticide-releasing systems.

Non-biodegradable fishing nets are a major plastic contaminant in marine environments. Policymakers are trying to force fishers to switch to degradable materials but face resistance. Nonetheless, their use is slowly on the rise and it is anticipated that the banning of non-biodegradable nets will stimulate and accelerate demand for specialized bioplastics over the course of the next 5 to 10 years.

RWDC Industries (Singapore) is for example harvesting plant-based oils using microbial fermentation to produce a natural PHA which can serve as agricultural film.
RWDC Industries' Solon is a polyhydroxyalkanoate (PHA), a natural aliphatic polyester manufactured using a technology that harvests plant-based oils or sugar using microbial fermentation.
The product is a biodegradable alternative to petroleum-based, single-use plastics.
Single-use plastics contain toxic substances that can severely damage the environment. These products are highly durable, do not break down easily and require hundreds or often thousands of years to degrade. Accumulation of plastics in the environment leads to water, air and land pollution.

Solon, in contrast, is biodegradable in nature and breaks down completely within weeks in soil, marine, and atmospheric conditions. Moreover, as it is manufactured from plant-based material, it does not release unwanted toxic materials during the degradation process.
Solon has been certified by TÜV Austria to be 100% biodegradable and stands apart from some competitors as it does not require the dedicated composting facilities that are needed by other compostable plastic alternatives that are available in the market.

In 2019 the company launched its first PHA-based product, a drinking straw, later followed by other kinds of products like single-use cutlery, coffee cups and lids while the company is exploring ways to use the fiber to produce alternatives to conventional plastic bags, food containers and agricultural mulch films as well as diapers and wipes.

It is the packaging sector, in particular for food applications, that is witnessing the most robust demand for bioplastics to replace single-use solutions

In addition to the positive impact from the reduction of fossil-based materials, the sector is becoming increasingly aware of the issue of rethinking the 'disposable' model in food packaging and distribution.
The first important step in this direction comes as a consequence of the Single-Use Plastics (SUP) Directive 2019/904/EU , issued in June 2019 and entered into force in January 2022, which calls on manufacturers to optimise packaging in terms of maximum possible weight reduction, use of bio-based alternatives when available, and mandatory labelling with clear and detailed information on disposal.

The combination of sustainable and **reusable** materials is the next challenge facing the agri-food industry, not least as a result of forthcoming EU regulations under the 'Green New Deal' and 'Fit for 55' initiatives.
The Commission's recent Proposal for a Packaging Regulation, for example, requires food containers to contain at least 30% recycled material by 2030 (and 50% by 2040) and coffee pods and disposable tea bags to be made of compostable bioplastic. It also calls on national governments to raise awareness, through communication campaigns and economic incentives, for the use of reusable containers for take-away food and beverages.

Regulation of the European Parliament and of the Council on packaging and packaging waste

Whether flexible or rigid, packaging is an accessory to products and is discarded more often than not but the imposition of mandatory life cycle assessments is increasingly making companies responsible for managing waste. As a result, many Food & Beverage (F&B) suppliers are looking to rethink their packaging designs, notably by switching to new alternatives to petroleum-based plastics.

Bioplastics are seeing high demand in the sustainable packaging space where the reduction of carbon footprints is a primary objective. Although demand for food packaging rose during pandemic, the overall direction of travel in the industry is focused on reducing the total weight of packaging and using intelligent material combinations.

Nevertheless, the industry is faced with a series of critical application issues related to contact with food and beverages, having to use high-performance packaging and containers for the different categories of use (e.g. contact with solid, liquid, fatty, acid substances, subjected to high-temperature processes and/or freezing) and to respond to the needs of consumers and the public, who, increasingly informed, aware and supported by EU legislation, are changing their consumption habits and pushing for a ban on certain types of packaging and wrapping.

Flexible films and trays work better with fresh products as they preserve organoleptic properties, in particular where their shelf life is limited. Compounders are therefore developing multilayer films with fewer and more specialized materials, an approach which opens the possibility of using polymers with the "best" characteristics on the inside and the outside of packaging for F&B applications. For example, some materials are suited to acting as an "inner" layer which is in direct contact with any edibles and fulfils safety and preservation functions while others are more appropriate for application in the "outer" layer by providing strength and/or allowing the use of complex consumer graphics.

In the *rigid* food packaging segment, biodegradable plastics are overall less relevant than non-biodegradables because they do not preserve the conditions of the product as effectively. This is particularly the case for carbonated drinks that require a gas barrier.

