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Review

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

Sameh Samir Ali [a, b, *], Esraa A. Abdelkarim [a], Tamer Elsamahy [a], Rania Al-Tohamy [a], Fanghua Li [c], Michael Kornaros [d], Antonio Zuorro [e], Daochen Zhu [a], Jianzhong Sun [a, **]

[a] *Biofuels Institute, School of the Environment and Safety Engineering, Jiangsu University, Zhenjiang, 212013, PR China*
[b] *Botany Department, Faculty of Science, Tanta University, Tanta, 31527, Egypt*
[c] *State Key Laboratory of Urban Water Resource and Environment, School of Environment, Harbin Institute of Technology, Harbin, Heilongjiang Province, 150090, China*
[d] *Laboratory of Biochemical Engineering & Environmental Technology (LBEET), Department of Chemical Engineering, University of Patras, 26504, Patras, Greece*
[e] *Department of Chemical Engineering, Materials and Environment, Sapienza University, 00184, Rome, Italy*

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ABSTRACT

The current transition to sustainability and the circular economy can be viewed as a socio-technical response to environmental impacts and the need to enhance the overall performance of the linear production and consumption paradigm. The concept of biowaste refineries as a feasible alternative to petroleum refineries has gained popularity. Biowaste has become an important raw material source for developing bioproducts and biofuels. Therefore, effective environmental biowaste management systems for the production of bioproducts and biofuels are crucial and can be employed as pillars of a circular economy. Bioplastics, typically plastics manufactured from bio-based polymers, stand to contribute to more sustainable commercial plastic life cycles as part of a circular economy in which virgin polymers are made from renewable or recycled raw materials. Various frameworks and strategies are utilized to model and illustrate additional patterns in fossil fuel and bioplastic feedstock prices for various governments' long-term policies. This review paper highlights the harmful impacts of fossil-based plastic on the environment and human health, as well as the mass need for eco-friendly alternatives such as biodegradable bioplastics. Utilizing new types of bioplastics derived from renewable resources (e.g., biowastes, agricultural wastes, or microalgae) and choosing the appropriate end-of-life option (e.g., anaerobic digestion) may be the right direction to ensure the sustainability of bioplastic production. Clear regulation and financial incentives are still required to scale from niche polymers to large-scale bioplastic market applications with a truly sustainable impact.
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1. Introduction

The consumption of plastics has been increasing for years due to their desirable characteristics, including durability, low cost, weathering resistance, light weight, and transparency [1,2]. The global production of plastics reached 338 million tons in 2019, representing an increase of over 640% compared to 1975 [3]. Although recycling plastics can increase resource circularity and lessen certain environmental repercussions of production, the recycling rate for plastics remains low, below 10% in the United States, for example [4]. Most plastics are not biodegradable, and their complete disintegration can take more than a century [5]. Between 1950 and 2015, approximately 80% of all discarded plastics ended up in landfills or natural environments [6]. Micro- and nanoplastics are released by the degradation of plastics in the natural environment [7,8]. These particles can have a negative impact not only on aquatic ecosystems but also on human health [7,9].

* Corresponding author. Botany Department, Faculty of Science, Tanta University, Tanta, 31527, Egypt.
** Corresponding author. Biofuels Institute, School of the Environment and Safety Engineering, Jiangsu University, Zhenjiang, 212013, PR China.
E-mail addresses: samh@ujs.edu.cn, samh_samir@science.tanta.edu.eg (S.S. Ali), jzsun1002@ujs.edu.cn (J. Sun).

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Therefore, biodegradable plastics, also known as "bio-based polymers" or "bioplastics", have been proposed as a potential solution for mitigating the detrimental impacts of petrochemical plastics on the environment and human health.

The production of bioplastics from food or biomass resources such as starch, corn, sugarcane, and lignocellulosic components (Fig. S1), enables a transition towards a circular economy, reduces the extraction of fossil resources, has a lesser carbon footprint, and has the potential to reduce environmental burdens that arise at end-of-life [10–12]. There are two main categories of plastics: bio-based (derived from biogenic feedstock) and fossil-based (derived from petroleum-based materials). Bio-based non-biodegradable plastics, such as bio-based polyethylene (bio-PE) and bio-based polyethylene terephthalate (bio-PET), are identical to their petroleum-based counterparts despite being made from biogenic resources [13] (Fig. S1). The total bioplastics manufacturing was approximately 2.36 million tons in 2021, roughly 1.55 million tons of degradable materials and 0.86 million tons of non-degradable materials [13]. The most common types of bio-based biodegradable plastics, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and thermoplastic starch (TPS), accounted for approximately 40% of the market for bioplastics in 2020 [14]. Various applications for these kinds of bioplastics include food packaging, medicinal implants, and building construction [15]. It is thus crucial to assess the environmental impacts of bioplastics versus petrochemical plastics through life cycle assessment (LCA).

LCA is a common tool to assess the environmental and economic performance of a product or process [16]. LCA is utilized, in producing a variety of polymers, to compare the environmental impacts of one type of polymer versus another or to assess the advantages of employing biopolymers before promoting their widespread use. Generally, the environmental implications of bioplastics are lower in terms of climate change and dependence on fossil fuels; nevertheless, they demonstrate higher impacts in eutrophication and toxicity [17]. For bio-based plastics to be compared to petrochemical plastics, the "full" life cycles of the various plastics should be represented (Fig. 1) [18]. Due to the potentially lengthy production-use-reuse-and-recycling value chains connected with various polymers, this can be a challenging undertaking. According to the European strategy for plastics in a circular economy, innovative materials and alternative feedstocks for plastic products should be developed and used wherever there is clear evidence showing that they are more sustainable than petrochemical plastics. This strategy was developed to achieve a "circular economy" [19]. Therefore, to give unambiguous data on the sustainability of bioplastics and how they benchmark in comparison to conventional petrochemical plastics, LCA studies that are both extensive and well-designed are very necessary.

The circular economy is based on the concept of restoring and regenerating by design, as illustrated in Fig. 2. It aims to redesign waste disposal systems while minimizing negative externalities through reimagining products and services via system-wide innovation. Environmental, economic, and social benefits are being realized using renewable energy sources in the circular model. Therefore, using biological resources, processes, and methodologies in conjunction with knowledge-based manufacturing to deliver products and services across all economic sectors sustainably may be an ideal strategy for reducing plastic waste accumulation. This covers the replacement of fossil fuels and the reduction of greenhouse gas (GHG) emissions. In addition, the risk-free generation of benefits for regional and local stakeholders, such as governments, investors, employees, and consumers, may be considered a crucial step in bioplastic production [20]. Polymer-containing hazardous chemical recycling may not be environmentally friendly. Circularity thus results in low environmental sustainability performance.

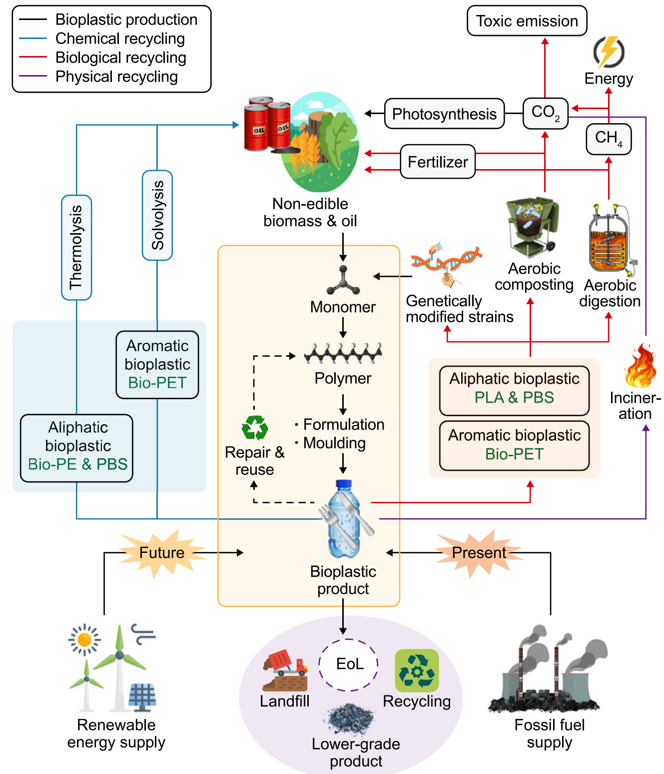

Fig. 1. Plastic value chain in life cycle assessment (LCA) and end-of-life (EoL).

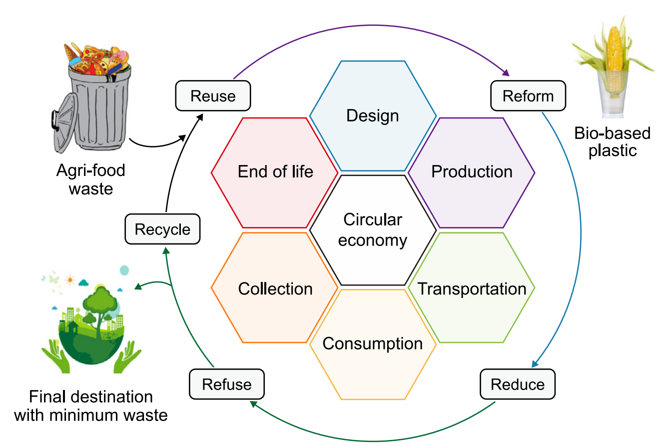

Fig. 2. Circular plastic economy concept and bioplastic end-of-life.

Consequently, the intensification of circular activities in this situation may result in increased damage. If the circular economy is to deliver on its promises, industry and policy practitioners must consider sustainability factors prior to adopting circular economy activities [21]. Therefore, sustainability and bioeconomy demand a paradigm shift in social and economic theory.

This study expands upon previous reviews by exploring the environmental implications of bio-based plastics versus petrochemical plastics using the concept of LCA. Consequently, this study aimed to conduct a comprehensive literature review to clarify the current state of knowledge by identifying important research gaps and, therefore, potential limitations in LCA outcomes to date. Bioplastic manufacturing from organic wastes and the bioplastic end-of-life strategy regarding sustainability, reuse, recycling, and biodegradation are reviewed. The environmental, social, and economic LCA methods are also estimated. Furthermore, challenges and innovation points for manufacturing bio-based plastics are suggested. The audiences targeted by this study include plastic production companies that can benefit from the information presented in this study to promote the production of bio-based plastics, LCA practitioners, scientists in academia, and end users or consumers who can choose their plastic alternatives.

2. Negative impact of fossil-based plastics

Fossil-based plastics are one of the most ubiquitous materials in modern society. However, their production is currently responsible for notable environmental impacts (Fig. 3a). The total plastic production worldwide reached 8300 million tons, with an increase of 415 million tons annually, while 6300 million tons of the total plastic production ended as waste. Among these, ~883 million tons are recycled, ~883 million tons are incinerated, and ~4542 million tons are released into the environment or being disposed off by landfilling [1]. Plastic productivity is predicted to reach 800 and 1600 million tons by 2035 and 2050, respectively [5]. Thereby, contamination from the accumulation of plastic waste in the environment poses a growing hazard to both human health and natural ecosystems. Carbon monoxide, dioxins, nitrogen oxides, and hydrogen cyanide are just a few of the dangerous gaseous compounds that are released into the air during the plastics production process and are a major threat to both human health and the environment (Fig. 3b). It has been reported that an increase of trace gases generated from low-density polyethylene (LDPE) after 212 days reached 14.5 nmol ethylene g^{-1} day^{-1}, 9.7 nmol propylene g^{-1} day^{-1}, 5.8 nmol methane g^{-1} day^{-1}, and 3.9 nmol ethane g^{-1} day^{-1} [22].

