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Linking bioeconomy, circular economy, and sustainability: Trends, gaps and future orientation in the bio-based and biodegradable plastics industry

Eleonora Foschi[1], Selena Aureli[2], Angelo Paletta[3]

[1] University of Bologna, Department of Business Studies - Via Capo di Lucca 34, Bologna - Italy
eleonora.foschi3@unibo.it

[2] University of Bologna, Department of Business Studies - Via Capo di Lucca 34, Bologna - Italy
selena.aureli@unibo.it

[3] University of Bologna, Department of Business Studies - Via Capo di Lucca 34, Bologna - Italy
angelo.paletta@unibo.it

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Abstract

Bio-based and biodegradable plastics (BBPs) are innovative materials, wholly or partially produced from biomass, with the potential to enhance the circulation of resources in the biological cycle of the Ellen MacArthur Foundation's butterfly diagram. Although BBPs are generally considered more environmental-friendly than conventional plastics, robust scientific evidence is still missing. The lack of tools and metrics to assess the circularity and sustainability of the BBPs industry poses relevant challenges for its upscaling and contribution to climate neutrality goals in Europe. It also calls for adopting system and life cycle thinking, guided by multi-level and multi-dimensional examinations, which are used in this paper to build a comprehensive picture of trends, gaps and future orientations that may boost a sustainable circular bioeconomy in the sector. The value- chain based and multi-faceted SWOT analysis that emerged from the intersection of system and corporate data reveals the need to establish a combined circular bioeconomy strategy where incentives to integrated local supply chain, dedicated EPR schemes, eco-design guidelines, revised EoL standards, new clear labelling schemes and harmonised sustainability criteria should be prioritized and conjointly pursued to accelerate the transition towards a sustainable circular bioeconomy of the BBPs value chain.

Keywords: Bioeconomy; Circular economy; Sustainability; Bio-based and biodegradable plastics

1. Introduction

The exploitation of fossil resources has defined recent decades. The oil demand moved from 2,720 million tons in 1975 to 4,070 million tons in 2020 (Ibrahim et al. 2021). The gradual rise of a fossil-based society has contributed to a massive increase in global greenhouse gases (GHGs) (Center for International Environmental Law, 2018), accounting for 52.6 billion

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tons in 2020 (Jones et al., 2023). The chemical and plastics industries are responsible for around 7% of global GHG emissions (World Economic Forum, 2016). Because of the demand for fuel as a raw material input in addition to energy, the chemical sector (including the production of ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol) was responsible for 935 million tons of GHGs in 2022, while 1.6 billion tons of GHG emissions were emitted in the same year in plastics production and conversion processes (OECD, 2023).

Indeed, oil and derivates are a leading cause of global warming (Kweku et al., 2018), responsible for about one-quarter of the greenhouse effect (Gleckman, 1995). To meet the climate neutrality mission by 2050, EU countries are forced to decouple economic growth from oil extraction. In this regard, the so-called bioeconomy plays a pivotal role (Ronzon et al., 2022). Bioeconomy is "the economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources" (McCormick and Kautto, 2013). Converting biomass (e.g. crops, wood, energy plants, agricultural and forestry residues, municipal, industrial, and food wastes) into high-value end-products, such as food, bioenergy, biofuels, biochemicals, bio-based plastics (Yang et al., 2021; Mougenot and Doussoulin, 2022), the bioeconomy model seeks to substitute fossil carbon with bio-based carbon and uptake biogenic CO2 (Leiplod and Petit-Boix, 2018).

Although bioenergy and biofuels are the most advanced applications (Adamowicz, 2017; Nazari et al., 2021), an acceleration in R&D for innovative materials under the bio-based plastics umbrella has been recently noticed. Driven by the increasing awareness about marine littering (Gold et al., 2013), the legislative commitment toward circular economy (CE) (Foschi and Bonoli, 2019), the green purchasing trend (Filho et al., 2021; Moorthy et al., 2021) and the multiplying challenges affecting global supply chains (Arikan & Ozsoy, 2015), the production capacity of bio-based plastics is expected to increase from 2.12 million tonnes in 2022 to approximately 6.3 million tonnes in 2027 (European Bioplastics, 2022). However, while extant literature deeply scrutinises the influence of bioenergy and biofuels to climate neutrality, more is needed to know about bio-based plastics. Indeed, bio-based plastics refer to a large range of materials (see section 2.1.) that may provide reasonable solutions to many environmental concerns. First, bio-based plastics may contribute to decarbonization because of their lower carbon footprint compared to fossil-based counterparts (Boonniteewanich et al., 2014; Muhammad Shamsuddin, 2017; Philp, 2014; Piemonte, 2011; Spierling et al., 2018; Bishop et al., 2021). Second, when compostable, bio-based plastics may solve the challenges faced by waste recycling facilities with regard to food contamination and complex product design (Paletta et al., 2019). Finally, when biodegradable, bio-based plastics may represent a panacea for microplastic generation, ecotoxicity and marine pollution in general (Meereboer et al., 2020). Yet, it has to be noted that many issues are still open when considering the contribution of bio-based plastics to circularity and sustainability. As Bishop et al. (2021) pointed out, the lack of a holistic picture of the environmental impacts of bio-based plastic products makes LCA studies unreliable. As a result, Yan et al. (2021) highlight the risk of biased or misleading estimates of climate mitigation contribution.