Bioplastic in Packaging: Growth Metrics, Global, 2022-2028
Source: Frost & Sullivan

Life Cycle Stage	Revenue	Demand
Growth	$10.94 B (2022) ↑	2,116.8 kTon (2022) ↑

Revenue Forecast	Base Year Growth Rate	Compound Annual Growth Rate
$18.21 B (2028) ↑	8.1% (2022) ↑	8.9% (2022-2028) ↑

In this context, it is important to highlight the role of bio-PET which is present in almost every bottle and can be recycled. Nevertheless, bio-PET often contains only one bio-based monomer out of two which represents a mere 30% of the carbon present in the solution.

The Coca-Cola Company is looking to address this issue by developing a process to produce bio-based terephthalic acid which allows the manufacture of 100% bio-based PET. In parallel, Avantium's production of polyethylene furanoate (PEF) has the potential to provide the F&B industry a new bio-based and biodegradable material for rigid packaging which outperforms conventional PET on laboratory levels but it still needs to develop its demand and capacity.

This market is valued at $10.9b and is growing at 8.1% to reach $18.2b in 2028.
This equates to 2,117 kT 2022.

Innovations are occurring in both flexible food packaging and in the rigid segment.
In the flexible packaging segment, **Metalchemy** (UK) is a bio-nanotechnology company that manufactures and distributes durable, organic packaging using nanotechnology. The company's main target market is the flexible food packaging industry where it aims to limit the use of synthetic plastic in packaging. Metalchemy currently has two active production facilities based in the United Kingdom.

Metalchemy

At the moment, most of the nanocomposites that flexible food packaging contains stem from non-biodegradable materials such as nylon and polypropylene, resulting in an influx of non-biodegradable materials to landfills. To combat this growing problem, food packaging technology developers are focusing on adopting greener materials to develop more sustainable packaging solutions.

Metalchemy has developed nano-enabled bioplastics that are completely biodegradable, biocompatible and plant-based. It has notably embedded silver nanotechnology into its bioplastic solutions which confer important antimicrobial properties that are capable of killing harmful bacteria, viruses and fungi and delaying food degradation over time.

The bioplastics that use Metalchemy's nanotechnology promise to improve foods' shelf life by three to four times when compared to "traditional" bioplastics. For instance, the company's laboratory research indicates that its solutions can allow users to keep meat for seven days more, cheese for five days and fresh salad for four days.
In addition to its effectiveness in this respect, the company claims its proprietary biochemical process can reduce the production cost versus conventional equivalents a hundredfold while also offering enhanced mechanical properties, notably including increased scratch and wear resistance.

Moving forwards, Metalchemy will need to commercialize its technology across international markets and effectively compete against a significant number of other biodegradable alternatives, such as polysaccharides for bioplastic manufacturing, which might hinder the technology's adoption rate. Nonetheless, the company has an opportunity to leverage the anti-microbial and antifungal properties of its bioplastics to expand into adjacent markets and applications in the future, such as healthcare and waste treatment industries.

In the short term, the company is focused on enhancing its nano-enhanced bioplastics technology to optimize its offerings. Metalchemy aims to scale up its manufacturing capabilities to 800 kilograms per year of bioplastic and to expand its reach across the UK market.

In the rigid packaging segment **Biofase** is a Mexico-based bioplastic company that produces biodegradable food containers and cutlery products. It has looked to address the first of these issues by developing a product which is composed of 60% biopolymer extracted from avocado seeds and 40% comprised of synthetic organic materials that enhance physical and mechanical properties.

Biofase

Its bioplastic has similar properties to polyethylene, polypropylene and polystyrene and can therefore be used for manufacturing products by injection molding, blow molding and thermoforming.

Currently, Biofase's solution is contract manufactured by Avoplast tec and is used for creating disposable straws amongst other F&B packaging products. The material does not alter the taste of food or drink which is consumed whilst offering resistance to heat and cold and possessing full approval from the US Food and Drug Administration (FDA). Biofase's products are being widely exported to Europe, North and Latin America and Australia.

Biofase's solutions have high potential. They can significantly reduce the carbon footprint and pollution stemming from conventional plastics as they can be easily decomposed in the ground without the need for dedicated facilities or particularly high temperatures.

These changes come with their share of challenges in terms of practical implementation during the transition phases.
There has been, for example, a strong growth in PET imports into Europe in recent years, which could be partly explained by the increased demand for rPET needed to comply with the SUP Directive. Figures show that PET imports doubled between 2021 and 2022, to a total volume of 1.9 million tonnes, equivalent to about 30% of European demand, compared to 23% in 2020.

