Preventing Petrochemical Plastics Pollution: Sustainable Material Alternatives

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Abstract: Achievement of some of the United Nation's Sustainable Development Goals will not be possible if global trends in pollution associated with petrochemical-based plastics continue. Alternatives to petrochemical plastics have been researched intensely, but they have not been developed to replace current plastic products in a commercially viable way. The demand for single-use plastic personal protective equipment created by the COVID-19 pandemic has stimulated urgency in developing pollution prevention strategies that transcend reliance on highly variable consumer behavior. Biological material plastics are potentially sustainable because their manufacture utilizes renewable resources, and they are biodegradable. In this paper, challenges facing the sustainable management of discarded single-use petrochemical plastics are discussed, and a material lifecycle perspective is proposed that would be integrated into a circular economy of biological plastics. Preventing petrochemical plastics pollution requires a shift to fossil-free feedstock and energy and the design of biopolymers with desired properties. In this work, strategies for improving the performance and recyclability of biological plastics by designing polymers with diversified functionalities are presented.

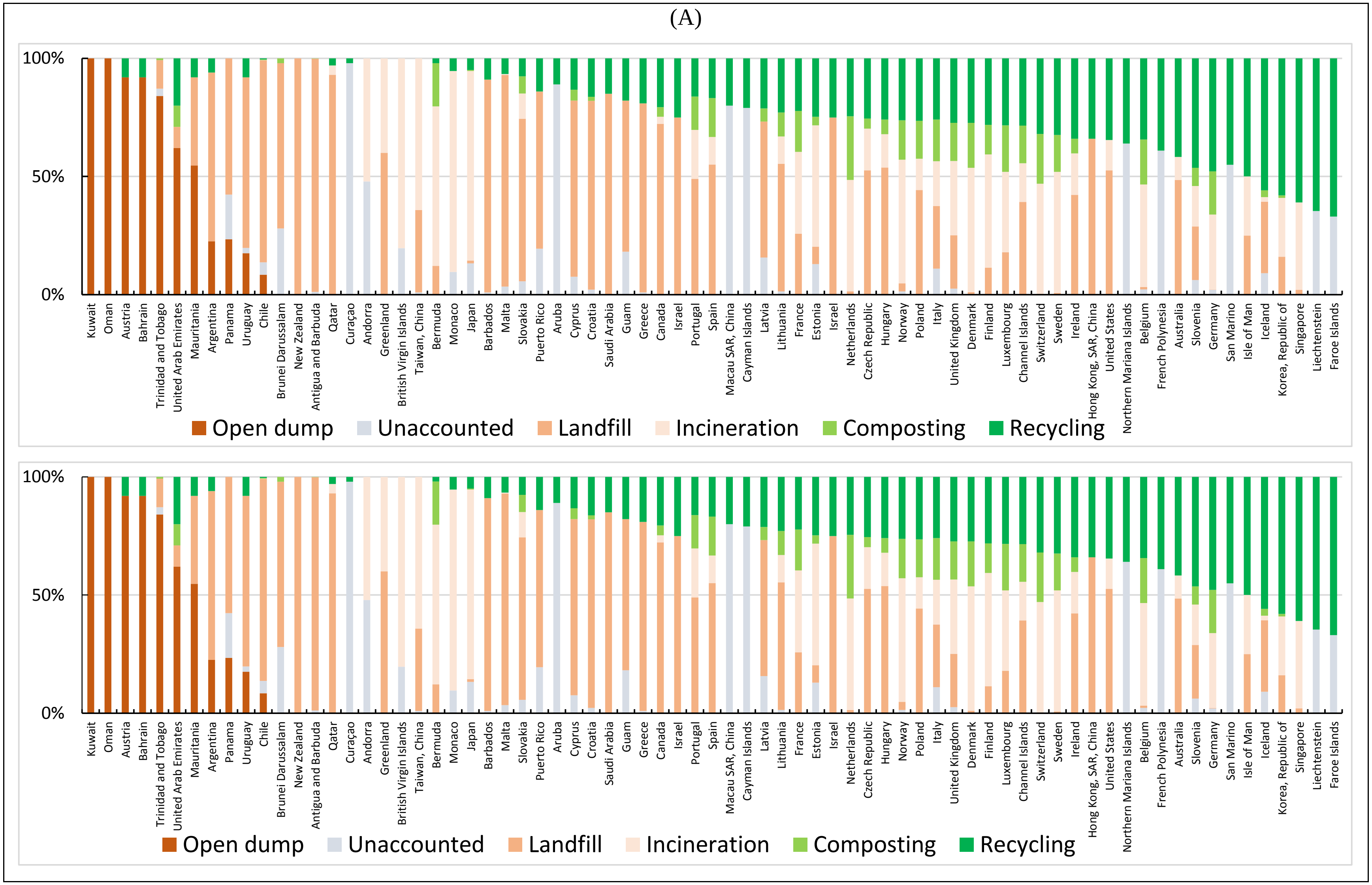
Keywords: Biological plastics; Petrochemical plastics; Circular economy; Environmental sustainability; Personal protective equipment (PPE); Pollution prevention; Waste Management