Others have questioned the impact of bio-based plastics on resource preservation, as their production is still primarily based on virgin feedstock, thus creating pressure on natural ecosystems and increasing competition for land usage (D'Adamo et al., 2020; Imbert, 2017). In addition, the one-to-one substitution trend from conventional to bio-based plastics observed among converters could undermine the expected environmental benefits if the design process does not consider the specific conditions of use and disposal. Indeed, these materials may not foster the loop closing if consumers are not well informed about the proper disposal pattern, dedicated waste infrastructures are not established, advanced biotechnological recycling technologies are not developed and more in general, when heterogeneity and fragmentation continue to characterize waste governance across Europe (Rosenboom et al., 2022). Although the above-mentioned critics highlight that tighter integration between bioeconomy and CE is necessary (D'Amato and Korhonen, 2021), many additional concerns related to carbon sequestration, biodiversity, biodegradability in soil and marine environments and toxicology still exist and compromise the overall reliability of these materials (Nessi et al., 2021; Arantzamendi et al., 2023). As pointed out by the European Commission (2018b) in the Bioeconomy Strategy "To be successful, the EU bioeconomy needs to have circularity and sustainability at its heart". Translating this intent into the BBPs industry, the present work aims to investigate what hinders and enhances BBP materials' transition to a sustainable and circular bioeconomy. In line with Leipold and Petit-Boix (2018), this study mobilizes the business community and policymakers, addressing the following questions:

RQ1. What legislative, economic, social and environmental trends may affect the circularity and sustainability of BBPs?

RQ2. Which are the key strenghts and weaknesses detected by business players and able to accelerate and/or hamper the circularity and sustainability of BBPs?

With the final objective of providing recommendations and future orientations for a more sustainable circular bioeconomy in the BBPs value chain.

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Given that circularity depends on the system in which materials or products are distributed (European Environment Agency, 2017), the analysis was contextualized to European countries. System and life cycle thinking were adopted in line with sustainability and circularity principles. Moreover, multi-dimensional analysis was used to collect and intersect legislative, economic, social and environmental aspects, while multi-level examination (i.e. at system level and corporate level) supported the authors in identifying mutual impacts, moving from system dimension to business environment and vice-versa.

The paper is structured as follows: bio-based plastics value chain is reported in section 2, followed by research design and methodological framework (section 3). Findings from the system (section 4) and corporate (section 5) analysis are summarized in the discussion and conclusion sections.

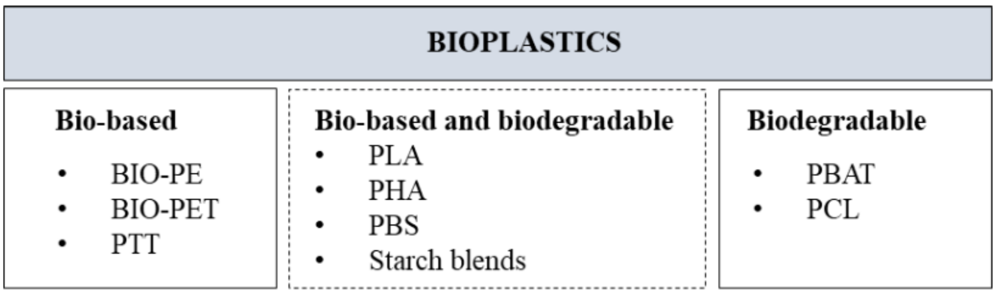
2. Background

2.1 Plastics and bioplastics value chain

The term plastics reflects a wide range of materials, but it commonly refers to conventional plastics that are petroleum-based and degrade over hundreds of years. The term bioplastics, by contrast, still needs a valid and recognized definition. The term has been used to describe bio-based and/or biodegradable plastics, which has generated misunderstandings among scientists and consumers. Under this consideration, the European Commission started a massive informative campaign to recommend using specific terminology (Filho et al., 2021) that could reflect both sourcing and biodegradability properties.

Bio-based plastics are mostly derived from renewable resources (Álvarez-Chávez et al., 2012; DiGregorio, 2009) where the bio-based plastics content is determined by CEN/TS 16137:2011 standard. Commercially available bio-based and potentially biodegradable polymers are polylactic acid (PLA), polyhydroxyalkanoates (PHA) and starch blends (see Figure 1). As circularity, biodegradability is a system property (European Bioplastics, 2015) that flows from the environment in which the material degrades. Many factors influence the biodegradability of materials, including the type of microorganisms, the molecular polymers' structure, and the product design (Molenveld and Zee, 2020). So, degradation in aquatic systems involves physical, chemical and biological processes and mainly depends on water temperature and polymer shape (Volova et al., 2010); biodegradation in the soil is determined by the presence of bacterial biomass (Adhikari et al., 2016) while experimental conditions influence biodegradation in industrial plants (Thakur et al., 2018).