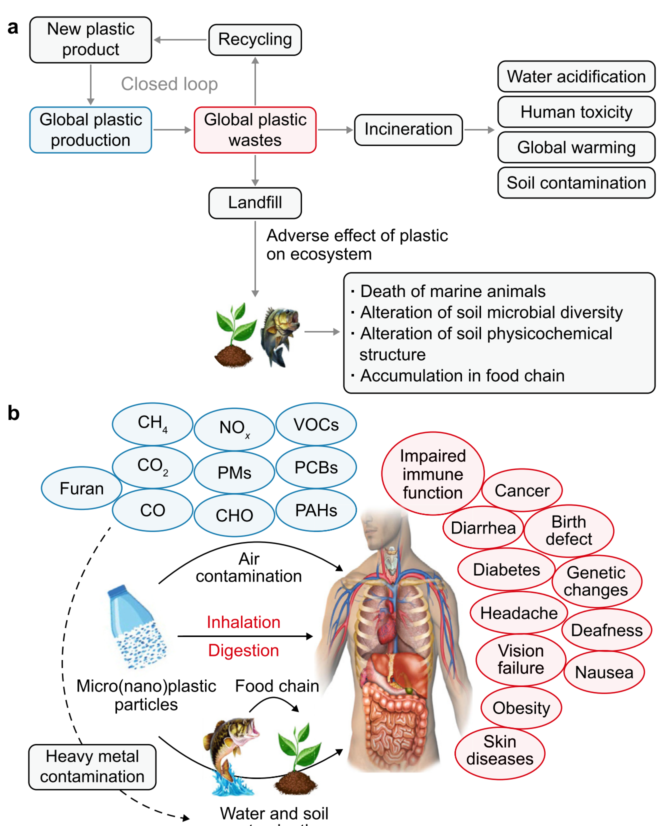

Fig. 3. Negative impact of fossil-based plastics on the environment (**a**) and human health (**b**).

Digestion and inhalation of micro- and nano-plastics have a serious toxic effect on human health (Fig. 3b). Micro(nano)plastics can cause a variety of biological reactions such as genotoxicity, oxidative stress, inflammation, necrosis, and apoptosis [23,24]. Furthermore, severe diseases, such as fibrosis, tissue damage, and carcinogenesis, can occur in cases of continuous exposure [8]. The micro- and/or nano-plastics can be transferred through the food chain and may end up to human food through other pathways (Fig. 3b) [1,5]. Most microplastics may accumulate in animals' digestive tracts because of their large size, but a limited quantity can reach the circulatory system through the lymph nodes in the intestinal tract [25]. The transfer of LDPE microparticles to chickens has been studied, and the authors found that LDPE microparticles in the gizzard and feces of chickens were 10.2 MPs per gizzard and 129.8 MPs per g feces, respectively [26]. These findings indicate the transfer of micro- and macro-plastics through the food chain.

Microplastics are challenging to enter the organs due to their size. The toxicity assessment of microplastics in vivo and in vitro is less thorough in the existing literature. However, when it comes to nanoplastics, they may penetrate the intestinal wall and enter the bloodstream [27]. Nanoplastics are easily accumulated in tissues and cells due to their persistence, which can lead to metabolic problems and localized inflammation. The transport and absorption of nanoplastics will be significantly increased, especially in patients with intestinal disorders, due to changes in tissue permeability causing inflammatory infection, which raises the risk of exposure (Fig. 3b) [28]. Consequently, there is a pressing need for novel strategies and alternatives to mitigate and remediate fossil-based plastic products and their accumulated wastes due to their negative influences on the environment and human health. In this context, replacing fossil-based plastic with bioplastic is an ideal way to avoid plastic waste accumulation's environmental, health, and economic problems. Hence, investigating bioplastic production, LCA, and sustainability is a mass need to improve and enhance the bio-based plastic industry.

3. Global production capacity of bioplastics

Global bioplastic production capacity is set to increase significantly from around 2.4 million tons in 2021 to 7.5 million tons in 2026 (Fig. 4a) [29]. Biodegradable plastics currently account for slightly over 64% (1.5 million tons) of the global bioplastics production capacity. Bio-based, non-biodegradable plastics make up almost 36% (0.8 million tons) (Fig. 4a) [29]. The production of bio-based biodegradable plastic is expected to increase from 0.88 million tons in 2017 to 5.33 million tons by 2026 [30]. There was a fluctuation in the production of various types of bio-based biodegradable plastics from 2017 to 2020, with an increase in PLA and polybutylene adipate terephthalate (PBAT) production of 81.5% and 170%, respectively. Conversely, by 2026, the production of starch blends is expected to decrease by 72.3%. However, PBAT, polybutylene succinate (PBS), and PHA polymers expect to increase by 500%, 226.5%, and 166.7%, respectively (Fig. 4b) [30,31]. Concerning the production of bio-based non-biodegradable plastics, the production is expected to increase from 1.18 million tons in 2017 to 2.3 million tons by 2026, with an increased rate of 94.9%. Bio-PET production was reduced by 70.3%. However, bio-PE increased by 8.2% from 2017 to 2020. By 2026, the production of bio-PE and bio-PET is expected to decrease by 33% and 95.4%, respectively. However, polyamide (PA) is expected to increase by 31.1% (Fig. 4c) [12,30]. From the aforementioned data, it is clear that the world is heading toward increasing the productivity of biodegradable

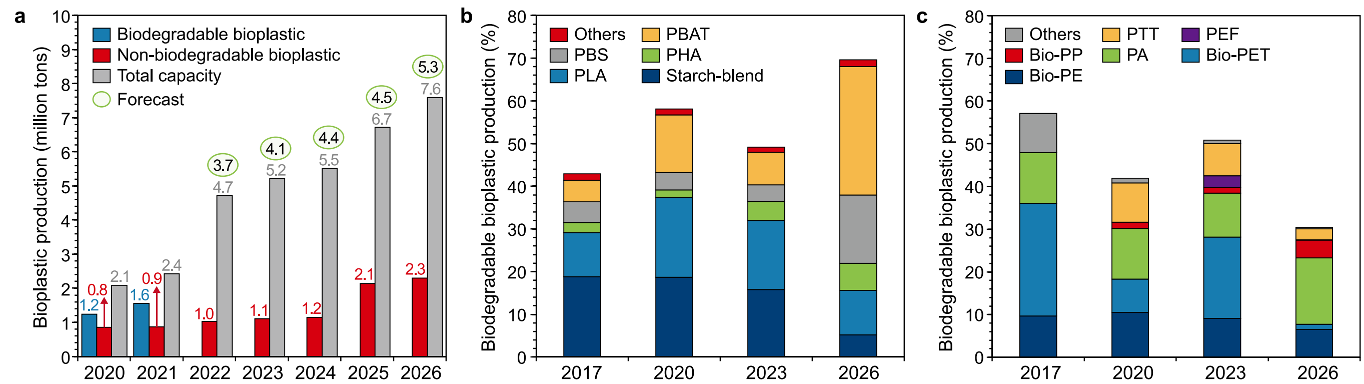

Fig. 4. **a**, Bioplastic production and forecast. **b**, Different types of biodegradable bioplastic. **c**, Non-biodegradable bioplastic production [29–31].

bioplastic over non-degradable bioplastic. This might be due to the eco-friendly effect of overcoming the negative impact of plastic waste accumulation in the environment.

Bioplastics account for less than 1% of yearly plastic generated [32,33]. However, the bioplastics market has continued to expand, despite a minor decline in worldwide plastic output generally. This growth might be due to the advent of increasingly useful products and applications combined with increased demand and the continuous replacement of fossil-based plastics. Furthermore, this may also due to the growing awareness of the world's need to transit to a circular economy and achieve sustainability at the environmental, economic, and social level. In addition to the increasing growth in innovation in the manufacture of bioplastics and the continuous improvement in their properties, new applications and relatively high quality for some types have been achieved [34–36].

Innovative biopolymers, such as PLA and PHA, are the primary drivers of growth in bio-based biodegradable plastics. PHAs are a polymer class that has been studied for a long time and is now considered commercially accessible, with manufacturing capacity predicted to expand in the next five years [37]. PLA is a versatile biopolymer with high barrier properties that may be utilized in more demanding applications, such as packaging, to substitute acrylonitrile butadiene styrene (ABS), polypropylene (PP), and polystyrene (PS). PLA, PHA, and starch-based polymers (SBPs) accounted for a significant portion of bioplastics manufacturing. More than 58% of worldwide bioplastics manufacturing capacity comprises PHA, starch blends, PLA, or other biodegradable biopolymers [38]. Non-biodegradable biopolymers, including bio-PE, bio-PET, and bio-PA, represent over 42% of worldwide bioplastics production capacities (nearly one million tons) [29,39]. However, initiatives to increase bio-PET manufacturing capacity have not progressed as quickly as predicted in previous years. For example, the PET rate declined from 9.8% in 2019 to 7.8% in 2020 [40]. This reduction may be because bio-PET products are chemically equivalent to their petroleum-based counterparts. Hence, bio-PET will be used and recycled similarly, and the emissions associated with these downstream processes will be the same.

The attention has shifted to polyethylene furanoate (PEF), a novel polymer that will join the plastic market in 2023 [30]. PEF is similar to PET; however, it is made completely of biomaterials. It's also thought to have improved thermal and barrier properties, making it suitable for the packaging industry, where PEF showed higher barrier performance, mechanical properties, and thermal properties. Furthermore, the PEF crystal growth rate is about one order of magnitude slower than PET and passes through a maximum at 165 °C [41]. This is an essential advantage in injection molding, where slow crystallization from the melt is preferred. In addition to PEF's lower melting point and high glass transition temperature, the possibility of recycling makes for a reduced carbon footprint. Moreover, PEF is cost-competitive at the industrial scale [42]. At the same time, it improves packaging sustainability since PEF produced from 2,5-furandicarboxylic acid (FDCA) is 100% bio-based when monoethylene glycol (MEG) is used. As a consequence, PEF will have the potential to replace PET products. Based on statistics, packaging manufacturing is the major business group that profits from the bioplastic industry [43]. Bioplastics may replace almost any type of regular plastic and its applications. Production capacity will continue to develop and diversify over the next few years as novel bioplastics, such as PHAs, PEF, bio-PP, and PLA, become commercially accessible. The worldwide capacity for bioplastics production is predicted to expand from roughly 2.1 million tons in 2020 to >2.9 million tons in 2025 [43]. However, Asia is expected to become the world's largest bioplastic producer, accounting for 56% of worldwide industrial output. Europe's present industrial potential is 18%, whereas North America's is 16% [44].