After the pandemic, high-quality recycled PET is increasingly scarce and expensive, with wholesale prices 30% higher than virgin PET, as demand exceeds supply. The risk is that cheaper rPET from South-East Asian countries will not have full traceability of the polymers used, due to the use of self-declarations as a means of certifying the minimum amount of PET sourced from secondary raw materials.

A typical example of this bottleneck concerns beverage companies, especially small ones, which currently have limited access to recycled PET from their own packaging.

Italy leads Europe in recycling of compostable bioplastics

In this context, Italy is currently the leader in Europe, with a rate of recycling of compostable bioplastics and organic waste that reached 60.7% in 2021, i.e. nine percentage points higher than the already record-breaking result of the previous year.

biorepack – La bioplastica

Novamont, a pioneering Italian SME and national leader in bioplastics, famous in particular for Mater-Bi, a family of bioplastics derived from maize starch, among its many applications has developed the biodegradable mulch film that provides crops with the same benefits as traditional mulching. It can be used in different environmental conditions and on crops with different cycles.

Thanks to its complete biodegradability, it does not have to be recovered and disposed of at the end of the crop cycle but is worked into the soil where it is biodegraded by microorganisms, thus saving time and resources. The thicknesses used to manufacture the bioplastic microfilm (15, 12 and 20 microns) guarantee a good yield per hectare.

In the food sector, the Italian start-up **Innovation Utility Vehicle**, having patented a composite utilising waste fibres, seaweed and weeds, is developing applications for edible food coatings. The film degrades in 30 days and increases the shelf life of fresh food by up to three times. Trials are already underway on fruit and vegetables and waterless mozzarella packaging.

Innovation Utility Vehicle

Seaweed is also the starting point for **Notpla**'s project. Notpla is a British company that has developed a series of fully biodegradable materials suitable for food packaging, as well as an edible bubble for holding liquids that made it famous at the 2019 London Marathon and as the winner of the Earth Prize 2022.

From Sardinia, **Relicta**, a spin-off from the University of Sassari, is also turning to the sea. In this case, the basic raw material is production waste from the fishing industry, with which the start-up is able to manufacture flexible packaging that degrades in water within 20 days and is particularly suitable for heat-sealing to vacuum-pack the most delicate products, from surgical masks to foods to be preserved, to medicines, while maintaining its insulating properties for 12 months.

Relicta

Among the multinationals, in the last three years **BASF** has industrialised a line of bioplastics called Ecovio, a material with high barrier properties against liquids, fats, and mineral oils, as well as thermal stability in hot water (up to 100°C) with which it is possible to coat many types of paper and cardboard for food use. The materials, based on a polyester blend with at least 70% bio-based content, even when used with paper and cardboard, maintain high compostability.

3.3 Automotive, Transportation & Logistics

The role of plastics in vehicle design and production has always been crucial, in the pursuit of greater passenger safety, lightweight components and efficiency in performance and fuel consumption.

It is estimated that an average vehicle consists of around 30,000 parts, almost a third of which are made of plastic. Although about 70% of the plastics used involve four main polymers, polypropylene (PP), polyurethane (PU), polyamide (PA) and polyvinyl chloride (PVC), up to 40 different types of plastics are used.

The gradual spread of electric vehicles, lacking the combustion engine and all related metal components, will increase the plastic component as a percentage of the car's overall weight, a weight that will tend to decrease as improvements are made in the electric components and batteries, in order to approach the performance, especially in terms of range, of endothermic or hybrid vehicles.

In some cases, new bioplastics will not necessarily have to replace traditional plastics with the same characteristics, because, for example, the lower operating temperatures of electric motors compared to combustion engines will require a lesser performance in terms of heat resistance.

In fact, the first applications of bioplastics for the production of car parts date back to the 1930s, with the aim of reducing weight compared to metal sheets and consequently improving mileage, but after World War II, the advent of fossil-based plastics, which were cheaper and more readily available, supplanted these early applications.
A return to bioplastics, with a view to greater environmental sustainability and as an initial attempt to escape the volatility of the cost of oil, has taken place over the last two decades, primarily by Japanese and Korean car manufacturers.

To date, the main areas in which bioplastics are used are:

- Internal components, such as connectors and pipes, for which high mechanical and heat resistance is required, as well as flame-resistant or highly flame-retardant properties. For these components, the most popular materials are bio-based polyamides (Bio-PA)
- Interior fittings, e.g. floor mats, soft door, roof and floor coverings, which should look nice and feel nice to the touch, can be produced from polylactic acid (PLA)
- External body components such as bonnets, mudguards, bumpers and hard interior parts, e.g. door panels, dashboards, armrests and parcel shelves, which are produced by moulding bio-based polypropylene (Bio-PP)
- Bioplastics are used extensively in seats both for their padding, e.g. bio-based polyurethane (Bio-PU) foams, and for upholstery fabrics, which are made of bio-polyester or plant-based materials that mimic the characteristics of leather.