Figure I. Commercially available bioplastics



Source: Authors' elaboration

However, not all bio-based plastics are biodegradable. Bio-based non-biodegradable plastics include bio-polyethene (bio-PE), bio-polyethene terephthalate (bio-PET), and polytrimethylene terephthalate (PTT). Biodegradable plastics but fossil-based, such as polybutylene adipate terephthalate (PBAT) and polycaprolactone (PCL), are also considered bioplastics, but the use of this terminology is discouraged (Pellis et al., 2021) since their production is still oil-dependent.

In addition, renewability and biodegradability properties strongly affect the upstream and downstream sides of the existing plastics' value chain. Depending on the surrounding conditions, both properties can have a completely different characterization. While fossil-based plastics are mainly made in petrochemical refineries—where oil is subject to distillation, cracking, polymerization and blending processes—bio-based plastics are manufactured through either chemical processes (hydrolysis, dehydration, etc.) or biotechnological processes (fermentation, extraction, etc.) in biorefineries (Ubando et al., 2020). Based on the type of biomass used, bio-based plastics can be sourced from three different feedstocks: (i) 1st

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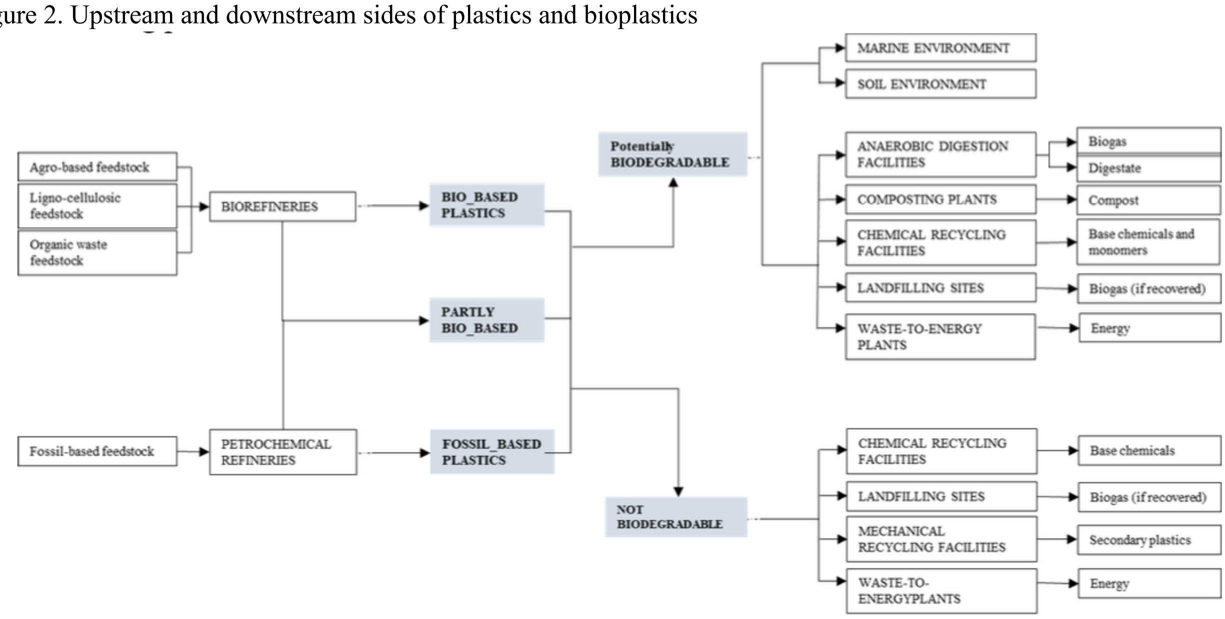
generation, such as corn or sugar cane; (ii) 2nd generation, which can be either non-food crops (e.g., cellulose) or agro-industrial waste; or (iii) 3rd generation, sourced from algal biomass, which has a higher yield than 1st and 2nd generation feedstock. Today, most bio-based plastics derive from crop-based feedstock (Philp, 2014), while the 2nd generation is available in small volumes, and the 3rd is still in early development.

Figure 2. Upstream and downstream sides of plastics and bioplastics



Source: Authors' elaboration

The end-of-life (EoL) opens the doors to a variety of waste management scenarios (See Figure 2), leading to first distinguishing controlled and uncontrolled environments. Industrial-scale facilities monitor and manage material recycling or energy recovery performances with the former. Meanwhile, the latter generally refers to an open environment, mainly soil and marine ecosystems (European Environmental Agency, 2018; Karan et al., 2019). Notwithstanding that existing ISO 17556 and ASTM D5988 provide criteria for the biodegradability of plastics in soils only and a standard for biodegradability in marine environments is under discussion (European Commission, 2022), recent studies bring into discussion the validity of these standards outside of laboratory conditions which on one side do not reflect what is commonly expected in a natural environment and, on the other, do not capture the extreme variation of natural conditions (Emadian et al., 2017; Briassoulis et al., 2017; Harrison et al., 2018; Di Bartolo et al., 2021).

