



Bio-based and biodegradable polymers - State-of-the-art, challenges and emerging trends

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Frontiers of bio-based and biodegradable polymers are constantly expanding in a view to achieve sustainability. Hence, designing sustainable bioplastics made of either bio-based or biodegradable polymers opens up opportunities to overcome resource depletion and plastic pollution. This review presents a broad perspective on state-of-the-art technologies in bioplastics manufacturing along with the challenges underlying their production, application and post-consumer waste management. Recent scientific advances are catalysing the sustainable design of bioplastics to overcome the present challenges of plastic waste and emerging end-of-life options are contributing to circular economy. As research insights into developing sustainable bioplastics are rapidly evolving, their production and waste management approaches are not limited to those discussed in this review.

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Introduction and market growth

The 21st century is thriving with tremendous economic growth but at the same time facing an irrecoverable ecological damage. Plastic pollution is recently being highlighted as global crisis at every stage right from the production of plastics to their disposal and incineration [1]. Bioplastics constituting both naturally and chemically derived materials from renewable or oil-based resources are being designed to feature minimal carbon footprint, high recycling value and complete biodegradability/compostability [2,3]. In order to ascertain no competition with food and agricultural resources, recent advancements

are emerging to develop next-generation bioplastics derived from renewable waste streams, microbial/microbial cells and biomass which eventually fosters carbon neutral infrastructure for bioplastics production and management [4,5]. Moreover, sustainable production and recycling mechanisms for bioplastics are considered to have huge compliance with the policies/actions set by United Nation's sustainability development goals (UN SDGs) and European circular economy strategy [6].

The global bioplastics production capacities are difficult to estimate and are usually based on forecast because of continuously emerging range of bio-based and biodegradable polymers and rising interests on investing in bioplastics sector. Recent report published by Nova Institute has predicted that global bioplastics production capacity is growing at a considerable pace from around 2.11 million tonnes in 2018 to 2.62 million tonnes in 2023 [7]. Europe ranks top in the research and development of bioplastics and stands next to Asia as major hub for bioplastics production and consumption [8]. With many innovative bioplastics entering the market segments for diversified applications, industries are interested in expanding the production capacity. Acute relevance to sustainability and circular economy has been indeed influencing the bioplastics industry to achieve substantial growth and technological maturity with multiple production routes.

Progress and trends in commercial bioplastics

Naturally occurring polymers like cellulose derivatives, thermoplastic starch (TPS) and their blends stand highest in terms of production capacity as these materials are replacing plastics particularly in flexible film packaging sector [9,10]. Recent bioplastics market update shows that polylactic acid (PLA) receives greater attention from both academia and industry due to its technological advances in productivity and functionality [11,12]. PLA is known for its versatility featuring excellent barrier properties thus gaining value to replace polystyrene (PS) and polypropylene (PP) in packaging and other challenging applications [13]. Next to PLA, polyhydroxy alkanates (PHA) receive interest as evidenced by greater number of international patents [14]. However, in terms of global production capacity, PHA stands next to poly(-butylene adipate-co-terephthalate) (PBAT) and polybutylene succinate (PBS). As per recent market report, current global production of PHA is about 25,320 tonnes,

which accounts to 1.2% as against PBAT and PBS holding 13.4% and 4.3%, respectively [15]. Polycaprolactone (PCL) and PBAT are fossil-based polymers but tend to biodegrade, signifying that biodegradability is not always dependent on the source of origin or the polymer building block. Schematic representation shown in Figure 1 clearly demarcates various technological approaches specific to different classes of bioplastics.