Plastic pollution and its toxic environmental impact have stimulated research and development to demonstrate bioplastics as viable alternatives to fossil-based plastics. Hence, the world's need for bioplastics is continuously increasing, and in particular, various bioplastics are considered ideal alternatives for fossil-based plastics with the same physicochemical properties. Cost-effectiveness and applicability are the main constraints limiting the productivity of various bioplastics. To reduce the production costs of bioplastics, cheap and abundant raw materials, such as lignocellulosic wastes, microalgae [11,12], and food wastes [45], can be an excellent feedstock for the bioplastic industry. Hence, this review suggests that future research should be directed toward novel waste pretreatment techniques, genetic engineering, and biorefinery platforms. More attention should be paid to creating sustainable recycling options and strategies for bio-based products as the output of bioplastics is predicted to increase.

4. Production of bioplastics from renewable resources during the transition to a circular economy

Bioplastic products and materials have attracted the attention of manufacturers, politicians, and decision-makers worldwide to replace conventional plastics and transition to a circular bioeconomy [46]. Bioplastics are the primary engine for attaining EU 2020's sustainable goals [47]. The major problem for EU nations is that they cannot scale up sophisticated biorefineries using developed technologies to create and market high-value bioproducts

[48]. The bioplastics industry lacks supporting policies due to the lack of an international pattern of support for bioplastics, except for the strategy of prohibiting single-use carrying bags, which has recently gained significant interest [49]. As a result, there are marketing problems in feedstock supply and pricing, which put the biomaterials and bioplastics industries at risk [50]. However, the relevance of the proposed research arises from the fact that bioplastics manufacturing using organic waste as a feedstock may overcome some constraints to expanding the bioplastics industry [51].

Bioplastics can be generated from primary feedstocks, including rice, sorghum, soy, beet, corn, palm, barley, sugar cane, wheat, and potatoes. However, they can also be produced from secondary feedstocks such as biowaste, cooking oil wastes, and petroleum-based feed [52]. Potato peel waste is a potential feedstock for value-added bioproducts such as biofuels, bioplastics, and biochemicals [53]. PHA was produced from purple sweet potato waste by a *Cupriavidus necator* (recombinant amylolytic strain), and the PHA titer reached 3.65 g L^{-1} [54]. Lignocellulosic biomass can be used for producing various types of bioplastic (starch-based bioplastic and lignin-based polymer) and active compounds (polyphenol, fatty acids, and polysterol) [55]. Implementing microalgae to treat food wastes and extract various polymer types as building blocks can be incorporated into bioplastic production [12]. The microalgal biomass obtained through biorefining approaches can be processed into a bioplastic polymer such as PHA to act as a potential feedstock during the bioplastic industry improvement process [11]. The downstream processing of microalgae to extract such bioactive compounds (cellulose and lipids) could be promising for bioplastic production [12]. Microbial-derived bioplastics are gaining more attention and are a promising option for ecological sustainability. Corn cob biomass waste was treated to generate fermentable sugars and, due to the bacterial activity, succeeded in producing PHA and astaxanthin [56]. PHA and a high value-added product (astaxanthin) can be economically generated from organic wastes as a cheap, renewable resource. Hence, using organic wastes as raw materials is essential to solving waste management problems. There is also a consensus that managing waste holistically decreases GHG emissions since waste prevention and recovery lower emissions in all other economic sectors.

5. Production pathways for bio-based plastics

Bio-based plastics are abundantly or partially generated from biological sources such as organic waste, algae, fungi, bacteria, and plants. Some bio-based plastic types are generated directly from polymers that naturally develop in microbes and plants [12,56]. Cellulosic materials, the primary ingredient of plant tissue and the most prevalent organic component, have been utilized since the 19th century [57]. Bioplastics derived from natural sources are also produced using synthetic processes [58,59]. Mostly, three major pathways to bio-based plastics may be identified: (1) bio-monomer polymerization, (2) naturally existing polymer modification, and (3) extraction from microorganisms [13,47]. This section discusses the most common bio-based plastics: polylactic acid (PLA), polybutylene succinate (PBS), cellulose acetate (CA), starch-based polymers (SBPs), bio-based polyethylene terephthalate (Bio-PET), and bio-polyethylene (Bio-PE). Table 1 summarizes the major characteristics of these six bio-based plastic types [11,39,60–81].

5.1. Polylactic acid (PLA)

PLA is one of the most prominent examples of biodegradable bio-based plastic. It is a thermoplastic linear aliphatic polyester produced from the fermentation of plant-derived carbohydrates, such as sugars or starch, and is considered an example of the initial pathway of bio-based plastic production [49]. Various bacterial species, such as *Lactobacillus* spp., are utilized in the fermentation process to produce lactate from carbohydrates [60,63]. As illustrated in Fig. 5, the hydrolysis of starch is utilized to obtain glucose, which is transformed into lactic acid. Lactic acid is polymerized to low molecular weight PLA, which is subsequently depolymerized to yield lactide, a cyclic dimer of PLA [82]. Lactide ring-opening polymerization will then yield high molecular weight PLA [83].

Based on the chiral nature of the polymerization building block polymer, three stereochemical variants of PLA can be produced [84]. The resultant polymer can be amorphous or have varying degrees of crystallinity depending on the D- to L-isomers ratio, which influences degradation and mechanical characteristics [85]. PLA can be utilized as a food packaging material because its processability is comparable to various commercial thermoplastics [61]. In addition, PLA biocompatibility has been elevated to the forefront of tissue engineering and biomedicine applications [13]. Moreover, PLA is a popular material for making filaments for fused deposition modeling, a typical 3D printing manufacturing technique [62]. PLA is still in its early stages of development, and its production and conversion processes are not as efficient as PE, the world's most widely produced plastic [86].

The life cycle of PLA can be studied in terms of its waste management scenarios to identify the primary factors influencing its environmental impact. As depicted in Fig. 6, the pathway consists of four distinct steps. Several LCAs are comparing PLA to other plastics regarding environmental impact, energy demand, and GHG emissions [87]. By exploiting the LCAs of PLA, the material can be optimized to be more eco-friendly. The GHG emissions attributable to the life cycle of PLA demonstrate that the conversion of biosources to lactic acid and then PLA is an energy-intensive process that emits a significant quantity of CO_2 into the environment. More than 50% (2.8 kg CO_2 per kg PLA) of the CO_2 released during the life cycle of PLA is due to its conversion [87]. Refining the PLA conversion process will have a high potential to make PLA a low-carbon material.

5.2. Polybutylene succinate (PBS)

Polybutylene succinate (PBS) is a thermoplastic polyester that can be produced from food waste [88]. PBS has properties similar to polyethylene terephthalate (PET) and polypropylene (PP) and is used in biomedical applications, hygiene products, biodegradable bags, and mulch film [89]. PBS has attracted considerable interest in biomedical applications because of its biodegradability and low toxicity profile, although its low degradation rate and relatively high rigidity should be modified by co-polymerizing or blending with other polymers, such as PLA [90].

The processing pathway is shown in Fig. 5. The major components of food waste are carbohydrates, protein, fat, and water. Pretreatment with $Ca(OH)_2$ and NaOH could improve PBS production significantly [91]. The enzyme hydrolysis was carried out using glucoamylase at an optimized temperature of 50 °C for 18 h, and the maximum glucose conversion was 86.5%. A*ctinobacillus succinogenes* ATCC 55618 was used for succinic acid production at 35 °C for 12 h, and the succinic acid yield was 1.51 g per g glucose [88]. The polymerization process is initiated by the reaction of 1,4-butanediol with succinic acid to produce PBS oligomers (Fig. 5). The oligomers are then polycondensed to yield high molecular weight PBS [64].

The utilization of waste feedstock can reduce the environmental impact. As depicted in Fig. 6, the LCA analysis of PBS is based on GHG emissions, land acidification, and fine particulate matter production [88]. GHG emissions from producing PBS from food waste are approximately 5.88 kg CO_2-eq per kg of PBS [88]. When petroleum-

Table 1
Key aspects of different bio-based plastics and end-of-life (EoL) in terms of LCA.

Bio-based plastic	Type	Characteristics	Conversion pathways	Applications	Price (€ kg^{-1})	Environmental impact	EoL options	References
Polylactic acid (PLA)	Bio-based/ biodegradable plastic	• Density: 1.24 g cm^{-3}	PLA is produced from the fermentation of plant-derived carbohydrates by different bacterial species. The glucose produced is converted to lactic acid. Lactic acid is polymerized to low molecular weight PLA, which is subsequently depolymerized to yield lactide and then high molecular weight PLA	• Agriculture	2.0	• PLA's carbon uptake is considered only for biopolymers, which is their advantage in terms of environmental aspects compared to fossil-based plastics	• Biodegradable	[11,60–63]
		• Tensile strength: 50 MPa		• Tissue engineering		• Due to natural conversion, PLA emits 2.8 kg CO_2 kg^{-1} during its life cycle.	• Compostable	
		• Flexural strength: 80 MPa		• Biomedicine		• PLA saves ~66% of the energy required to produce conventional plastics	• Recycling	
		• Impact strength: 96.1 J m^{-1} • Shrink rate: 0.37 −0.41%		• 3D printing			• Landfill • Incineration	
Polybutylene succinate (PBS)	Bio-based/ biodegradable plastic	• Thermoplastic with melting point of about 90–120 °C	PBS is produced from the hydrolysis of non-edible lignocellulosic biomass. The polymerization process is initiated by the reaction of 1,4-butanediol and succinic acid produced by various microbial strains to generate PBS oligomers.	• Biomedicine	4.0	• Non-edible lignocellulosic biomass and food wastes in the production can decrease PBS environmental impact	• Biodegradable	[64–68]
		• Glass transition temp. of about −45 to −10 °C		• Hygiene products		• GHG emissions from PBS are ~5.88 kg CO_2-eq kg^{-1}	• Compostable	
				• Biodegradable bags • Mulch film			• Recycling • Landfill • Incineration	
Cellulose acetate (CA)	Bio-based/ biodegradable plastic	• Density: 1.28 g cm^{-3}	CA is derived from cellulose through acetylation of some of the hydroxyl groups	• Textile industries	5.0	• The CA green synthesis pathway has lower environmental consequences and is a more sustainable route when compared to	• Biodegradable	[69–72]

						the conventional processing method.		
		• Tensile strength: 30 MPa		• Plastic films		• CA can be biodegraded or hydrolyzed after consumption into cellulose and acetic acid in the natural environment. These compounds return to the environment with no adverse effects.	• Compostable	
		• Water absorption: 2.2%		• Photography films			• Recycling	
		• Heat deflection temp.: 60–63 °C		• Packaging			• Landfill	
		• Melting temp.: 170–240 °C		• Separating membranes				
				• Cigarette filter				
				• Biomedical porous beads				
				• Based on the LCC and S-LCA, CA-derived products are significant materials				
Starch-based polymers (SBPs)	Bio-based/biodegradable plastic	Variable depending on the type of starch and blends used	SBPs are materials derived from granular native starch by extrusion with the addition of plasticizer agents	• Textile	2.0–4.0	• Starch utilization in bioplastics production causes a reduction in GHG emissions (>80%) and fossil fuel consumption (>60%)	• Biodegradable	[73–75]
				• Packaging		• When compared to synthetic plastics, starch might cause an increase in eutrophication potential and land usage	• Compostable	
				• Pharmaceutical		• SBPs have better environmental profiles than PE in all categories evaluated	• Landfill	
				• Biomedicine				
Bio-based polyethylene terephthalate (Bio-PET)	Bio-based/non-biodegradable plastic	• Density: 1.38 g cm^{-3}	• Produced from first-generation ethanol, which is oxidized to produce ethylene oxide, which is then converted to Bio-PET	• Durable bottles	1.2	• Bio-PET plastic is highly resistant to biodegradation because of its high aromatic content, which also promotes its accumulation in the environment	• Biodegradable by few strains such as *Ideonella sakaiensis* 201-F6	[76–78]