Although BBPs are mainly incinerated or landfilled today, mechanical, organic and chemical recycling are the preferred EoL options in controlled environments (Ramesh Kumar et al., 2020). Mechanical recycling is suitable for the management of the drop-ins (bio-PE, bio-PET, bio-PTT, etc.) since they have the same chemical composition as their fossil-based counterpart, which are widely present in Europe for the treatment of traditional plastic waste streams (Paletta et al., 2019). Organic recycling theoretically treats bio-waste streams with compostable and biodegradable plastics certified by the European EN 13432, EN 14995, or the international ISO 17088. Organic recycling infrastructures include anaerobic digesters and/or composting plants (Carlini et al., 2017). Another emerging scenario is chemical recycling, which is based on hydrolysis, alcoholysis, glycolysis, aminolysis and ammonolysis (Lamberti et al., 2020) and allows the extraction of high-value chemicals/monomers from different biopolymers. However, chemical recycling infrastructures need to be well-established in Europe, slowed down by the high costs of depolymerization (Di Bartolo et al., 2021).

2.2 Bio-based and biodegradable plastics in the context of sustainable circular bioeconomy

CE is a system where the value of products, materials and resources is maintained in the economy for as long as possible while waste generation is minimized (European Commission, 2018a). In other words, CE is an economic system where the

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EoL concept is replaced with production, distribution and consumption processes that reduce, reuse, recycle, and recover materials in service of sustainable development. As less dependent on oil, bioeconomy is perceived as an opportunity to mitigate climate change while sustaining economic growth and human well-being (Phil et al., 2018). However, combining CE with bioeconomy has prompted reflections on the circular bioeconomy. Indeed, while CE and bioeconomy definitions are trending among practitioners and academics (Kirchherr et al., 2017), circular bioeconomy has yet to be fully explored in the literature. Even so, the residual research stream dealing with circular bioeconomy reveals conflicting opinions on the interlinkages between the two economic models: while some authors consider the bioeconomy to be "circular by nature" (Sheridan, 2016), others express concerns about the risks of following a linear business-as-usual approach (Bezama, 2016; Stegmann et al., 2020; Tan and Lamers, 2021). The most recognized definition comes from Stegmann et al. (2020), who defined the circular bioeconomy as "an economic model in which bioresources are used to make products with the highest possible added value in a sustainable way, with a cascaded use of materials and minimizing resource inputs and outputs to the natural environment". In line with the biological cycle of Ellen Mac Arthur Foundation's butterfly diagram, circular bioeconomy emphasizes the use of renewable resources, cascading the use of biomass and reintroducing biological nutrients in the biosphere (Ellen Mac Arthur Foundation, 2019; Karan et al., 2019). Applying this concept to bioplastics, only BBPS, and consequently, compostable plastics, have the potential to circulate and recirculate in that cycle. From this, we can surmise that BBPs are:

H1. Circular when added value is created and retained in further production and consumption cycles.

H2. Sustainable when natural resources are not depleted and environmental impacts are minimized.

Unfortunately, the analysis along the value chain reveals the emergence of a take-use-dispose model characterized by virgin biomass supply in the upstream stage and immature EoL scenarios downstream. Since existing circularity and sustainability metrics are still at the infancy stage for these applications (Bishop et al., 2021; Chioatto and Sospiro, 2022; European Commission, 2018b; Yates and Barlow, 2013), results are often contradictory and, consequently, inconsistent. Moreover, the integration of economic, social and environmental impacts needs to orientate decisions towards a sustainable circular bioeconomy (Blum et al., 2020; Rosenboom et al., 2022). It follows that a major interplay between the circularity and sustainability of BBPs needs to be investigated. To do that, a better understanding of what sustainable circular bioeconomy pragmatically means in the BBPs industry is necessary.

3. Method and materials

3.1 Research design

To scrutinize the circularity and sustainability of BBPs, the research design has been informed by a combination of life cycle and system thinking. Life cycle thinking is crucial in CE studies to assess the impacts of materials, products or services from raw materials supply to EoL and make evidence of closing, narrowing or slowing resource loops (Heiskanen, 2002). Instead, system thinking is commonly used in sustainability transition theories (Barbier and Burgess, 2017) to understand how different parts of the system where firms operate are interrelated and evolve over time. Multi-dimensional analysis contributed to examining system dynamics from multiple domains (Meadows, 2009). Coherently, multi-level investigation supported better identifying relationships between macro and micro levels. Macro-level analysis has been conducted through a literature analysis of legislative, economic, environmental, and socio-cultural trends characterizing BBPs. Micro-level analysis has been advanced through the realization of semi-structured interviews with the key players of the bio-based plastics industry, including EU material suppliers, converters, end-users and waste managers.