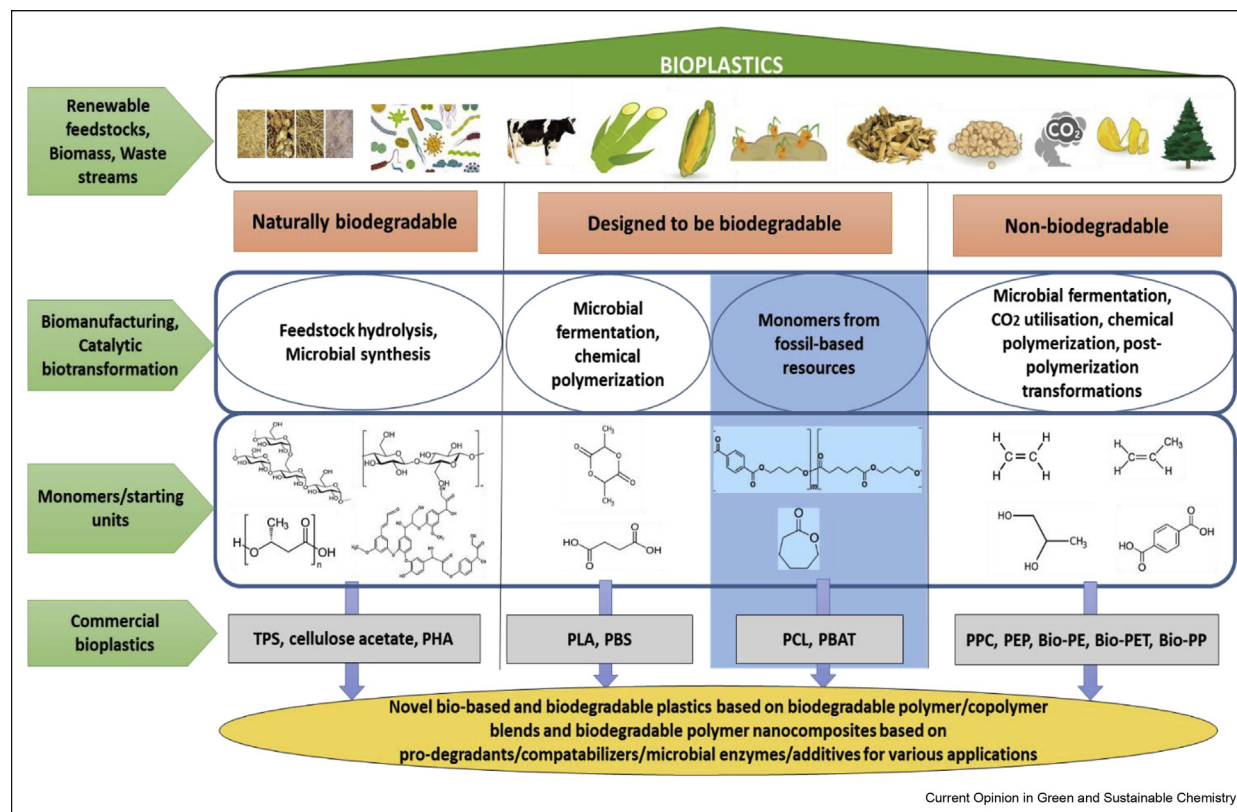
Majorly used commodity polymers like polyethylene terephthalate, polyamide and polypropylene have also been manufactured from bio monomers-derived glucose fermentation or lignin fermentation, which facilitate the resurgence of Bio-PET, Bio-PA and Bio-PP respectively [16]. Growing interest in novel bioplastics constituting two or more existing biodegradable polymers would eventually result in second-generation bioplastics, thus offering advantage of developing scalable counterparts to synthetic plastics [17]. Hence, the goal would be to design novel composites comprising only of bio-based building blocks having specific desired functionalities suitable for applications and at the same time completely biodegradable and recyclable building blocks having specific desired functionalities suitable for technological applications [18]. For example, in a recent work, synergic blends of PLA and PCL were highlighted

as completely biodegradable (in domestic composting conditions) alternatives to conventional, petrochemical-based plastics [19]. Emerging bio-based polymers like poly(ethylene 2,5-furandicarboxylate) (PEF)/poly(trimethylene terephthalate) (PTT) and polypropylene carbonate (PPC) produced from bio-based furan monomers and alcohols/epoxides respectively are characterised by excellent thermal and barrier properties comparable to their petroleum analogues [20]. For instance, blending PEF with PLA or PHA would ultimately contribute to superior functional and biodegradable properties enabling practical application in packaging applications [21]. The trade-off between biodegradability and functionality brings huge research scope on blending and compatibilisation of various bio-based polymers to push their performance efficiency and versatility [22,23]. Table 1 shows the widely known bio-based and biodegradable polymers and their respective starting materials and feasible end-of-life options [18,24].

State-of-the-art technologies for bioplastics innovations and production

The current bioplastic sustainable production model relies on design and development of novel valorisation

Figure 1



Schematic representation of technological approaches in producing commercial bioplastics (shaded in blue: biodegradable polymers derived from oil-based resources).

Table 1

Commercial bioplastics including both biodegradable and non-biodegradable polymers, their production source, capacity and end-of-life options (adapted and modified from Ref. [18]).