(*continued on next page*)

Table 1 (*continued*)

Bio-based plastic	Type	Characteristics	Conversion pathways	Applications	Price (€ kg^{-1})	Environmental impact	EoL options	References
		• Melting point: 250–260 °C	• The second pathway is the fermentation of sugar into isobutanol, which is involved in the Gevo process to generate terephthalic acid, which is polycondensed to generate Bio-PET	• Packaging			• Compostable	
		• Boiling point: ~350 °C		• Textile manufacturing			• Recycling	
		• Thermal conductivity: 0.15–0.24 W m^{-1} K^{-1}		• Medicine			• Landfill	
		• Refractive index: 1.57–1.58					• Incineration	
Bio-polyethylene (Bio-PE)	Bio-based/non-biodegradable plastic	• Specific gravity: 0.941–0.965 g cm^{-3}	Produced from first-generation ethanol, which is catalytically dehydrated to generate ethylene and polymerized to yield Bio-PE	• Toy manufacturing	2.3	• The manufacture of bio-ethylene would not be cost-competitive with ethylene obtained from petrochemicals	• Biodegradable	[39,79–81]
		• Tensile strength: 3100–5500 psi		• Cosmetics		• Bio-PE leads to GHG emissions that are around −0.75 kg CO_2-eq per kg polyethylene, which is 140% lower than the production of petrochemical PE; the savings on the use of non-renewable energy are approximately 65%	• Compostable	
		• Elongation: 20–1000%		• Personal care		• One kilogram of bio-PE costs around 30% more than 1 kg of fossil-based PE	• Recycling	
		• Tensile modulus: 0.6–1.8		• Food packaging			• Landfill	
		• Heat deflection temp.: 110–130 °C					• Incineration	

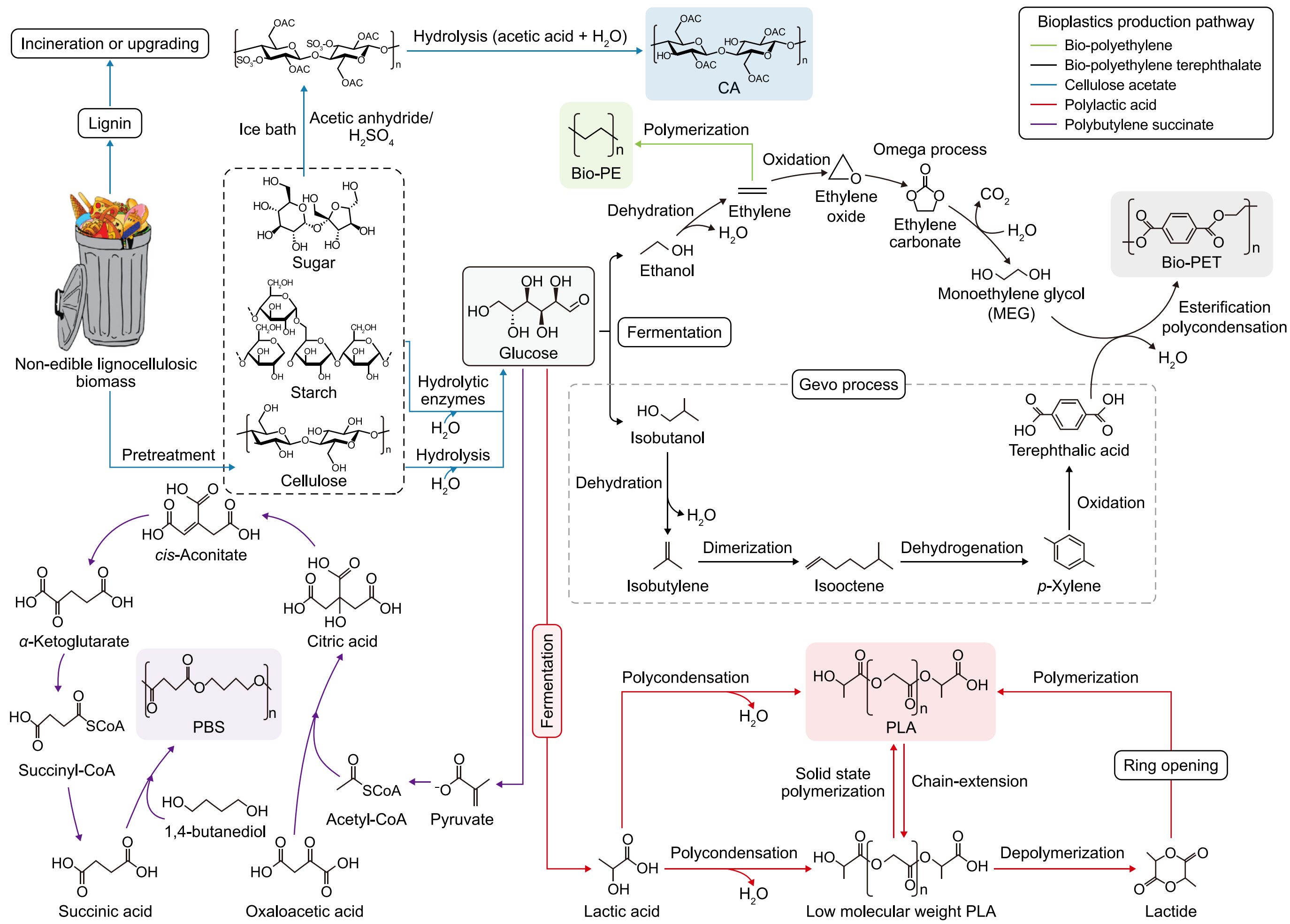

Fig. 5. Polylactic acid (PLA), polybutylene succinate (PBS), cellulose acetate (CA), bio-based polyethylene terephthalate (Bio-PET), and bio-polyethylene (Bio-PE) production pathways from non-edible lignocellulosic biomass [64,72,79,83,106].

based 1,4-butanediol was used, GHG emissions increased [92]. Following hydrolysis and PBS separation, a large amount of steam was used in the drying process. The succinic acid fermentation process necessitates a substantial amount of electricity [88]. Increasing the biomass loading ratio in hydrolysis, reducing solvent usage in PBS separation, and adopting alternative steam and electricity sources will positively impact the environment [93].

5.3. Cellulose acetate (CA)

CA is a commonly used, chemically modified natural polymer that is considered a semi-synthetic polymer [94]. Among the many applications of CA are textile industries, plastic films, photography films, packaging, membranes in separation technologies, cigarette filter tows, and biomedical porous beads [69,70]. CA is mostly derived from cellulose through acetylation of some hydroxyl groups (Fig. 5) and is an eco-friendly material [72]. Cellulose is primarily derived from wood through the pulping process. It may be transformed into a variety of compounds such as rayon and cellophane (regenerated cellulose), cellulose esters (e.g., butyrate and acetate) for molding, film, and fiber applications, and cellulose ethers (e.g., carboxymethylcellulose, hydroxyethylcellulose, and ethylcellulose) for use as gums [95].

The LCA of cellulose-derived compounds, particularly CA, showed that the greener development routes have lower environmental consequences and are more sustainable when compared to the conventional processing method [71]. Fig. 6 depicts the LCA of CA polymers. CA can biodegrade. However, the biodegradation rate is controlled by the intricate interaction between structural and environmental degradability [72]. The primary mechanisms responsible for the degradation of cellulose-based polymers are chemical and biological hydrolysis. The chemical hydrolysis process can be catalyzed by strong acids and bases. For instance, the incorporation of phosphoric acid into CA films accelerated the films' subsequent biodegradation rate in soil [96]. The degradation rate can be considerably increased by using the appropriate combination of enzymes; for instance, the degradation of CA by cellulases is improved when combined with enzymes capable of deacetylation [97]. After 150 days, the CA-degrading *Rhizobium meliloti* and *Alcaligens xylosoxidans* induced a 34% and 23% weight loss of the CA membrane, respectively [98]. A mixture of enzymes that could deacetylate and randomly cleave CA chains to produce shorter CA fragments was the most appropriate catalyst for an enzyme-catalyzed reaction [99]. Because deacetylation is crucial for further CA biodegradation, a deeper understanding of the delicate dynamic between structure, environment, and the deterioration process is still required to maximize the potential of the different end-of-life alternatives.