3.2 Data collection and elaboration

Precisely, a literature analysis was performed to reconstruct the legislative roadmap that framed the bio-based plastics industry and gathered qualitative and quantitative data on the market and community behaviours. Then, an empirical analysis was run to collect insights at the corporate level by directly engaging business players. In total, 40 key players operating in the European market were invited by e-mail to participate in the research. Specifically, the top five market players were

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invited for each stage of the value chain. Per each company, the sustainability or product manager was interviewed. The interview protocol is reported in Appendix I. Each interview lasted for about one hour on average. Interviews were recorded, transcribed and manually coded. Two researchers always participated in the interviews and jointly performed the text analysis to increase reliability.

Then, secondary data collected through a desk research of scientific papers, policy documents and research outcomes published by organizations outside of the traditional academic communication channels (i.e., the so-called grey literature), were intersected with the primary data obtained from interviews to get insights on the key elements driving a sustainable circular bioeconomy in BBPs value chain.

4. System analysis: existing trends in the European bio-based biodegradable plastics industry

4.1 Normative and legislative perspective

The establishment of the EU Strategy for Bioeconomy in 2012—and its revisions in 2018—have served as a roadmap for European economies (Ronzon et al., 2022). Compared to the first version, the updated statement shows a better integration of environmental, economic and social aspects by promoting local bioeconomies and ensuring that the same legislative and financial efforts are applied to all sectors, including bio-based plastics (Ronzon and Sanjuán, 2020). This new approach has prompted European countries to build up their own orientations for a sustainable and competitive bioeconomy in Europe (Bracco et al., 2018; McCormick and Kautto, 2013).

Concerning bio-based plastics, the key EU policy document is the Circular Economy Action Plan and its updated version published in 2020 that still allocates resources to these materials through a focus on sustainable sourcing and standardized labelling schemes (European Commission, 2021). As part of the Green New Deal, this intention is operationalized in a public consultation aimed at examining the sustainability of the feedstock as well as the role of biodegradability and compostability in specific environments. From the legislative point of view, the Directive 2015/720 (European Commission, 2015) has compelled a solid push for the BBPs market by introducing a progressive elimination of very lightweight plastic carrier bags and a transition to biodegradable and compostable single- use bags and long-life reusable bags (Foschi and Bonoli, 2019). Furthermore, the Directive 2018/851 allocates attentions to EPR schemes and their role to foster shared responsibility among packaging users, consumers and recyclers but their scope should be extended to industries (European Commission, 2018b).

Almost simultaneously, the Directive on Single-Use Plastics (SUP) introduced market restrictions to reduce the consumption of certain categories of SUPs like straws, plates, cutlery, food containers, beverage containers and beverage cups (EU Directive 2019/904). Alongside the market-based instruments, legislators introduced a plastics tax in 2021 on non-recyclable plastic packaging waste (European Commission, 2020) to accelerate reusable, recyclable and compostable plastic packaging, as promoted by the European Strategy for Plastics in a Circular Economy (European Commission, 2015). The recent policy framework on bio-based, biodegradable and compostable plastics sets out the conditions that have to be met to ensure overall positive environmental outcomes from the production and use of these plastics, including a) supply of sustainable feedstock; b) use of bio-based plastics in long-lived products; c) use of plastics that biodegrade in open environments only wherein applications and contexts where the full biodegradability has proven under specific real, local conditions and timeframe; d) use of compostable plastics only in applications and contexts where a compatible waste collection and treatment system is in place (European Commission, 2022).

A comprehensive overview of the normative aspects is summarized in the following Figure.

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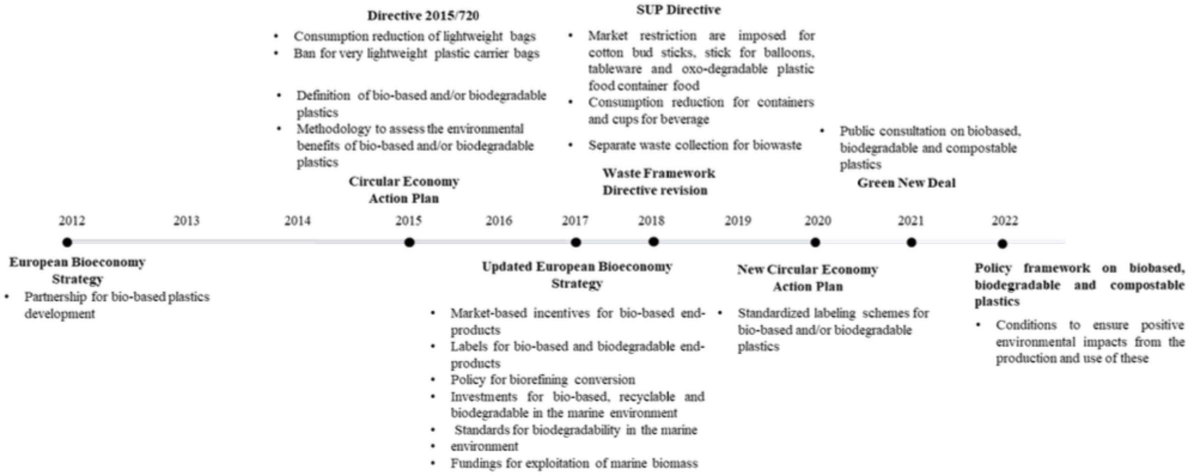
Figure 3. Relevant EU policies affecting the BBPs industry