1. Introduction

Rapidly declining prices in the global market for petrochemicals due in part to the COVID-19 pandemic has generated incentives for the increased production of petrochemical plastics, while also causing an unprecedented increase in the volume of municipal solid waste due to the widespread disposal of single-use plastic personal protective equipment (PPE) [1]. Until 2019, the global production of petrochemical plastics amounted for nearly 359 million tonnes? annually, consuming an average of 10% of the global petroleum resources [2]. Increasing demands for PPE and single-use plastics due to the ongoing pandemic have led to increased concerns about the disposal of used PPEs and packaging plastics [3]. The material compositions of PPEs include plastics as major constituent, representing 20–25% by weight, and the plastics used in packaging materials represent nearly 40% of the total plastic production worldwide [4]. These trends in plastic consumption are responsible for approximately 150–200 million tons of annually discarded plastics worldwide [5]. Early in the pandemic, the urgent health issues and demands for PPEs including face masks, gloves, goggles, and medical gowns, which were inadequate for the need in many countries caused by limited supply, added an unforeseen dimension to the environmental and public health consequences [6].

The World Health Organization recommended the rational use of PPEs in the hospitals and also estimated that to meet the increasing global demand for PPEs, the world required an estimated 89 million masks, 76 million pairs of gloves, and 1.6 million pairs of goggles each month [7]. For example, Singapore, an island country of approximately 6 million people generated an additional 1,470 tons of plastic waste, particularly from food packaging, within the first two months of the pandemic lockdown [8]. The city of Wuhan in China generated nearly 240 tons of medical waste per day at the peak of the pandemic, nearly six times more than before the pandemic [9]. In Thailand, owing to the social distancing and isolation policies, the country generates approximately 6,300 tons of household waste per day, including a 15% surged amount of plastic waste, nearly seven times more than the amount before the pandemic [10]. Manila, a city of 14 million people, is causing an additional 309 tons of healthcare waste daily due to the COVID-19 pandemic [11]. In the United States and other parts of the world, the pandemic has spurred a rapid expansion in the production of desperately-needed PPEs and other plastic products [6, 12]. These production trends appear to be reversing the momentum of years-long global strategies to reduce the use of single-use plastics [13]. Discarded face masks are reported to be piling up on Hong Kong's beaches and nature trails [14]. The consequences of single-use plastic products add to the staggering economic costs of the pandemic [15, 16].