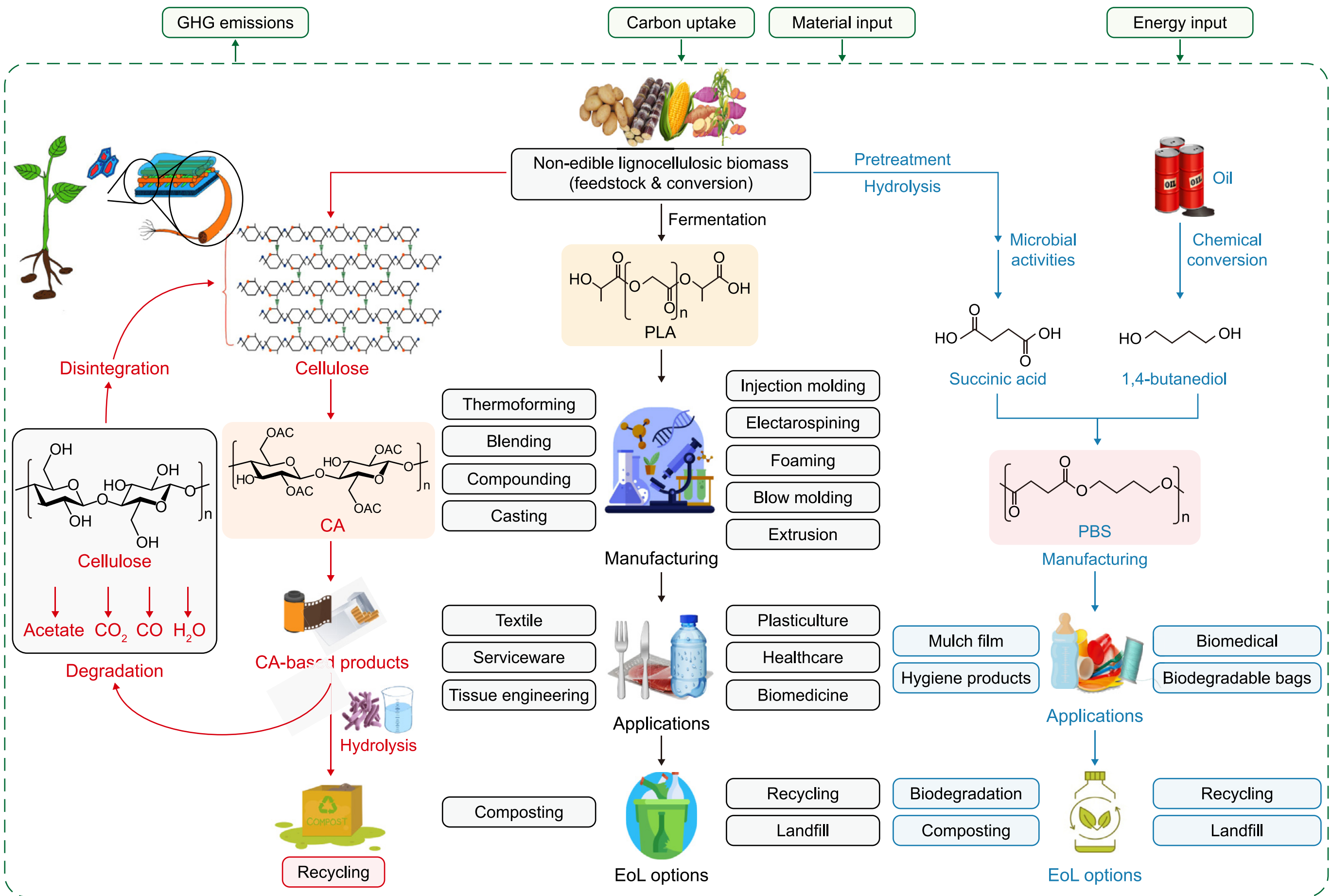

Fig. 6. Life cycle assessment of polylactic acid, polybutylene succinate biopolymer, and cellulose acetate biopolymer.

5.4. Starch-based polymers (SBPs)

SBPs are a promising class of bioplastics. Starch is a polymer derived from different feedstocks such as potato, corn, or wheat [75]. The general scheme of utilizing non-edible lignocellulosic biomass for SBP production is depicted in Fig. 7a. Starch is a polysaccharide composed of two major components: amylopectin and amylose. Thermoplastic starch is a material derived from granular native starch by extrusion with the addition of plasticizer agents [73]. Plasticizers, such as polyols, citrate, amine sugars, and amides, are commonly used to increase the processability of thermoplastic starch. Thermoplastic starch may be used on its own or employed in polymeric mixes with other polymers, such as PLA and other polyesters, to enhance its features and characteristics to fit several applications. SBPs are used in various industries, including textile, packaging, pharmaceutical, and biomedical applications [100,101].

Fewer LCA studies have been found on SBPs [74,75]. Fig. 7b depicts the LCA of SBPs. Regarding NREU and GWP, the food packaging of Mater-Bi (34% starch derived from corn) performed better than PE and PET [102]. On the other hand, Mater-Bi (36% starch) shopping bags performed better than PE, although 16 g of additional material was required to achieve equivalent mechanical properties [103]. SBPs have better environmental profiles than PE in all categories evaluated, excluding EP, despite having larger impacts in other categories that are often outside the scope of LCAs [104]. Similarly, the Mater-Bi shopping bags had greater consequences in ecological quality and human health damage [103]. In terms of both NREU and GWP, the impact of SBPs was significantly lower than that of petrochemical polymers, although it was recognized that these SBPs could not compete with recycled petrochemical polymers [104].

5.5. Bio-based polyethylene terephthalate (Bio-PET)

Bio-PET is a colorless, transparent, hygroscopic resin, semi-crystalline, and has outstanding physicochemical properties [105]. Although the production of total bio-PET is not yet economically feasible, bio-PET is partially produced from renewable resources and is considered one of the most significant bioplastics. The applications of bio-PET vary from packaging to textile manufacturing [106]. The entire output of bio-based PET was 0.54 million tons (26.3% of global bioplastic production annually), and it was expected to reach up to 7 million tons by 2020 by utilizing ethanol as a feedstock [19]. The annual production rate may be reduced to 7.8% of total bioplastic production in 2020 and then to 1.2% of total annual bioplastic production in 2021. Fig. 5 shows that bio-PET is made from ethanol sugar or starch fermentation, which is then converted into various metabolites and transformed to MEG and combined with fossil-based terephthalic acid (TPA) by conventional transesterification to generate partly bio-PET (23% bio-based polymer) [106]. TPA and MEG are the monomers polymerized into PET throughout the production process. The pathway is a polycondensation of the two monomers with water as a by-product (Fig. 5). Therefore, to obtain a bio-PET made entirely from renewable materials, both precursors should be obtained from such renewable materials. Only the MEG component of biomass, which accounts for thirty percent of the entire biocontent, is currently available on a large scale. The remaining seventy percent of bio-PET is still produced from fossils [107,108].

A few LCA studies on bio-PE have been described in the literature [78,108,109,110]. Fig. 8 depicts the LCA of bio-PE. Piccinno et al. [111] established that LCA studies of laboratory operations have limitations since they do not reflect the idiosyncrasies of large-scale production. The authors developed a methodology for scaled-up LCA that consists of five components. For instance, it was found that the environmental impact per kilogram of the product might be significantly lower compared to laboratory production. The authors suggested that the framework for scaled-up LCA may be an effective support for eco-design purposes and could help identify critical steps for process improvement [111]. Through LCA, bio-PET plastic is highly resistant to biodegradation because of its high aromatic content, which also promotes its accumulation in the environment [112]. Concerning the environmental life cycle assessment pillar and the upcycling of PET wastes, Yoshida et al. [113] reported that the newly identified bacteria *Ideonella sakaiensis* 201-F6 can use PET as a sole source of energy and carbon. *I. sakaiensis* hydrolyzes the polymer to its two monomers (ethylene glycol and TPA). The main enzymes in the biodegradation process were PETase and MHETase [113].

5.6. Bio-polyethylene (Bio-PE)

Bio-PE is currently produced utilizing first-generation ethanol derived from food crops such as sugarcane [79]. Fig. 5 depicts the pathway of bio-PE production. Ethanol is then catalytically dehydrated to yield ethylene, which is subsequently either polymerized to yield PE or oxidized to yield ethylene oxide before being hydrolyzed to yield bio-based mono-ethylene glycol (bio-MEG), the bio-based component of bio-PET. The subsequent conversion of ethylene to bio-PE is unaffected by the feedstock source; it can be either petrochemical or bio-based [80]. Bio-PE has various applications, including toy manufacturing, cosmetics, personal care, and food packaging [39].

LCA is used to evaluate the environmental impacts of Bio-PE products and services (Fig. 8). LCA is widely applied in environmental assessments of bio-based materials [114], and it can also be used for comparative assertions between products that deliver equivalent functions. Bio-PE is a type of plastic made from renewable resources [114,115]. Formerly, in terms of LCA, it was believed that the manufacture of bio-ethylene would not be cost-competitive with ethylene obtained from petrochemicals, but starting in 2008, the cost of one barrel of ethanol made from sugar cane started to match the cost of one barrel of crude oil (about US$115 against US$80) [79]. One kilogram of bio-PE costs around 30% more than 1 kg of fossil-based PE [39]. Bioethylene is used to synthesize other polymers such as PS, rubbers, epoxy resins, PVC, and ethylene propylene diene monomer rubber, which might be further bio-based possibilities for bio-based ethylene utilization. The mechanical properties of Bio-PE following the inclusion of natural fibers were employed to boost the stiffness of the resultant composites [81]. Particles and natural fibers with low cost and minimal environmental effect were employed to increase mechanical strength and modulus, and bio-PE was selected as a bio-based polyolefin green matrix for structural wood plastic and

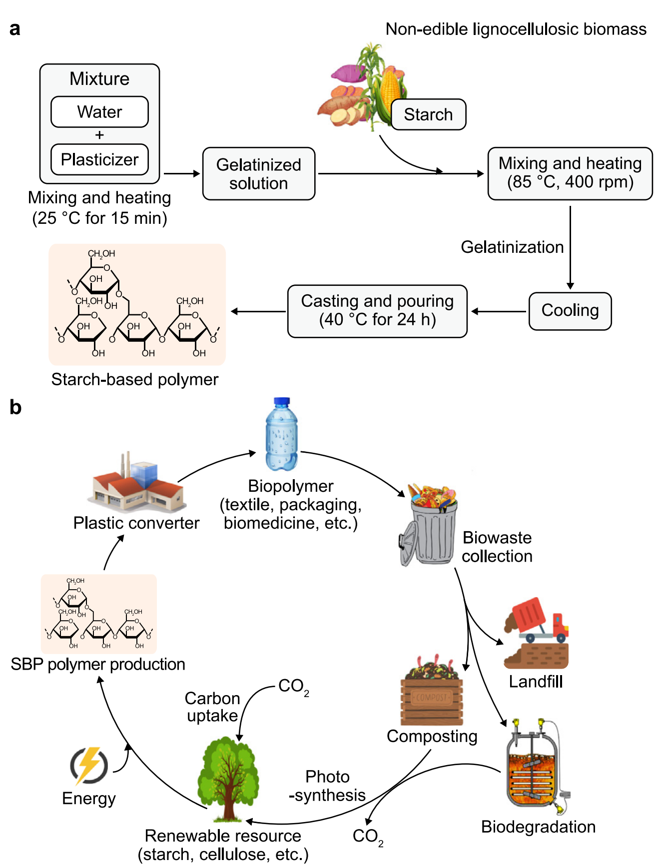

Fig. 7. General scheme of utilizing non-edible lignocellulosic biomass for starch-based polymer (SBP) production (**a**) and SBP life cycle assessment (**b**).