The global market for bioplastics in *Automotive, Transportation and Logistics* is valued at $1.1b and is growing at 15.1% to reach $2.4b in 2028
This equates to 231 kT 2022.

Here, bioplastics have a direct and indirect impact as a lightweight substitute for heavy components and a replacement for conventional petroleum-based products.

The mobility space represents a focus area for governments' efforts to promote sustainability. Here, the shift to electric vehicles has started in earnest and, moreover, many countries are banning the production – or at least restricting the use – of vehicles that run on fossil fuels, with a view to reducing and, ultimately, eliminating emissions that stem from the sector.

Bioplastics have the potential to play a double and vital role in "greening" the Mobility industry

Bioplastic in Mobility: Growth Metrics, Global, 2022-2028
Source: Frost & Sullivan

Life Cycle Stage	Revenue	Demand
Growth	$1.07 B (2022) ↑	231.3 kTon (2022) ↑

Revenue Forecast	Base Year Growth Rate	Compound Annual Growth Rate
$2.43 B (2028) ↑	15.1% (2022) ↑	14.6% (2022-2028) ↑

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Firstly, they can be used as a lightweight material to substitute for conventional heavy and often metallic parts, thereby reducing vehicles' total weight and improving fuel consumption. *Secondly*, blending drop-in bioplastics with fossil-based plastics – or replacing them altogether – reduces the carbon footprint coming from vehicles' manufacture and operation.
Polypropylene is the most widely used plastic in the mobility industry and its bio-based monomers can be deployed in any proportion through a mass-balance approach. Bio-based polyamides, such as Arkema's Bio-PA-11, were the first bioplastics to be used in vehicles, with other companies following suit, boosting their production and consumption.

In the coming decade, the role of bioplastics is expected to grow significantly in the mobility industry, helping vehicle manufacturers reduce their carbon emissions which is the principal challenge in the space. Bio-based polypropylene and polyamides will account for the greater part of demand while PLA will contribute most of the biodegradable share.

OEMs across the board are looking to leverage natural constituents as the basis for bioplastics, primarily for interior applications in cars.

PLA is increasingly used in interior vehicle parts with good results in terms of performance. Despite being biodegradable in industrial composting conditions, PLA will not degrade in use. It is therefore still suitable for long-term and hard-wearing applications. Nonetheless, **automakers will never be able to use 100% biodegradable plastic** because certain car components – often on the exterior of the vehicle – need to withstand exposure to light, heat or micro-organisms without degrading.

BMW uses kenaf to replace petroleum-based plastics in interior surfaces, including the dashboard and trim in its *i3*. These components are 30% lighter than conventional ones. **Mercedes-Benz** similarly makes seat covers from 100% recycled PET plastic bottles for its *Daimler S-Class* and the company is also experimenting with wool and bamboo.

Some notable applications of bioplastics in the automotive industry

Constituent	OEM and model	Application
Soy	**Ford** vehicles in North America	Foam in seat cushions, backs and head restraints
Corn	**Mazda** MX5	Various interior parts
Oil	**Sonata** (7th generation)	Bio foam pads
Wood	**Kia** Soul EV	Door trims and parts of the front and rear consoles
Kenaf	**Toyota** Prius	Front and rear door scruff plates and rear deck trim cover
Sugarcane	**Toyota** Sai	Seat trims and carpets
Bamboo	**Lexus** CT200h	Luggage compartment, floor mats and speakers

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Humble Bee Bio (New Zealand) is addressing this demand by applying **biomimicry** to supply plastic-like materials which could be deployed for automotive upholstery.
Humble Bee Bio started its operations in 2010 from its headquarters in Wellington, New Zealand. Its product attempts to replace some of the polymers that are clogging up the oceans and the harmful chemicals which are used in plastics manufacturing but being phased out. In parallel, it attempts to address the market's need to stay ahead of compliance while retaining product performance.

Humble Bee Bio

Plastic pollution is a big issue in New Zealand where surveys regularly place it in the top five in lists of issues people should worry about. By applying biomimicry to one of the globe's most difficult problems, Humble Bee is creating a clear link between an environmental problem and a major market opportunity by working to understand bees' potential from a product and market perspective.