There are three common routes for the disposal of the plastics globally: mechanical recycling, landfilling, and incinerating, with the latter two the major routes used worldwide [17, 18]. In many countries, existing facilities for solid waste management (including medical waste) may not be able to sustain the increased inflow due to COVID-19-related wastes [19-23]. Figure 1 shows the treatment techniques for municipal solid waste in the four income groups: high-income, upper-middle-income, low-middle-income, and low-income countries. [23, 24]. High-income countries show that they do have a quarter of total waste proportion that are properly recycled and the remaining of the waste is scientifically landfilled or incinerated with the few exception countries where most of the wastes are openly dumped. However, the situation of the waste management in upper and low-income countries is not very promising, where most of the wastes are open dump and unaccounted for management, with a limited amount of waste that is dealt with proper handling.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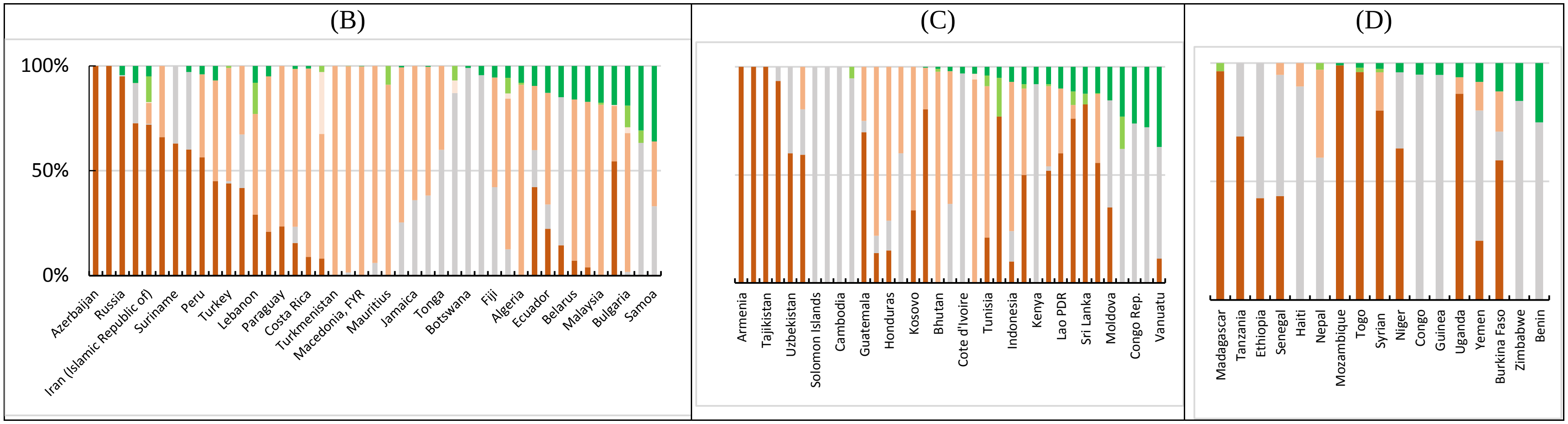

Figure 1. Municipal solid waste treatment and disposal by income groups: low, lower-middle, upper-middle, and high-income countries. A) High-income countries, B) upper-middle-income countries, C) low-middle-income countries, and D) low-income countries [24].

In this work, strategies for a sustainable response to the increasing demands of the current pandemic on resources for plastics and their end-of-life management are focused on. Plastics are a key component of a wide range of industrial applications and in the healthcare and packaging sectors, and plastic is requisite due to its ability for different requirements [25, 26]. The production of polymers that are the key unit for plastic making majorly depends on fossil fuel inputs, such as oil and gas refining and petrochemical manufacturing [27, 28]. However, plastics can also be produced from non-fossil fuel inputs, such as bio-based materials from plants, animals, and marine life, but at present, such production contributes less than 1% to the total global plastic production [29, 30]. This work aims to investigate strategies to pursue a sustainable production of bio-based plastics that includes current challenges of the bioplastics and future requirements for enhancing performance, degradability, recycling, and circular design of the bioplastics. Current global plastics production and consumption by regions is also discussed, and the scope of the bioplastics and their impacts on the environment is critically assessed using a life cycle analysis. It has been demonstrated that the application of bio-based materials for plastic products has greatly improved the thermal resistant capacity of polymers, which is a great advantage for plastic use for wider applications. This study has great importance for understanding the global plastic crisis, and the outcome provides a unique opportunity for future sustainable plastics production and use.

2. Global plastic production and consumption

Since the introduction of mass produced plastic products in the mid-1950s, global plastic production has quadrupled, and most of the production is based on fossil fuel feedstocks (Figure 2) [31-33]. In 2018, more than 99% of global plastic production used approximately 360 million tons of fossil fuels, while the production of bio-based plastics accounted for less than 1% of the total plastic production. By region, Asia accounted for more than half of the total production of plastics. North America and Europe accounted for 18% and 17%, respectively. However, the consumption of plastics in the Asia region was also high, as compared to other regions (Figure 3) [34]. Asia, including China, Japan, and India, were the highest production and consumption regions, followed by Europe and North America. According to the reports, if the production rate continues in the same trend, plastic production will account for approximately 15% of greenhouse gases (GHG) emissions and in number, the discarded plastics in the ocean will overtake the number of fishes by 2050 [35]. Studies have shown that nearly 90% of used plastics are not properly managed across countries, and nearly 8 million plastic items are discarded in the oceans annually. Of these, single-use plastics account for approximately 49 % [33, 36]. In 2019, 180 countries reached an agreement to cooperate on reducing plastic waste [37]. Yet, many countries have either rolled back or postponed the embargo measures on anti-plastic legislation due to the COVID-19 outbreak, and the pressures from the societal stigma that using single-use plastics are safer than reusable bags made of non-plastics [38-41]. However, the scientific data have shown otherwise claiming that SARS-CoV-2 is more stable on plastics and metals than other organic materials [42].