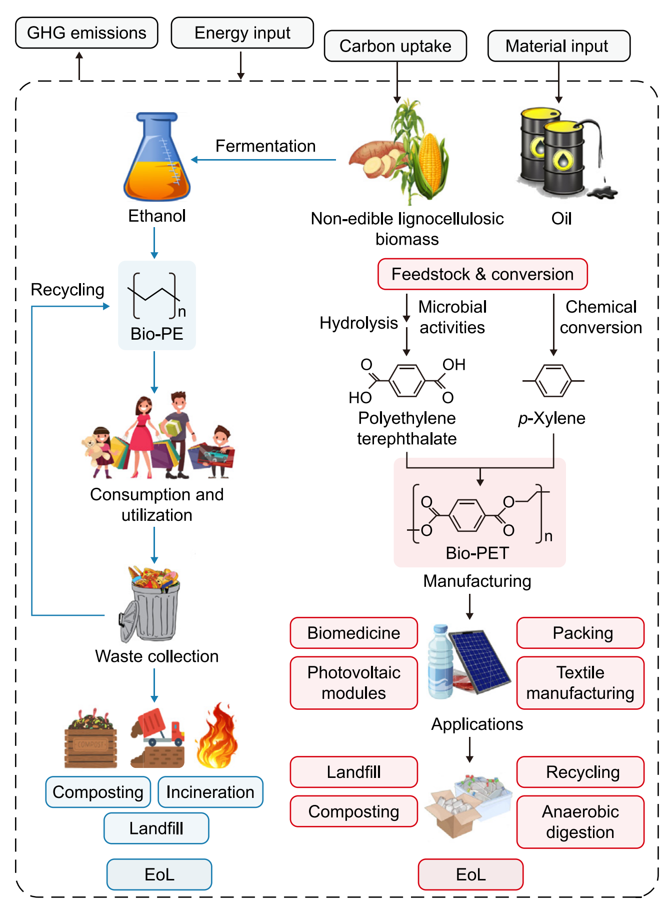

Fig. 8. Life cycle assessment of bio-based polyethylene terephthalate (Bio-PET) and bio-polyethylene (Bio-PE).

natural fiber composites [116]. The problem with utilizing such fillers in structural applications is that when exposed to moisture and a water environment, PE-based wood-plastic composites or natural fiber composites become hygroscopic, resulting in physicochemical changes and aging [117]. This behavior could result from water-swollen filler, filler degradation, and intersection adhesion between polyolefins and the filler.

The production of bio-PE leads to GHG emissions that are around −0.75 kg CO_2-eq per kg polyethylene, which is 140% lower than the production of petrochemical PE; the savings on the use of non-renewable energy are approximately 65% [80]. Using biomass as a steam source for the manufacturing process can further minimize GHG emissions. The impact of bio-based polymers is up to two orders of magnitude higher on human health and the quality of ecosystems, mostly due to the usage of pesticides, pre-harvesting burning practices, and land occupation [80]. Improvements to the supply chain, such as pesticide management and eliminating burning, can lessen the impact of bio-based polymers. Realizing such improvements will allow for reducing GHG emissions and other types of emissions and alleviating additional pressure on fragile ecosystems.

6. Life cycle assessment methodology and software tools

The environmental LCA methodology is an integrated approach that analyzes environmental implications throughout the product's life cycle [118]. Therefore, LCA can be used to evaluate these implications of each construction material. The LCA methodology comprises four analytical phases interlinked by iterative cycles [118] (Fig. S2). These phases include the definition of the goal and scope of the assessment, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle impact interpretation (Fig. 9a).

The description of the product that will be evaluated, the boundary of the associated system, and the functional unit are all included in the definition of the purpose and scope of the assessment. It also includes the selection of the environmental interventions and the method (or methods) of environmental impact assessment, as well as the description of the study's purpose, among various other concerns and aspects of the situation [119]. LCI consists of an inventory, a quantification, and a compilation of the relevant inputs and outputs of the processes that compose the life cycle of the studied product [119]. In order to complete the LCI of a product, each flow (such as mass or amount of materials, energy, and emissions to the air, water, or soil) must be identified, quantified, and compiled for each life cycle and its associated activities (Fig. 9a). The first step of the LCIA process is to choose impact categories, category indicators, and characterization models. The LCI results are then assigned to the various categories of impact based on the classification technique. The stage of characterization is when the calculation of the results of each category indicator takes place. A characterization model takes the LCI results that have been assigned to a particular environmental category and turn them into common units by assuming that there is a cause-effect link between the two. The information required for the life cycle interpretation phase can also be obtained during the LCIA phase [120]. Consequently, here is a compilation of the LCIA category indicator results for all impact categories. The LCA of biomass feedstock or resources offers quantifiable information (environmental effects) that ensures that the designer selects the greenest solutions. To be functionally equivalent or have comparable technical and functional performance, items must be used to evaluate the LCA findings for various bioplastic products [121]. In the end, only a fair comparison between competing alternatives that are similar in functional terms will allow achieving the design project,

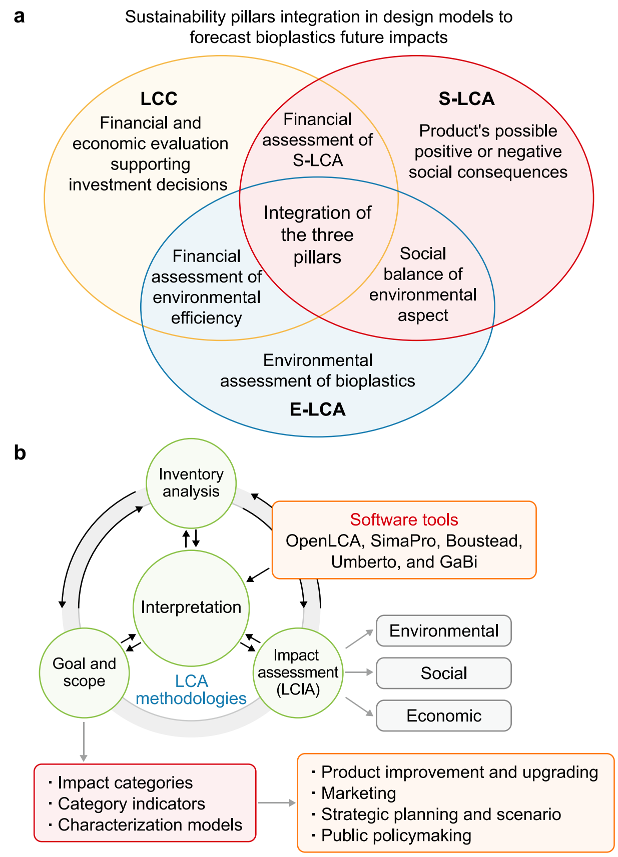

Fig. 9. **a**, Methodologies and software tools used in LCA analysis to improve and upgrade the bioplastics sector. **b**, The proposed framework of bioplastic economy as an alternative to conventional plastic to achieve sustainability [130].

including the minimization of the materials/energy/water consumption, the reduction of the use of hazardous materials, and the prevention of waste and emissions (Fig. 9a).

LCA software tools have grown incredibly significant in recent years. Due to the complexity of environmental systems, LCA modeling can be challenging. As LCAs are frequently data-intensive, software tools are utilized for their management and editing. Additionally, LCA software helps with the construction of the modeled scenario, the presentation of process chains, and the analysis of the results. Several software tools, such as OpenLCA, SimaPro, Boustead, Umberto, and GaBi, are utilized (Fig. 9a) [122,123]. OpenLCA and SimaPro are software for sustainability and LCA evaluation. These programs provide calculations and analysis results, identify main drivers throughout the life cycle by process, flow, or impact category, visualize results, and locate them on a map [124]. Also, GaBi software is a modeling, reporting, and diagnostic tool that drives product sustainability performance during design, planning, and production [125]. GaBi software provides comprehensive LCA functionality and database content to enhance the process's sustainability and provides access to the new LCA hub-based tool for easy LCI data collection [126]. Moreover, Umberto software assesses the environmental impacts according to ISO 14040 and ISO 14067 to reduce carbon emissions and optimize resource and energy efficiency [127].

A typical LCA software tool consists of a database and a modeling module (Fig. 9a). Data manipulation and modeling are performed on an interface. During the modeling phase, successive processes are related to material flows to form the process chain.

Each process is defined by its inputs and outputs. Simple process chains are modeled using a single layer, with the output of one process serving as the input for the next. Hierarchical structures are required for more sophisticated process chains. The top layer models the primary stages of the process, such as extraction, manufacturing, and disposal. Each phase can be defined in further detail in its own sublayer. Thus, sophisticated and complex processes can be modeled and presented clearly. Additionally, when a process chain includes multiple outputs, the various outputs can be tracked using software [128].

However, when performing an LCA using software, one of the challenges is that the results can vary depending on which software was used [124]. The users are the ones who are responsible for ensuring that the results are consistent as well as determining whether or not there are differences in the outcomes that can be attributed to the software that was used [129].

7. Socioeconomic aspects of sustainable development

Sustainability has three interconnected dimensions, comprising societal, environmental, and economic aspects. To achieve sustainable development, it is necessary, among other things, to ensure that products meet the required performance standards. In addition, each of these dimensions needs to be reviewed and satisfied. The idea of life cycle sustainability assessment (LCSA) was established to meet this criterion. This encompasses life cycle cost (LCC), social life cycle assessment (S-LCA), and LCA (Fig. 9b) [130].

LCC is a financial and economic evaluation parameter that focuses on profits, net savings, and/or the savings-to-investment ratio; however, it is incompatible with LCA. As a result, using LCC as an important aspect of sustainability evaluation is still debatable [131]. The LCC model, constructed following the LCA method, provides a tally of all costs that appear throughout the product's life cycle [123]. LCC is effective for supporting investment decisions if the original expenditure is substantial and if extra monetary flows occur during the life cycle, such as maintenance, disposal costs, or cleaning [132]. To minimize double-counting, the probable costs due to environmental damage are not quantified in LCC [133]. The total cost of ownership is a method for estimating economic value that considers not only investment expenditures but also all expenses related to using a service or product [134]. The total cost of ownership is frequently calculated from the customer's vantage point. Unlike LCC, the total cost of ownership includes transaction expenses, allowing suppliers to be compared [135]. It is typically employed for products or services with minimal investment costs, hence elevating the significance of transaction costs. LCC is generally utilized for investment projects since procurement, and operating expenses frequently exceed transaction costs and are therefore not critical to decision-making [20]. Despite being a useful tool in economic evaluation, LCC cannot provide a holistic picture of economic sustainability due to the inherent disparity between user goals (reducing costs) and societal goals. Therefore, the researchers suggested that LCSA should go beyond LCC and make an effort to analyze long-term economic sustainability rather than short-term economic cost [123].

S-LCA is an assessment tool used to study a product's possible positive or negative social consequences across its entire life cycle, including raw material, processing, manufacture, distribution, use, reuse, maintenance, recycling, and final disposal [136]. Currently, there are no standards or codes of practice available; all that can be used to evaluate the social dimensions of products and their influence over their life cycle are guidelines. The guidelines categorize social impacts into five classes: consumers, society, local community, workers, and value chain actors [123]. The major objective of S-LCA is to facilitate the improvement of social circumstances and the comprehensive socioeconomic performance of a product throughout its whole life cycle for all stakeholders. Compared to assessing ecological effects of value chains via LCA, S-LCA evaluation is a relatively new field of study that has recently received less attention from LCSA. This can be explained by the view of environmental concerns as a more pressing issue and the complexities of economic and social issues and their interdependence. Although S-LCA is a relatively new technology, it has garnered a lot of attention in a short time, and there is increasing scientific research into developing suitable theoretical frameworks [137]. Currently, there are no standardized approaches for S-LCA. Nonetheless, the guideline issued by the UNEP/SETAC life cycle initiative represents a substantial step in addressing these difficulties and developing a system that may one day be standardized [138]. There are several challenges associated with S-LCA. Many stakeholders may perceive the evaluation of social impacts, and there is a dispute over the social impact categories and quantification approaches [139]. In addition, the strategy is more applicable to businesses than consumers because it is at least somewhat related to corporate social responsibility. To increase the efficacy of S-LCA, the analysis must cater to broader market and societal needs [140].