Humble Bee Bio is on a mission to synthesize bee biology to provide a biodegradable alternative to plastics. The Australian masked bee is a solitary bee that produces a nesting material for depositing larvae which possesses numerous plastic-like qualities. The company's researchers are therefore employing a synthetic biology technique which entails delving into the bee's genes and proteins that are responsible for the creation of the nesting material. Humble Bee has retrieved the code and is attempting to replicate it in the lab. The company will then try to synthesize plastic-like materials, focusing on developing different biomaterials that it can transform into both fibers and fabric.

It envisages that the resultant biomaterial will be

- *resistant to acidic and basic natures*, meaning that it will not corrode
- *hydrophobic*, meaning it will be waterproof
- *flame retardant*, meaning it will be stable even at high temperatures of up to 240 Celsius

For Humble Bee Bio to be a commercial success, the company will need to accelerate time to market and be wary of the cost of its technology. Researchers also have yet to prove the degradation credentials of the product.
On the upside, the technology can scale and provide an opportunity – and showcase – for superior, biologically-inspired materials to serve as alternative polymers to industry, to improve human health and the environment and to reduce plastic pollution.

The automotive industry is developing easier-to-recycle materials aimed at improving safety, lightness and efficiency - in particular for bodywork, upholstery, and soundproofing materials - in order to reduce overall pollutant emissions during the production phase and not only during vehicle operation.

The sector has a large engineering component that has often borrowed and scaled up innovations in the use of **materials tried and tested in the aerospace sector**. In this context, the need to rethink the design of products and services in order to comply with regulatory obligations and the emerging environmental awareness of consumers is met with ample resources and know-how. The engineering capacity of the automotive supply chain has faced (and continues to face) major design challenges in order to make the use of bioplastics compatible with the standards required by car manufacturers.

Firstly, new bioplastics must maintain or improve the physical and mechanical properties of the metal or plastic materials they are replacing, taking into account the stresses that a vehicle undergoes. A non-exhaustive list of these characteristics includes resistance to temperature fluctuations, shock-absorption capacity, electrical and chemical safety requirements, and decades-long resistance to wear and tear and weathering.

Moreover, visual appeal and social status play a key role in consumer choice, which demands bio-based solutions from the industry that also maintain these aspects.
The most obvious examples relate to the need for bioplastics to be totally odourless, to allow a wide range of colours or coatings, and to be pleasant to the touch.
Since 2013, the **Eindhoven University of Technology** has been developing and testing sustainable vehicles, improving project after project the sustainability and scope of the results presented.
In 2018, with the Noah project, they created the first 'fully circular' vehicle, with a significant proportion of components made from biodegradable and compostable bioplastics, while the components using materials that do not have these characteristics were designed for full recyclability or reuse.
In 2022, the Zem project not only further improved the use of bio-based materials, but also introduced a series of measures to capture carbon dioxide from the air (DAC systems) that make the **vehicle carbon neutral**.

Zem Net Zero

Korean car manufacturer **KIA**, within the framework of its climate-neutrality goals set to be achieved by 2045, has outlined a number of material changes on upcoming cars to be marketed, including:

- the introduction of bioplastics for dashboards, interior uprights and trim components
- recycled plastic for door seals
- bio-based polyurethane (Bio-PU) to completely replace natural leather
- soft polyurethane foam for headrest padding
- organic coatings based on rapeseed oil for some interior components

The Turkish company **B-Preg** has patented a thermoformable composite laminate, called EcoRein, which can be used to replace interior car components, saving weight while providing the same technical characteristics. The material is also suitable for other automotive applications, such as parcel shelves or underbody panels.

Vegea was founded in 2016 in Milan, Italy, with the aim of fostering the integration of chemistry and agriculture through the development of new environmentally sustainable products. The focus of its work is the development of plant-based alternatives to synthetic materials derived from oil. In cooperation with Italian wineries, it has developed a process to turn wine waste into eco-leather for textiles, fashion and car interiors. No toxic solvents, heavy metals or hazardous substances are used in the production process.

Vegea

3.4 Consumer Goods

As already seen in the previous sectors, the rediscovery of bio-based materials can be traced back to the beginning of the new century, partly as a result of increased consumer attention to sustainability issues.

The global market for bioplastics in *consumer goods* is valued at $2.8b and is growing at to reach $3.5b in 2028.

This equates to 479 kT 2022.

Here, bioplastics are being boosted by the implementation of regulations.
Consumer Goods made from plastic can, in most cases, also be made from bioplastic so the potential application market is very significant and more than large enough to attract suppliers' attention. Nevertheless, given bioplastics' high price when compared to their fossil-based alternatives, they must – perhaps in this segment more than elsewhere – also add real value to compete.