Biodegradable polymers				
Polymer name	Source/Feedstock	Production capacity (Kt/Year)	Trademark/Company	Sustainable end-of-life options
TPS, Cellulose, Cellulose acetate, Starch blends	Biomass, agro-residues, lignocellulosic derivatives	384	Mater-Bi/Novamont, Agrana starke, NaturePlast, Indochine Bio Plastiques	HC, IC, AD
PLA and PLA blends	Lactic acid from dairy whey, corn starch or organic residues	225	Ingeo/NatureWorks, Luminy®/Total Corbion, Lacty/Shimadzu Cor. Vyloecol/Toyobo, Danimer Scientific	IC, MR, CR
PHA, PHB, PHO	Volatile fatty acids, glucose/glycerol from fermentation of municipal solid waste or any carbon feedstocks	30	Minerv-PHA™/Bio-On, PHBH™/Kaneka, Tephaflex®/Tepha, Nodax™/Danimer Scientific, AirCarbon®/Newlight Technologies	HC, IC, AD, CR
PCL	Chiral hydroxy acids, lactones	—	CAPA™/Perstorp (Ingevity)	HC, IC, CR
PBS	Succinic acid, 1,4-butanediol	97	GS PLA®/Mitsubishi Chemical, Bionolle™ 1000/Showa Denko K.K., Skygreen®/SK Chemicals, Succinity, BioPBS™/PTT MCC Biochem	CR, ED
PBAT and PBAT blends	Terephthalic acid, adipic acid, hydroxymethyl furfurals (HMFs), butanediol	152	Ecoflex®/BASF, Wango/Zhuhai Wango Chemical Co., Ecoworld/JinHui ZhaoLong, Eastar Bio/Eastman, Origo-Bi®/Novamont	IC, CR
Bio-based and non-biodegradable polymers				
Bio-PE	Bioethanol from sugarcane	200	Braskem	MR
Bio-PET	Furan dicarboxylic acid from HMFs	560	PlantBottle™/Coca Cola	MR, CR, ED
Bio-PTT	1,3-propanediol	45	DuPont Corterra™, Sorona®/Shell Chemicals	MR, CR
Bio-PEF	HMFs	—	Synvina/Total-Corbion	ED
Bio-PP	Isobutanol	—	Technoform, LanzaTech	MR
Bio-PA	Volatile fatty acids, HMFs	—	Evonik VESTAMID® TERRA, Dupont, FKUR, BIOFED	MR, CR
Bio-polycarbonates	Bioethanol/dialkyl carbonate/epoxides and carbon-dioxide	—	Asahi Kasei Corporation, Saudi Aramco Converge®	CR

AD, Anaerobic Digestion; MR, Mechanical Recycling; CR, Chemical/Catalytic Recycling; ED, Enzymatic Depolymerisation; IC, Industrial Composting; HC, Home Composting.

*Emerging options in bioplastics waste management with either limited or no evidence on technology commercialisation.

protocols of renewable resources derived from urban, agricultural and food wastes. Approaches to develop monomers and biodegradable polymers from biomass feedstock received great attention in chemical industries by leveraging on the innovative biocatalytic transformation and synthetic chemistry [25,26]. Sustainable bioplastic materials are currently under development, and innovation relies either on developing completely new types of polymers or drop-in substitutes derived from renewable resources. Advancements in industrial biotechnology offer various chemo-enzymatic or bio-catalytic synthetic routes for

converting biomass or renewable feedstocks into high-value building blocks or monomers [27]. Additionally, engineering of consumer-grade bioplastics based on monomers derived from waste residues represents a sustainable production value chain, which accounts for establishing circular bioeconomy. Growing global demand for bio-based and biodegradable polymers prompted investments in research to promote and establish large-scale production of bioplastics. Bio-based industries (BBI) consortium in partnership with European Union (EU) is investing about 3.7 billion on large-scale flagship projects to encourage

new technologies for production of bio-based monomers and polymers from waste biomass/renewable feedstocks [28]. As one of the specific impacts of BBI's programme is to replace at least 30% of fossil-based raw materials with bio-based and biodegradable ones by 2030, potential scope for bioplastics manufacturing processes is foreseen in the coming decade [29].

Bioplastics production by utilising greenhouse gases like carbon dioxide is one of the sustainable carbon upcycling approaches, which is gaining huge attention [30]. Recent report by Nova Institute has highlighted the projected estimation of directly converting 70% CO₂ for bioplastics manufacturing [31]. Breakthrough research in areas of selective copolymerisation process has resulted in the commercial production of polycarbonates constituting about 30–50 wt.% of waste CO₂ [32]. CO₂ upcycling efforts are constantly evolving for meeting the predicted demand of producing 450 million tonnes plastic by 2050, which are completely made from renewable carbon [31]. This CO₂ recycling approach holds benefit of being easily retrofitted in the fossil fuel-based polymer-manufacturing infrastructure thus exerting both economic and environmental benefits. Indeed, lesser dependence of agro-feedstocks, monomer extraction/transformations and complex pre-treatments are considered highly advantageous against bioresources-derived polymers [33].