Existing LCC and S-LCA analyses have thus far focused on technically mature and well-established products because of the availability of data and a comprehensive understanding of manufacturing processes and customer attitudes toward the product. Companies will be hesitant to reveal specifics on cost drivers and prospective incomes while developing a product to avoid disclosing proprietary information to competitors. LCC provides information that decides whether a company will produce benefits with its products and commodities and thrive in the long term [141]. LCC or S-LCA make sense for established product systems. Economic, environmental, and social assessments of new materials will detect shortcomings and improvement opportunities, supporting sustainable biomaterials development and legislation to enhance the bioeconomy transition [142]. Because there are no global standards for S-LCA and LCC, researchers can develop novel techniques or alter existing methods within the LCA framework to generate more appropriate sustainability evaluation methodologies that correspond to real scenarios.

LCA was used to compare the environmental and socioeconomic performances of PE and PP obtained from biomass to their equivalents based on fossil fuels [143]. The findings of the LCA indicated that GHG emissions could possibly be reduced by substituting ethylene and propylene derived from biomass for those based on fossil fuels. As a result, synthesizing polymers generated from biomass could increase value addition in an economy while simultaneously reducing GHG emissions. Thorough LCA assessments can give useful reference information to policymakers. Various methodologies for conducting LCA studies on PLA bioplastics already on the market have been developed [144]. For example, the LCAs of PE and PET are compared to those of fossil-based plastic. By replacing all fossil-based plastic with PLA and recycling all annually-made plastics, the world could reduce its annual GHG emissions by 800 million tons [145]. Furthermore, as long as quality standards are satisfied, PLA pellets are less expensive than synthetic polymers. Compared to traditional petroleum-derived polymers, PLA and thermoplastic starch considerably decrease CO_2 emissions, with the former reducing emissions by 50–70% [146]. Bio-polyurethanes and polytrimethylene terephthalate emit 36% and 44% fewer GHGs than petroleum-derived plastic [147]. However, to maintain the wise management of bioplastic wastes, GHGs should be reduced to zero emissions [148].

Consequently, the socioeconomic aspects of a product's life cycle need to be analyzed in conjunction with the product's influence on the environment to provide an all-encompassing evaluation of the product's sustainability. The creation of methods and tools for the quantitative analysis of socioeconomic issues ought to be a top priority. The required LCC and S-LCA studies have not yet been carried out, and more work needs to be done in this direction. Similarly, research on polymers, their composites, and nanocomposites using comparative LCC and S-LCA methodologies has not yet been carried out. These kinds of activities would add a new facet to the creation of environmentally friendly products in a variety of different markets.

8. Anaerobic digestion and composting of bioplastics in terms of LCA

The regulated end-of-life (EoL) alternative for biodegradable substances is organic recycling by composting or anaerobic digestion (AD). Table 2 summarizes the LCA studies regarding bioplastics in anaerobic digestion as an EoL option [149–158]. Several EoL scenarios for PLA have been investigated, and it was expected that all of the biogas would be burned to satisfy the plant's requirement for energy, with any surplus offsetting the demand on the European electrical grid [159]. The digestate produced can be used in place of conventional soil conditioners and synthetic fertilizers in agricultural settings. By applying for these credits, the GHG emissions for the EoL of PLA dropped by nearly 55%, from 1.47 to 0.67 kg CO_2-eq kg^{-1} [160]. Additionally, the methane produced by the thermophilic AD of PLA could be utilized as a substitute for natural gas in electricity production, and the digestate could replace peat [161]. These credits more than halved the EoL GHG from 2.2 to 0.9 kg CO_2-eq kg kg^{-1} for PLA. These substantial variances underscore how important it is to have a solid grasp of the potential of AD by-products to act as replacements for compost and electricity [14].

Organic recycling may not necessarily be the most sustainable EoL option for biodegradable materials (e.g., composting) when considering LCA and infrastructure accessibility [162]. Composting bioplastics and biowaste (organic materials) can be a valuable solution for diverting bioplastics and biowaste away from landfills that emit GHG, produce heat, and spontaneously ignite. Plant operators and waste contractors believe that biodegradable bioplastics are a pollutant for the AD process, which poses a difficulty for the bioplastics' biodegradation. This is due to the small amount of bioplastic in the waste stream and the uncertainty surrounding their impact on the production of the micro(nano)-plastics and the quality of the resulting fertilizer, as well as their usage as a soil amendment [163].

The advantages of using bioplastics and organic recycling as EoL solutions should be thoroughly investigated and compared to the advantages of other existing materials and EoL procedures. The study, titled "Relevance of biodegradable and compostable consumer plastic products and packaging in a circular economy" [164],

Table 2
Bioplastics biodegradation and biogas production potential through the AD process as an EoL option.

Bioplastic type	Anaerobic conditions	Time (day)	Findings in term of bioenergy recovery and E-LCA	References
PLA	35–37 °C	40–150	• Mineralization was less than 1 and reached 7%	[149]
PLA	Mesophilic conditions	70–280	• Degradation: 10.8–66%	[150–152]
PLA	37 °C	100	• Degradation: 60%	[153]
PLA	55 °C	30–60	• Degradation: 24–68%	[154]
Starch-based polymer and PLA	pH 8.3, 55 °C, C/N 4.2	33	• AD of bioplastics can be a sustainable approach, reducing bioplastic leakage and producing bioenergy, respecting circular economy principles • AD may represent a valorization treatment for bioplastics' wastes contributing positively to the sustainability of the entire bioplastics' life cycle.	[155]
PHB and PLA	35.7 °C and 350 rpm	170	• PHB and PLA pretreatment increased average methane production by 100%. • AD co-digesters of PHB with sludge caused 80–98% conversion of PHB to methane • AD or co-digestion is a feasible EoL option for bio-based plastics.	[152]
PLA	PLA size (125–250 μm), 37 °C, and co-digestion with cow manure and vegetable waste	277	• Biodegradation: 49% • Methane production: 4.82 L	[154]
PBS	PBS size (125–250 μm), 37 °C, and co-digestion with cow manure and vegetable waste	30	• Methane production reached 0.81 L • PBS was not biodegraded by anaerobic sludge bacteria	[154]
Cellulose-based metallised film	Particle size (1 × 1 cm), co-digested with domestic food waste and card packaging	65	• Weight loss: 78.2% • Methane yield: 0.374 m^3 CH_4 per kg VS	[150]
Starch-based film blend 1	Particle size (1 × 1 cm), co-digested with domestic food waste and card packaging	65	• Weight destruction: 7.9% • Methane yield: 0.113 m^3 CH_4 per kg VS	[150]
Mater-Bi® (a family of maize starch-based flexible films)	37 °C, co digestion with anaerobic sludge	NA	• Methane yield: 33 mL per g VS	[156]
Starch-based bioplastic	Cut into a size of 20 × 20 mm, co-digestion with anaerobic sludge from OFMSW and food waste, 55 °C and static incubation	23	• Biodegradation: 85%	[157]
Cellulose based bioplastic, foil	Cut into a size of 1 × 1 cm, co-digested with anaerobic sludge (thermophilic sludge), 55 °C static incubation	35	• Biodegradation: 18.3% • Methane yield: 283 mL per g VS	[158]

Abbreviations: AD, anaerobic digestion; EoL, end-of-life; PBS, polybutylene succinate; PHA, polyhydroxyalkanoates; PHB, polyhydroxy butyrate; PLA, polylactic acid.

aids decision-makers in finding advantageous and sustainable applications. As a result, novel, sustainable, and profitable biorecycling methods are required to ensure optimal bioplastic recycling. The chemical composition of the bioplastics and the microbial community structure, particularly the acid- and methane-producing bacteria, altered the biodegradation of bioplastics during the AD process [13,165].

The AD of bioplastic is still in its early phases, which calls for additional research and a deeper understanding of the activity of microbes and their metabolic activity, as well as the mechanisms of bioplastic deterioration and the practicality of controlling operating conditions. Controlled environments, such as microorganisms, enzyme type, concentration, humidity, light, oxygen, pH, and temperature according to the biopolymer type, can only be achieved in industrial applications, where composting periods are usually shorter than the time needed for bioplastics to degrade effectively [18]. Concerning the microbial communities analysis involved in bioplastic biodegradation during AD, it has been found that the relative abundance values of major bacterial operational taxonomic units (OTUs) during pre- and post-co-digestion periods changed significantly after polyhydroxybutyrate (PHB) bioplastic was fed to the co-digesters [166]. The major OTUs represented numerous bacterial phyla, including Actinobacteria, Bacteroidetes, Chloroflexi, Cloacimonetes, Deferribacteres, Firmicutes, Proteobacteria, Synergistetes, and Thermotogae, and their abundance fluctuated prior to and after the addition of PHB [166]. The microbial community analysis of PHB co-digested with food waste revealed that the predominant bacterial species belonged to the genera *Defluviitoga*, *Candidatus*, *Cloacimonas*, and *Rikenellaceae*, and that the predominant methanogenic archaeal species belonged to the genera *Methanosaeta*, *Methanosarcina*, and *Methanomassiliicoccus* [167]. In addition, *Bacillus megaterium* and *Alcaligenes faecalis* significantly accelerated the degradation process by a beneficial shift of both functional bacterial and archaeal species [167].

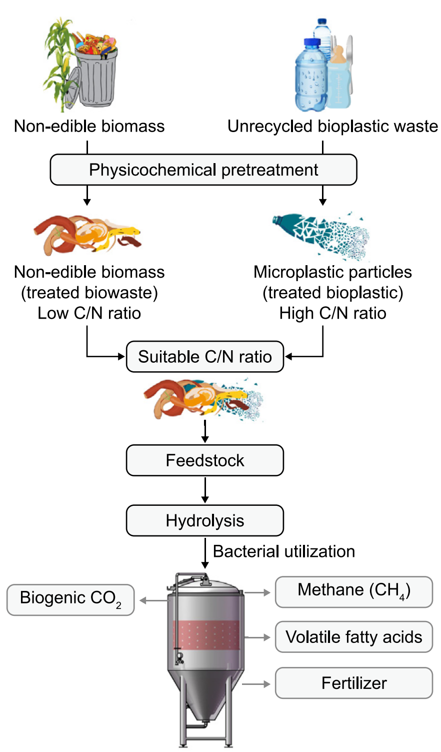

Fig. 10. Biogas production using the co-digestion process of biowaste and bioplastic wastes as a promising end-of-life option.