Bioplastic in Consumer Goods: Growth Metrics, Global, 2022-2028
Source: Frost & Sullivan

Life Cycle Stage	Revenue	Demand
Growth	**$2.47 B** 2022 ↑	**479.3 kTon** 2022 ↑

Revenue Forecast	Base Year Growth Rate	Compound Annual Growth Rate
$3.52 B 2028 ↑	**3.7%** 2022 ↑	**6.1%** 2022-2028 ↑

Overall, however, the case for using non-biodegradable bioplastics in durable consumer goods is similar to that in other segments. Drop-in bio-based monomers have the potential to replace petroleum-based monomers partially or completely but biodegradable plastics have specialized applications as **their characteristics make them superior** to other types of plastics.

Many companies that produce consumer goods offer alternatives made from bioplastic as they show producer and consumer commitment to sustainability; in essence, they provide options to those who choose tackling climate change as a way of life. This phenomenon is becoming more commonplace, especially in geographies where purchasing power is high and the trend is growing.

Packaging is a key application area in Consumer Goods too

Again, packaging is a key application area with TGP Bioplastics (India) pushing a new biodegradable composite for ecommerce vendors.

TGP Bioplastics appeared on the scene in 2018 with the goal of advancing the mass commercialization of eco-friendly plastics. The company focuses on the business-to-business manufacturing of retail packaging to replace single-use plastics in bags and notably ecommerce shipments.

TGP Bioplastics

In India, the few biodegradable materials and composites that are available in the plastics market are expensive. Raw materials used in bioplastics can cost more than $3.50 per kg. The most cost-effective biopolymer in the Indian market is polybutylene adipate terephthalate (PBAT) which sells for $3.50–$3.75 per kg. In contrast, raw materials for conventional plastics cost around only $1.13 per kg.
TGP Bioplastics has developed a new composite material that is biodegradable, scalable and can cost $2.25 per kg to manufacture. Its solution stems from thermoplastic starch (TPS) glycerin which is modified chemically to achieve higher strength. Users of TPS-based granules can mold them into different shapes depending on the product's needs. The plastic is compostable and can replace flexible retail and ecommerce packaging in particular.

In the first instance, the company's manufacturing plant will seek to produce 880 tons of bioplastics per year. TGP's plastic bags are equal in strength to conventional single-use plastics and easy to produce at mass scale. They also have a competitive advantage in that India imports most of its biodegradable plastics while TGP will manufacture its product locally, improving cost-competitiveness and driving penetration in the domestic market.
India has recently announced it will be phasing out single-use plastics by imposing a ban on manufacturing, stocking, importing, distributing and selling single-use plastic items. Due to the lack of commercially viable alternatives, TGP has an opportunity to build a strong position in the local market if it can commercialize its product successfully and rapidly, and continue to reduce prices.

Retailers are also stepping up to the mark by switching polystyrene foam for **mushroom-based technology**.
IKEA, the Swedish furniture designer and retailer, has pledged to eliminate conventional plastics from packaging and replace them with bioplastics. The company has switched non-biodegradable Styrofoam polystyrene foam with technology based on Mycelium materials which are very highly compostable; the product has been created by Ecovative Design in collaboration with local farmers to experiment with plant-based packaging.

Kelpi (UK) is biorefining seaweed to produce compostable polybags for B2B and B2C shipments in the fashion industry.
The bioplastic produced by **Kelpi** is marine-safe and home-compostable and readily and rapidly decomposes, leaving no toxins in the environment. It forms part of a circular packaging approach and leverages a unique methodology of producing biopolymers from seaweed which is currently in the research and testing phase. Industry participants can leverage the benefits of bioplastics developed by Kelpi to reduce their carbon footprint. The bioplastic can also enhance the nutrient value of soil for agricultural purposes once degraded.
Recently, Kelpi was announced as the finalist in the Tom Ford Plastic Innovation prize which rewards and recognizes bioplastic innovators. In this context, the company is working with fashion brands to evaluate the potential of its materials to form polybags for fashion products.

Kelpi

A number of companies, including the Dutch Avantium and Corbion, are experimenting with the industrial opportunities of PEF as a 100% plant-based, recyclable and degradable alternative to the much more widely used chemical equivalent PET. Although it was patented in 1951, its better barrier properties against oxygen, carbon dioxide and water vapour have only recently been rediscovered and taken into consideration.

The regulatory framework now being defined will certainly provide a strong impetus for rethinking everyday design with features that also take into account a different end-of-life path for the object itself.
The Finnish beauty products company **Lumene** was the first to launch a bio-based packaging application in which both the jar and the label are made from renewably sourced material produced by UPM, through bio-naphtha synthesised from the processing waste of wood from Finnish forests.