Source: Authors' elaboration

4.2 Economic perspective

According to the statistics published by European Bioplastics (2022), the 2022 European bioplastics demand can be estimated at slightly more than 2.2 Mt, with a slight prevalence of bio-based and biodegradable compared to the non-biodegradable ones. Indeed, bio-PE, BIO-PA and bio-PET and PTT contribute to 48% of the total share. Besides the competition with r-PET, only a few beverage companies such as Coca-Cola, Pepsi and Nestle have launched bio-based bottles to the market (Lamberti et al., 2020). Among the biodegradable fractions, PLA, PHA, and starch blends are the most demanding biopolymers, accounting for 52% of the total share in 2022 (European Bioplastics, 2022). Even if these blends are predicted to increase in the following years, one of the most challenging elements characterizing the market of biodegradable and compostable plastics is the limited availability of the materials due to the small production capacity and the difficulties of reaching economy-of-scale. Indeed, about 20 compounding sites are active in Europe, some of which have multiple value propositions. They are generally backwards-integrated on intermediates and even base chemicals, while some are downward-integrated on manufacturing semi-finished and finished goods. Because of this situation, there are difficulties in collecting and sharing official data (Castellano, 2018). However, among the leading companies, only a small-scale PLA polymerization plant is located in Europe while the key player is NatureWorks LLC, with a manufacturing facility in Nebraska and a new site in Thailand, expected to be ready by 2024 (PlasticConsult for Assobioplastiche, 2020). The European output of thermoplastic starches (TPS) is estimated at over 200,000 tons in 2019, with the highest capacity detected by Novamont, recently acquired by Eni-Versalis, followed by minor Dutch and German companies (PlasticConsult for Assobioplastiche, 2019 and 2020). PHA is not commercially available in Europe, but nearly 50% of the global production (estimated to be less than 100,000 tons) comes from Metabolix, Danimer Scientific and RWDC Industries, whose production sites are in USA and Singapore (Rosenboom, 2022).

4.3 Social perspective

About the circularity of BBPs, end-users and consumers play a crucial role in preserving the intrinsic value of BBPs, especially during consumption and disposal patterns. Driven by the increasing awareness about the impact of plastics in worldwide oceans, consumers' attitudes toward the proper use of plastics are massively growing. Filho et al.'s (2021) survey of 16 European countries revealed that 74% of respondents segregate plastic waste and dispose of it properly in specific containers, per their country's regulations. However, compostability and biodegradability properties are still confusing

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(Lynch et al., 2017). Moreover, the distinction between conventional plastics and BBPs for consumer packaging largely challenges European and international consumers (Dilkes-Hoffman et al., 2019).

Several studies have examined the general influence of consumers' sociodemographic characteristics on the green purchasing trend (Reinders et al., 2017). The study by Klein et al. (2019) revealed that gender, age and education do not influence the purchase intention or bioplastic products; instead, values, attitudes, product experience and interest in information have the strongest impacts. Several previous studies have identified a clear link between consumer psychological traits such as attitudes, perceptions and motivations, and consumer acceptance of alternative plastics such as those that are bio-based or biodegradable (Fletcher et al., 2021, Barbir et al., 2021, Filho et al., 2022, Stasiškienė et al., 2022).

4.4 Environmental perspective

Although BBPs are perceived as more environmental-friendly compared with conventional plastics (European Commission, 2022), robust scientific evidence still needs to be included. Existing LCA studies need to be more comprehensive regarding methodology, data source and results, making comparability difficult. If cradle-to-gate studies laid down on the uptake of biogenic carbon through the feedstock, the GHG-emissions profile is acute when considering EoL, Comparative cradle-to-grave study analysed by Spierling et al. (2018) on eight bio-based and conventional plastics shows negative impact categories for the first compared with the second, mainly due to energy consumption during the waste management (Hottle et al., 2017). Moreover, EoL impacts are difficult to estimate because of the lack of traceability for compostable and biodegradable plastics today and, at the same time, the lack of estimation about biodegradability performance of different biopolymers in different environments first, and the impacts of biodegradation processes on the environment and human health then. Additionally, most of the studies are based on examining the global warming potential impact category, underestimating other relevant impacts such as land use, water use and biodiversity (Di Bartolo et al., 2021).

5. Corporate analysis: strengths and weaknesses influencing the sustainability and circularity of the bio-based and biodegradable plastics value chain

Data collected from the semi-structured interviews allowed the researchers to move from the system to the corporate level and identify strengths and weaknesses influencing the sustainability and circularity of the bio-based and biodegradable plastics value chain. Sustainability and circularity are values that have pushed firms to invest in the sector (see Table 1). However, challenges (see Table 2) remain predominant and must be addressed. Findings are categorized by a group of actors to let emerge their different perceptions in the value chain.