There are two primary processes for manufacturing plastic materials: polymerization and polycondensation, and both methods require specific catalysts. The final product of plastic production has its properties, structure, and size depending on the types of basic monomers that have been used. Based on the characteristics of the final polymers, plastics are grouped into two primary families: thermoplastics and thermosets, and the details are shown in Table 1 [43, 44]. Bioplastics, in contrast, are made in whole or part from renewable biomass, such as sugar cane, beet, and cornstarch. Depending on the biomass materials used for polymerization, bioplastics have different properties. For example, polylactice acide (PLA), bio-polyethylene terephthalate (PET), bio-polyethylene (PE), and starch blends are mostly used for packaging applications, while bio-based succinic acid is used in sportswear, automotive, agriculture, and textile applications [45-48].

Table 1. Types of plastics and their commercial polymer names [44, 45]

Thermoplastics	**Thermosets**	**Bioplastics**
Polypropylene (PP)	Polyurethane (PUR)	Starch blends
Polycarbonate (PC)	Epoxide (EP)	Polylactic acid (PLA).
Polyethylene (PE)	Phenol-formaldehyde (PF)	Polyhydroxyalkanoates (PHAs)
Polystyrene (PS)	Unsaturated polyester resins (UP)	Polyhydroxybutyrate (PHB)
Polyethylene terephthalate (PET)		Polybutylene succinate (PBS)
Polytetrafluoroethylene (PTFE)		Polyethylene terephthalate (bio-PET)
Polyvinyl chloride (PVC)		poly trimethylene terephthalate (PTT)
Polymethyl methacrylate (PMMA)		Bio-polyethylene (bio-PE)
Acrylonitrile butadiene styrene (ABS)		Bio-polyamide (bio-PA)
Expanded Polystyrene (EPS) Polycaprolactone (PCL)		Polybutylene adipate (PBA)

The current global plastic industry is one of the major users of the world’s petroleum refinery output, accounting for approximately10% of the total output of nearly 650 million tons annually [2]. The demand for plastics is also growing rapidly worldwide, and in 2019, plastic demand outpaced all other bulk materials, such as cement, aluminum, and steel [49]. Approximately 70 million tons of thermoplastics are used in the textile industry alone annually [50]. Other than the fossil fuel feedstock, bio-based materials are also used for plastics production. While still a relatively small market, innovative progress in recent years, in the development of bioplastics has proven to be an environmentally friendly alternative to fossil fuel plastics, providing recyclable plastics that have thermal resistance and are mechanically strong. These innovations in bioplastics are also attracting attention in various countries that could foster large-scale adoption and supportive regulations [47, 51-53]. For example, from July 2019, 7–11 Japan has adopted bio-based plastic wrappers for foods [54] and, similarly, Germany has supported the use of certified bioplastic bags since 2015 [55]. These innovations and adaptation in these countries could be the right step toward a circular and bio-economy in the immediate future to switch to bioplastics, or at least reduce dependence on fossil fuel-based plastics.