Lumene – Sustainability

Israeli company **UBQ** has patented the first thermoplastic material produced entirely from organic waste and residues, certified to contain a minimum of 50% bio-based material. Originating from waste, it is fully recyclable at the end of its life.

UBQ material

Among the various applications, the company reports working on trays for McDonald's restaurants, the production of clothes hangers, some plastic components for the Mercedes Benz group and the production of a filament for 3D printing with Plastic App.

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3.5 Final considerations

As seen thus far, Advanced Materials have a vast untapped potential to be key drivers in the fight against climate change and toward sustainable development. Their properties allow for innovative uses and technological advancements in potentially every field, with consumer goods, mobility, and the food industry being only some of the possible examples, as the previous chapter has shown. Through extensive research and development, these materials have demonstrated their potential to address the environmental concerns associated with conventional plastics, such as carbon emissions, non-renewable resource depletion, and waste management challenges.

While the progress made in bioplastics and advanced materials is promising, challenges remain. Scaling up production, improving material performance, and ensuring cost-effectiveness are key areas that require continued research and development. Cooperation between academia, industry, and policymakers is crucial to drive innovation, promote standardization, and establish supportive regulatory frameworks that encourage the adoption of these materials.

Guidelines published at the European level are already paving the way for member states' initiatives for cooperation in advancing the research and accelerating the development and employment of these materials, as they can be pivotal catalysts for the twin green and digital transition.

When it comes to consumption and perceptions at the citizens' level, extensive evidence shows widespread positive attitudes of consumers toward the shift from conventional petroleum-based plastic to bio alternatives.
From studies carried out at the global level, to the European, and the Italian one, results continuously showcase an overall positive predisposition of consumers toward choosing to purchase bioplastic products rather than their conventional alternatives, which is especially true when looking at the most educated pockets of society.

There is a direct correlation between the level of knowledge of bioplastics and the propension to buy them

This attitude has been shown to also be positively correlated with knowledge on the topic: when given more information about bioplastics, participants reported a higher inclination to buy them, highlighting the need for a correct education of the public about these new materials and their positive environmental impacts to effectively transition.

As regards environmental impact, it should also be pointed out that the damage caused by fossil-based plastics dispersed into the environment is twofold: firstly, and in a relatively short span of time, plastic objects, either individually or in heaps of varying size, directly damage ecosystems, causing irreversible damage to biodiversity. Secondly, in the medium and long term, they enter the human food chain directly, as their micro-fibres are absorbed by animals and plants, which in turn are used in our diet.

While it is true that the rate of recycling in Western countries is steadily increasing, looking at the problem on a global scale, even today **about 85% of the plastics produced are then dispersed into the environment**. Therefore, while waiting for the widespread adoption not only of a recycling culture, but also of infrastructure and operational processes that make it widely feasible, a massive migration towards biodegradable bioplastics (see Chpt. 2.2.1) is an effective first response to a problem that, if not addressed, will remain as a heavy legacy for the next five centuries, i.e. the average time our planet needs to degrade fossil-based plastics.

The necessity of proper education of consumers on Advanced Materials and their properties is also crucial as a tool to debunk common myths and misconceptions which may hamper citizens' willingness to consume them or even lead to detrimental practices; for example, misinformation about bio-based plastics can lead consumers to litter as they are not aware of the specific conditions needed for the materials to effectively biodegrade.

From a holistic perspective, from all that has been written so far, we can clearly see how **the circular economy approach is closely linked to the development of advanced materials**. Particularly when it comes to bioplastics, there is a close synergy and interconnection related to the protection and regeneration of the natural environment.

If we adhere to the three founding principles of the circular economy, (i) designing without waste and pollution, (ii) keeping products and materials in use for as long as possible and (iii) regenerating natural systems, the replacement of fossil-based plastics with bio-based materials becomes an enabling factor for all three principles.

Firstly, reducing dependence on fossil resources enables a pathway for the abatement of climate-changing gases by contributing directly and indirectly to an overall improvement in the use of natural resources.

If this approach is integrated into the design phase, both for the materials themselves and for the products, the advantages in terms of efficiency, optimisation and recovery of resources generate multiple benefits in the long term, with decisive impacts also on the regeneration of what has been compromised to date through the exploitation of the planet resulting from the linear economic model that still prevails.
In an ideal virtuous circle, the adoption of circular economy principles encourages innovation in the bioplastics sector, which in turn enables the increasingly stringent application of circular business models.
A fully sustainable economic model requires an approach that includes the responsible use of bioplastics within a broader circular economy system that takes into account the greatest possible reduction, reuse and recycling of all materials.