Table 1. Strengths points emerged among the actors of the BBPs value chain

Interviewees	**BBPs allow to.../are attractive because....**
Material suppliers	• "offering new solutions where renewability and biodegradability are value-added (e.g. mulch films)" • "being recognized as innovative and green" • "increasing interest among our customers in offering green end-products" • "use of EU funds that are more oriented to BBPs" • "acquisition of existing non-efficient or obsolete petrochemical plants that are converted to the bio-chemistry" • "use of marginal land for crops that are low-water dependent" • "with certification it is possible to attest compostability" • "cooperation with different actors of the value chain that increase intangible capital" • "allow the use of 2nd generation feedstock by valorizing lignocellulosic waste streams" • "create multiple value along the entire value chain that can be demonstrated with the use of life cycle-based tools" • "increasing cooperation with organic waste treatment plants to solve technical challenges at the EoL"

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Converters	• "major inclination toward BBPs because it is the most eco-friendly solution" • "differentiate the product offer" • "with BBPs it is possible to provide tailored solutions, often associated with consulting or training service" • "entering new markets" • "no need of high investments in machinery due to the possibility of processing to process BBPs in the same machinery where conventional plastics are transformed" • "use of innovation labs to co-design and test new materials and applications" • "new collaborations with suppliers and new partners to manufacture high-performance products"
End users	• "customers and society at large have a rising need for greener end-products" • "proliferating interest toward compostable food packaging among brand owners" • "increasing interest toward eco-friendly and bio-based reusable goods" • "create partnerships with upstream players of the value chain to tailor and customize the solutions" • "increasing trend of green public purchasing"
Waste managers	• "strengthen the local closed-loop supply chain to reduce disposal costs" • "closed collaboration with materials suppliers to test compostability and biodegradability performance and provide feedbacks to converters on product eco-design" • "creation of networks working on specific waste streams"

Source: Authors' elaboration

Table 2. Weakness points emerged among the actors of the BBPs' value chain

Interviewees	**BBPs are hampered by …**
Material suppliers	• "small production capacity and difficulties in reaching economies of scale" • "difficulties in investing in other countries because of the lack of harmonized policy and orientations across Europe" • "difficulties in supplying a high volume of bio-waste to experiment with 2nd generation feedstock and so, minimize the purchasing costs of virgin feedstock, reduce the land occupation and decrease competition with food" • "need to make very large investments in R&D" • "high transportation costs of raw materials to the biorefineries and emissions to transportation" • "high production costs" • "lack of knowledge among stakeholders about the implications of biodegradability properties" • "lack of skilled workforce" • "need for more clusters focusing on bioplastics that allow dialogue between different subjects like institutions, companies, universities, and research centers" • "necessity to make policymakers aware of the lower total cost of ownership, i.e. the cost for the system related to BBPs vs. fossil-based plastics"

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Converters	• "discontinued materials supply" • "increasing competition because of the higher demand for bioplastics from high-value industry (e.g., medical, cosmetic)" • "challenging export because of different legislation and waste governance." • "agitation derived by the measures imposed by the SUPs Directive" • "investment on compostable tableware that is now banned by the SUPs Directive" • "insufficient performance of BBPs for certain applications" • "continuous need for higher R&D capabilities to improve BBPs' performance" • "high testing costs for EoL performances"
End users	• "lack of efficient labelling scheme for better communication to the consumer" • "high testing costs for contamination and health security issues (especially in the food sector)" • "effort in understanding the different EoL scenarios in place in exporting countries (e.g., home composting is different from industrial composting)" • "hostile disposition among consumers toward BBPs because of the food competition, the land occupation and the use of virgin feedstock" • "customers' skepticism and/or preference for other materials, like paper, wood, algae, etc." • "increasing customer orientation toward reusable applications" • "efforts in communicating the properties of the end-products and implications on consumption and disposal patterns"
Waste managers	• "lack of harmonized waste treatment that is municipality- and country-oriented" • "lack of adequate waste management plants to treat BBPs" • "inefficiencies of lab-scale compostability tests • "difficulties of composting rigid products in composting plants"

Source: Authors' elaboration

6. Discussions and concluding remarks

Key interesting findings emerge from the analysis of trends detected at system level with the perceptions collected 'from the bottom' by interviewing value chain actors (Table 3). Several elements contribute to the uptake of BBPs; opportunities emerge from legislative/EU policy, economic trends, socio-cultural changes and environmental aspects. However, the same domains also embedd challenges that migh hinder the diffusion of BBPs that really contribute to circularity and sustainability.

A key element seems necessary to foster BBPs: collaboration along the value chian. Results reveal that despite being recognized as innovative and green when using BBPs, material suppliers understand the potential to collaborate along the value chain to use alternative biological feedstock, with the resulting valorization of local economy and rural areas. However, no attention is currently paid to waste collection and valorization. Looking at the conversion stage, value is generally captured in biowaste bags, food packaging and agricultural mulch films and collaboration is basically fostered to improve technical and mechanical performances. Nevertheless, increasing interest is detected among end-users and brand owners intensively for using BBPs in durable products. Actors operating in waste management call for collaboration to test compostability and biodegradability performance in real other than lab conditions, thus trying to reduce the cost of uncompostable waste in composting facilities.