AD may represent a valorization strategy for bioplastic waste to positively attribute to the bioplastics' life chain sustainability (Fig. 10). However, the use of AD to digest biodegradable polymers may result in significant material loss and CO_2 production due to the low market value of the biogas produced by the process [168]. When biogas is utilized for heat and power generation units, it requires the funding of €20–50 MWh^{-1}, and when it is injected into natural gas grids, it requires an upgrade cost of €0.9–1.3 m^{-3}, which is higher by €0.3–0.6 m^{-3} than natural gas [169]. Alternately, the acidogenesis stage could promote a circular bioeconomy by recovering high-value byproducts, such as volatile fatty acids, that can be used as a renewable carbon source [170]. AD of bioplastic faces various problems and obstacles, such as bioplastic hydrolytic retention times (HRTs) variation between batch and large-scale reactors [171]. Furthermore, bioplastics such as PHB might be stored on-site to complement AD by providing a dense supply of carbon that could be blended with other influent waste streams. The bulk theoretical oxygen demand (TOD) of PHB is 2200 g TOD L^{-1}, whereas synthetic municipal primary sludge comprises only 50 g COD L^{-1}. The findings of anaerobic batch studies are frequently used to estimate AD feasibility. However, they may not adequately reflect the functioning of continuously fed digesters in a quasi-steady state. Furthermore, because of the lack of nitrogen, the C/N ratio of most bioplastic types is too high and will never be suitable for microbial activity [172]. Therefore, anaerobic co-digestion can be an effective EoL option for reducing synthetic and bioplastic waste and recovering bioenergy (biogas production), particularly when co-substrates have high nitrogen content [173]. The methane production from PLA and PHA co-digested with food waste has been estimated in a batch experiment conducted under different temperature conditions at various mixing ratios for 20 days [68]. The methane production from PHA was 153.8–172.0 mL CH_4 per g chemical oxygen demand (COD), and methane production from PLA was significantly lower (<25.6 mL CH_4 per g COD). A higher methane yield was obtained at thermophilic temperatures. The co-digestion process (food waste and bioplastic) produced 178.9–246.4 mL per g COD at mesophilic conditions and 228.3–260.7 mL per g COD at thermophilic conditions [68]. Hence, the co-digestion of food wastes with bioplastic wastes might be a possible treatment option for effective biogas production.

Unrealistic modeling of the AD process in LCAs could provide misleading information regarding the environmental impacts of such processes, making it more difficult to make well-informed judgments regarding appropriate waste management procedures for bioplastics. As a result, future LCA modeling should make an effort to incorporate the implications of the AD systems that are currently in use.

9. Imperfection of bioplastics

The evaluation of the environmental impact of bioplastics seems to be highly controversial. However, bioplastics are typically characterized as superior alternatives to polymers derived from fossil fuels [174]. In the presence of water and/or oxygen, biodegradable bioplastics can decompose into natural components via biological processes and merge innocuously with soil [175]. When a cornstarch-based bioplastic is composted, the cornstarch molecules slowly absorb water and expand when buried. This causes the starch bioplastic to disintegrate into microscopic fragments utilized by bacteria [176]. Some low-degradable or non-biodegradable bioplastics, on the other hand, decompose only when handled in digesters or at high temperatures [177]. Moreover, many biodegradable polymers can only decompose at specific active landfill sites under tested conditions [178].

Bioplastics can be produced from proteins, carbohydrates, or lipids, which are the main components of microalgae. Despite the potential of algal plastics, few studies investigate this point from various perspectives, such as algal strain selection and optimization, as well as their bioplastics production mechanisms [179]. Additionally, bioplastics are environmentally beneficial; for example, PLA saves ~66% of the energy required to produce conventional plastics [180]. Furthermore, using corn-based PLA bioplastics instead of standard plastic reduces GHG emissions by 25% [181]. Such examples demonstrate that new bioplastics can be produced utilizing renewable energy while lowering GHG emissions significantly [182].

A bioplastic derived from plant biomass illustrates the evolution of bioplastic incorporations. The carbon, environmental, and water footprints of ordinary PP plastic were combined with those of bioplastic fibers. The results indicated that bioplastic fibers had a smaller carbon footprint and a lower environmental impact than PP [183]. The use of starch in the production of biodegradable bioplastics reduced GHG emissions and non-renewable energy usage by up to 80% and 60%, respectively [184]. Compared to petrochemical plastics, starch may enhance eutrophication potential (up to 400%) and land consumption (0.3–1.3 m^2 yr kg^{-1}) [184]. Recycling agro-industrial and urban wastes could mitigate the adverse effects of using plant-based bioplastics or additives since this technique may limit the consumption of water resources and arable land, as well as the cultivation and harvesting of these biomasses [185]. Utilizing agricultural, industrial, and municipal biowaste decreases the aforementioned ecological repercussions and is a management alternative for agricultural, industrial, and municipal biowaste [186]. Compared to pure starch, blends with starch residues show a reduction in land use (up to 60%), eutrophication potential (up to 40%), GHG emissions (up to 10%), and non-renewable energy use (up to 60%). Reducing the water footprint can also be accomplished by utilizing residual vegetative biomass, which can be derived from many crops [184].

There are some disadvantages associated with bioplastic production. Composting produces methane and other GHG emissions that are several times more harmful than CO_2 [68]. In addition, the development of bioplastics from plants like corn and maize requires the reallocation of land that would otherwise be used for agricultural purposes to produce plastics rather than food [182]. Moreover, the price of food could dramatically increase when more agricultural land is used to produce biofuels and bioplastics, which will affect the more economically disadvantaged segments of society [187]. The production of bioplastics produced more pollutants due to the use of pesticides and chemical fertilizers during the cultivation of crops and the chemical processing necessary to convert biomaterials into bioplastic [188]. The production of conventional plastics from fossil fuels contributes less to the depletion of the ozone layer than the production of bioplastics [189]. The cost of production is another aspect that influences bioplastic production [190].

During industrial applications, the cost of the carbon and nitrogen sources required for the bulk production of bioplastics is a limiting factor [191]. Several companies, for instance, have terminated PHA production since it is a more expensive process than plastics derived from fossil fuels. In 1998, Bipol produced commercially PHA that was 1700% more expensive than fossil-based plastic; nevertheless, this price has decreased to €5 per kg PHA compared to €0.80–1.5 per kg synthetic plastic [192]. Despite efforts, the cost of PHA production is still higher than that of synthetic plastics. The high price of PHA is mostly attributable to delayed microbial growth, limited conversion of raw material into PHA, high energy requirements during sterilization and aeration, and expensive downstream processing [193]. Consequently, using inexpensive renewable sources, such as organic waste, may be an alternate option for economical bioplastic production.

10. Outlook

Several biopolymer products' sustainability in terms of LCA was discussed. A significant part of the social, environmental, and economic factors is the evaluation of bioplastic sustainability pillars. It is difficult to determine definitively whether bioplastics are more practical and environmentally friendly than petroleum-based plastics because there is a lack of data. Additionally, it is difficult to determine what benefits and/or drawbacks bioplastics may cause as a feedstock for the long-term advancement of a sophisticated circular bioeconomy. To produce sustainable bioplastic, it is necessary to explore and balance the sustainability pillars LCC and S-LCA, utilizing a variety of quantitative analyses to reveal new facets of sustainable development. In light of the findings of this analysis, numerous strategies can be proposed as potential contributors to sustainable development. These include the following:

(1) LCA studies that have been meticulously carried out can provide decision-makers with useful reference material and address the most effective method for managing and disposing waste from bioplastics. Therefore, the utilization of biowaste in the production of bioplastics and biofuels presents a significant opportunity to contribute to developing a sustainable environment and economy by lightning the load placed on non-renewable resources.
(2) One critical component of displaying sustainable growth is the reformation of production techniques, processing methods, and disposal practices pertaining to plastics. Using bio-based plastics can have some drawbacks (e.g., consumption of fertilizers, sociological issues, etc.). Nevertheless, biodegradable bioplastics offer an alternative to production that relies on fossil fuels. However, biomaterials such as compost bags offer advantages since compost bags (bioplastics) and biowastes (e.g., agricultural, municipal, and industrial biowastes) may co-digest. This reduces the necessity for separation while simultaneously producing compost and energy.
(3) The bio-valorization of organic waste into diverse bioprocesses for bioplastics and biofuels, such as biogas or other high-value-added products, significantly promotes a sustainable circular economy. This transitional phase represents a low-carbon economy via reducing GHG emissions.
(4) Since bio-based biodegradable plastics are produced from renewable feedstock and do not accumulate in the environment, they do not have the same disadvantages as conventional plastics. In addition, the GHG emissions that result from biodegradation can further exacerbate the negative impacts on the ecosystem. Inadequate infrastructure and the high cost of composting could create further complications. Better agricultural technology can lower the environmental impact of the agricultural phase of bio-based bioplastic feedstock and boost its sustainability.
(5) It is necessary to recognize and protect the particular needs of vulnerable stakeholders in manufacturing processes. Regarding financial and legal clarity, government and non-government organizations' support is crucial. In order to examine the availability of data on bio-based plastics, additional research on methodological harmonization and improvement is required to evaluate the full potential of bioplastics in all regards.

(6) Bioplastic products should be engineered to degrade effectively while maintaining mechanical qualities throughout the "usage" phase without producing technological problems. Another claimed benefit is using biodegradable biopolymers to prevent environmental pollution. However, this looks overly optimistic at present. Natural ecosystem conditions are dynamic and are affected by the season, geographical location, plastic waste types, density, size, and accumulation of other wastes; these factors can influence and determine the magnitude of the impact. In addition, using biodegradable alternatives does not compensate for the economic loss caused by plastic waste. Strict rules, fostering an ecologically friendly mentality, and supporting sustainability-focused education can be better implementations of resources in this regard.

11. Conclusions

There is currently a shift from petrochemical to bio-based plastics (bioplastics). High environmental repercussions result from the production of polymers derived from fossil fuels. Therefore, bioplastics is anticipated to continue to expand as a promising alternative. The application of comprehensive and appropriately designed LCA studies is imperative to provide clear evidence on the comparative sustainability of bioplastics. This review explores the growing collective of LCA studies that compare the environmental footprints of specific bioplastics to those of petrochemical plastics. It also investigates important methodological choices regarding impact category selection, inventory completeness, choice of EoL scenarios, and LCA type. Several types of biodegradable bioplastics were studied, demonstrating their potential to compete with conventional plastics. However, to improve the environmental advantages of bioplastic materials and reduce GHG emissions, further studies are required to comprehend LCA's environmental, economic, and social impacts. Also, the biodegradation behavior of these materials in various environments should be explored as an EoL alternative. This review paper reveals that the AD process may be a practical, environmentally friendly, and cost-effective EoL option for bioplastic wastes. In addition to S-LCA and LCC, the life cycle thinking and EoL of bioplastic products in the context of the transition to a circular bioeconomy and sustainability have been highlighted. Future studies may consider using a more eco-friendly substitute for fossil-based plastics, and policymakers should focus on making disposal pathways for bioplastics apparent and accessible to consumers to reduce the mismanagement of plastic waste.

CRediT authorship contribution statement

Sameh Samir Ali: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Esraa A. Abdelkarim:** Writing – original draft. **Tamer Elsamahy:** Writing – original draft. **Rania Al-Tohamy:** Writing – original draft. **Fanghua Li:** Investigation, Writing – review & editing. **Michael Kornaros:** Investigation, Writing – review & editing. **Antonio Zuorro:** Investigation, Writing – review & editing. **Daochen Zhu:** Investigation, Writing – review & editing. **Jianzhong Sun:** Conceptualization, Data curation, Validation, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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