Ultimately, it is also the responsibility of each one of us to actively sponsor the migration to a sustainable economic model by making more informed and conscious consumption choices that are in full harmony with the planet that hosts and sustains us.

Acronyms & Abbreviations

AA Adipic Acid

AC Aerobic Composting - the large-scale composting of products of a particular thickness or particle size, in the presence of oxygen, at elevated temperatures and with specific moisture conditions, oxygen levels and nutrient ratios

AD Anaerobic Digestion - the break down of biodegradable material by microbes in the absence of oxygen

AS Australian Standard

ASTM American Society for Testing for Standardization

BDO Butanediol

CAGR Compound Average Growth Rate

CEN European Committee for Standardization

DIN Deutsches Institut Für Normung OR German Institute for Standardization

EOL End Of Life - the ultimate disposal destination or recovery method after a products' use

EPR Extended Producer Responsibility

EU European Union

EVOH Polyethylene vinyl alcohol

FCM Food-Contact Materials

FDCA 2,5-Furandicarboxylic Acid

GHG GreenHouse Gases

HDPE (#2) High-density polyethylene

JBPA Japan BioPlastics Association

LCA Life Cycle Assessment - cradle-to-grave or cradle-to-cradle analysis techniques to assess environmental impacts associated with all the stages of a product's life

LDPE (#4) Low-density polyethylene

LLDPE (also #4) Linear low-density polyethylene

LUC Land Use Change

LULUCF Land Use, Land Use Change and Forestry

MEG Monoethylene Glycol

OECD Organization of Economic Co-operation and Development

OPRL On-Pack Recycling Label

PA Polyamide

PBAT Polybutylene adipate terephthalate

PBS Polybutylene succinate

PBSA Polybutylene succinate adipate

PBT Polybutylene Terephthalate

PCL Polycaprolactone

PE Polyethylene

PECA Poly(Ethyl Cyanoacrylate)

PEF Polyethylene Furanoate

PET (#1) Polyethylene terephthalate

PGA Polyglycolic Acid

PHA Polyhydroxyalkanoate

PHB Poly(3- & 4-hydroxybutyrate)

PHBH Polyhydroxy-butylhexanoate

PHBO Poly(3-hydroxybutyrate-co-3-hydroxyoctanoate)

PHBV Polyhydroxy-butyratevalerate

PLA Polylactic acid

PP (#5) Polypropylene

PPWR Packaging & Packaging Waste Regulation

PS (#6) Polystyrene

PTA Terephthalic acid

PTT Polytrimethylene Terephthalate

PUR Polyurethane

PVAC Polyvinyl Acetate

PVC (#3) Polyvinyl Chloride

PVOH / PVA Polyvinyl Alcohol

RED Renewable Energy Directive

SA Succinic Acid

TPS Thermoplastic Starch

ZWE Zero Waste Europe

About Intesa Sanpaolo Innovation Center
Intesa Sanpaolo Innovation Center is the company of Intesa Sanpaolo Group dedicated to innovation: it explores the world of cutting-edge innovation, invests in applied research projects and high-potential startups and accelerates the implementation of the circular economy criteria, to make Intesa Sanpaolo the driving force behind a new economy that is socially and environmentally aware.
Based in the Turin skyscraper designed by Renzo Piano, with its national and international network of hubs and laboratories, the Innovation Center is an enabler of relations with other stakeholders of the innovation ecosystem - such as tech companies, start-ups, incubators, research centres and universities - and a promoter of new forms of entrepreneurship in accessing venture capital.
Intesa Sanpaolo Innovation Center focuses mainly on circular economy, development of the most promising start-ups, venture capital investments of the management company Neva SGR and applied research.

About Materias
Materias is an innovative SME aiming to create new businesses, supporting the development of innovative solutions in the advanced materials sector and accelerating their market entry. Materias invests in science-based new ventures supporting the most promising technologies to overcome the "Death Valley", through the connection of the research world with industrial companies.
The company operates on scientific knowledge-based technologies, which require more costs and risks than digital innovations. The work carried out by Materias has allowed the scouting of over 1.100 ideas in the advanced materials sector, going from life science, civil engineering, food-tech to industrial engineering.
The development of applied research projects and the management of intellectual property has allowed the company to increase its value and strengthen its intangible assets by feeding the technology database and the patent portfolio. Materias has created an innovation ecosystem that has allowed the company to come into contact with excellent public and private research Centers of international relevance.
The ecosystem has generated a valuable contribution in terms of technology transfer and first industrialization in partnership with universities and Public Research Centers.

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