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Table 3. Value-chain based and multi-faceted SWOT analysis

	Legislative perspective	Economic perspective	Social perspective	Environmental perspective
S	Identification of end-products where BBPs may create added value	Exploitation of local and integrated supply chain based on the valorization of agro-industrial waste	Increasing awareness about marine plastic pollution	Compostability and biodegradability for specific applications
W	Lack of clear policy orientations	High price of bio-based plastics compared with the conventional ones	Lack of clear labeling scheme for BBPs and relative disposal patter	Dependence of biodegradability and compostability performances from applications and contexts
O	Introduction of EPR scheme to manage compostable plastic applications across Europe	Public funds for new integrated biorefineries	Increasing green purchasing trends	Renovation and/or introduction of new standards and eco-design guidelines assessing compostability, biodegradability, and more in general circularity
T	Market bans on end-products made of BBPs	Introduction of the plastic tax	Skepticism behaviors and confusion among consumers	Lack of clear criteria to perform LCA analysis

Source: Authors' elaboration

More broadly, results reveal the urgency to develop a combined CBE strategy to capture and retain multiple values from biological resources. Specifically, dedicated roadmaps should be established for each end-product, including BBPs.

From the legislative point of view, well-defined waste governance with a dedicated EPR scheme would facilitate better value retention from bio-based, biodegradable, compostable but also mechanically recyclable plastics.

From the social point of view, end-users and consumers should be better informed about the proper disposal of bioplastics, especially when compostable. Harmonised labelling schemes facilitating consumers' choices and robust, informative campaigns stimulating demands are envisaged. To reduce scepticism among end-users, customized solutions that match the local conditions should be pursued case-by-case, especially for applications involving biodegradation in open environments.

From an economic point of view, it is essential to develop an integrated and local supply chain to address the limited production capacity and, consequently, the high costs of raw materials supply. When the supply chain is based on symbiotic exchanges of residues among local farmers, it can also push the identification of valuable resource streams to valorize into 2nd generation feedstock while reducing the demand for pesticides, land and water to cultivate virgin biomass, thus contributing to more circularity and sustainability. The need to increase production capacity can be stimulated by investing in brownfield sites, thus providing an additional boost to the local economy and reducing the risk of land availability exacerbation.

From the environmental point of view, since the key issues are detected at the EoL, new eco-design guidelines and EoL standards need to be provided and/or revised. It is possible by enforcing formulations that tailor the degradation timescale according to the products' purpose and expected life. Eco-design guidelines can support identifying the correct application that, in line with circularity goals, can regulate the conversion processes. At the same time, the tendency to use BBPs in durable products creates boundary conditions for a user-centric chain where lifetime extension strategies, like reuse, repair and refurbishment, can be exploited. Standardised eco-design and strict EoL measurement criteria may support the establishment of a harmonized LCA methodology for these materials, thus stimulating comparability and benchmarking.

To sum up, our study shows that although BBPs are generally considered more environmental-friendly than conventional plastics, robust scientific evidence on their impacts compared to fossil-based plastics is still missing. The lack of tools and metrics to assess the circularity and sustainability of BBPs industry poses relevant challenges for its upscaling and contribution to climate neutrality goals in Europe. It calls for the adoption of system and life cycle thinking, guided by multi-level (system and corporate) and multi-dimensional (legislative, social, economic and environmental) analysis, which led

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researchers to build a comprehensive picture of trends, gaps and future orientations that may boost a sustainable circular bioeconomy in the sector.

To the authors' knowledge, the paper is the first to discuss the value of BBPs in the broader sustainable circular bioeconomy model. Specifically, the paper makes several contributions to the bioplastics discourse. From the research point of view, it identifies the key area of investigation that needs to be explored in further research agenda. Specifically, 4x4 significant topics have been identified for theoretical underpinnings. Managerial implications include a list of recommendations for EU policymakers for an integrated circular bioeconomy strategy aimed at (i) adding value to BBPs through alternative raw materials supply, (ii) retaining value through reuse and recycling, (iii) ensuring lower environmental impacts through cross-sector collaboration and well-functioning waste governance.

Data availability statement

The datasets generated during and/or analysed during the current study are not publicly available due to their confidential nature but are available from the corresponding author upon reasonable request.

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Appendix

1. PRESENTATION QUESTIONS

A. Please provide a brief description of the company: what is its business? what type of plastic resins (in general) does it use?

2. QUESTIONS ON HOW, WHEN, WHY IS A MATURE DECISION THE INTRODUCTION OF BIOBASED MATERIALS

B. Do you use compostable biopolymers according to the norm EN 13432: 2002? Do you use compostable biopolymers from renewable sources?

C. When and why did you introduce bio-based plastics in your product/ process/product line? (interviews were prompted to indicate opportunities detected, main motivations, customer requests, etc)

D. What were the problems or obstacles that generated doubts about the technical feasibility and/or economic feasibility of starting using bioplastics? How have these issues been overcome?

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