Sustainability and end-of-life options for bioplastics

On a global trend, plastic production from fossil-based resources and plastic waste incineration together accounts to about 400 million tonnes of CO₂ every year [34]. Replacement of fossil-based plastics with bio-based/biodegradable ones will certainly reduce carbon footprint at the production level. However, assessing their sustainability aspects in terms of end-of-life management is vital to exert bioplastics as an environmentally friendly alternative. Not all bio-based polymers are deemed biodegradable and in contrast, some of the biodegradable polymers could also be produced from fossil-based raw materials. Indeed, popularly known bioplastics families like PHB, PCL and starch and their blends are proven to be biodegraded in both managed and specific unmanaged environments [19]; however, failing to manage their disposal would result in uncontrolled biodegradation adding to existing plastic pollution [35]. Hence, it is of utmost importance to practice specific end-of-life management considering the properties and processing conditions of each bioplastics rather than a generic waste management plan. Life cycle analysis (LCA) is an indispensable tool to gauge and quantify the benefits or impacts of any bioplastics, subjecting to the boundary conditions and assessment considerations [36].

Despite being resources-efficient and derived from renewable bio-based feedstocks/residues, it is crucial to look closely into environmental impacts of bioplastics waste. Disposal of bioplastics waste in landfill certainly contributes to management problems similar to those of conventional plastic waste. Hence, advocating best end-life management of post-consumer bioplastics waste is needed to achieve lower carbon footprint [37]. Sustainable management of bioplastics waste is highly challenging as some of the bioplastics are designed to only biodegrade in specific managed conditions thus creating huge ill effects when disposed in non-ideal environments like soil, fresh water and marine. Indeed, scientists aim at developing bioplastics that could achieve complete and quicker biodegradation in any environment as per ASTM and ISO standards [38]. However, most of the reported biodegradability of various biodegradable polymers was demonstrated at the lab scale and it is essential to establish biodegradation of the commercial bioplastics and their blends at the appropriate industrial scale [39,40].

Recycling is considered the most preferred option to manage bioplastic waste similar to conventional plastic waste [41]. However, recycling can either be mechanical, chemical/catalytic and organic depending on whether the bioplastics are biodegradable and/or if the considered polymeric material biodegrades only under managed conditions. The distinct recycling options shown in Figure 2 represent the state-of-the-art on closed-loop management of post-consumer bioplastics waste. Prime challenges in recycling of post-consumer bioplastic waste are attributed to its heterogeneity, low market volumes, diverse sources and high potential for plastics waste contamination. These challenges indicate a clear need for more efficient chemical and biochemical processes to valorise the bioplastics waste into perpetually reusable high-value end products. Implementing combined recycling and recovering concepts including extraction of high-value chemicals/monomers via chemical recycling, solvent extraction [42] and cogeneration of biofuel and volatile fatty acids through anaerobic digestion [43] would certainly create positive impact towards a circular bioeconomy. Perhaps, some of the management approaches would not directly recycle back the bioplastics into their starting monomer. However, it is worthwhile to invest on valorisation of post-consumer bioplastic waste and provide incentives for recycling or energy recovery for contributing to circular bioeconomy and sustainable management of bioplastics waste [44].

Future outlook

Rationally designing the bioplastics to impart desired functionality and recyclability [45,46] and utilising unaccounted biomass as a valuable resource would together establish a sustainable production value

Figure 2



Schematic representation of recycling strategies for sustainable management of bioplastics and contribution towards SDGs.

chain for bioplastics. Despite that some of the bioplastics production technologies are lacking the scalability and productivity comparable to petroleum-based routes, governmental regulations and consumer pressure have been fostering the bioplastics industry to adopt and implement sustainable production routes. Circular bioeconomy is also gaining global momentum, which in turn triggers a wide range of stakeholders to leverage the synergistic potential of bioplastics manufacturing and upscaling/recycling strategies [47,48]. Innovations in fundamental re-designing of bioplastics with improved economics for recycling will pave a way for the next generation of sustainable bioplastics.

Conflict of interest statement

Nothing declared.

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