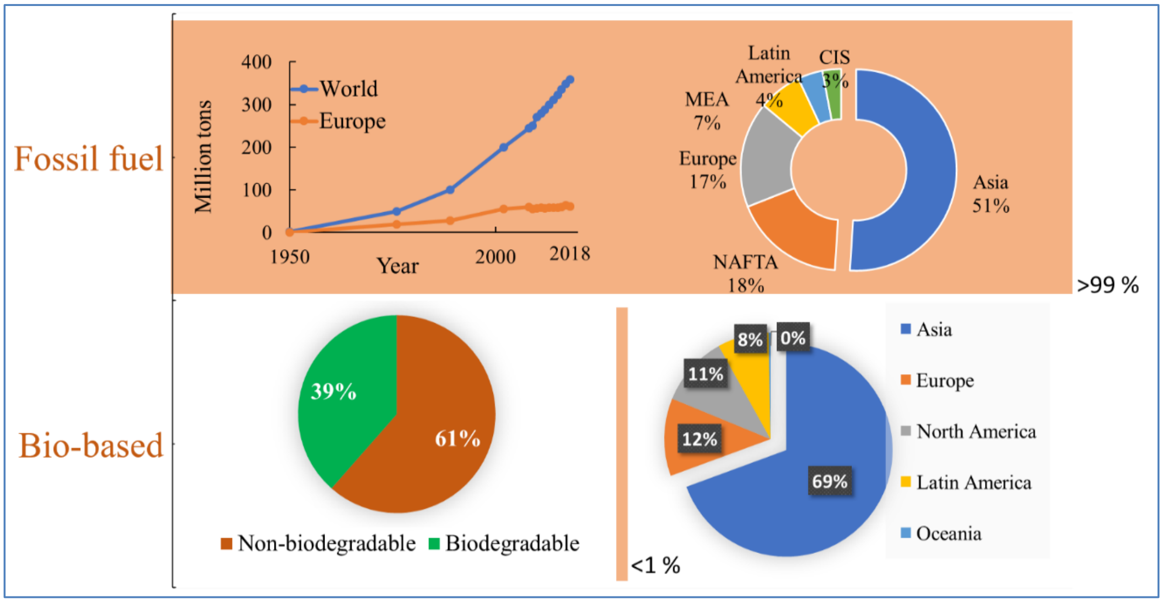

Figure 2. Global plastic production is based on feedstock and share percentages on the different continents. The bio-based feedstock production includes the biodegradable and nonbiodegradable material types and their segment production in the different regions [32-34].

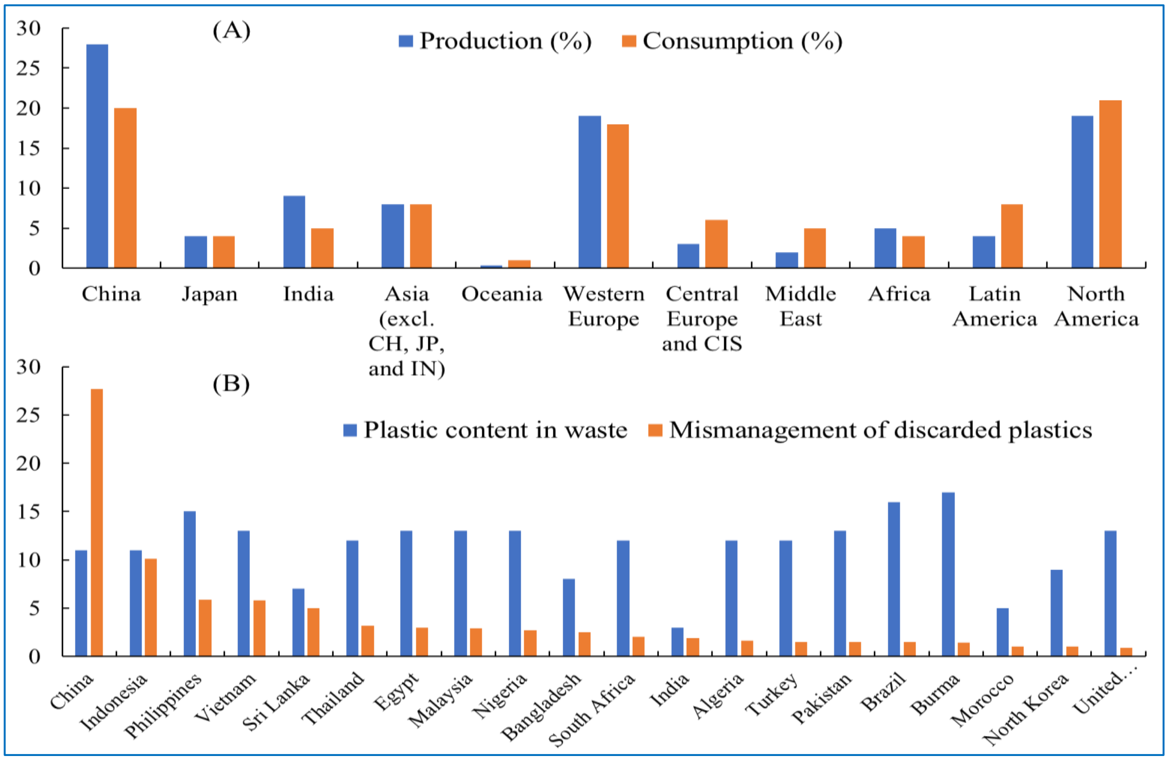

Figure 3. Global plastic production and consumption by regions. A) Major countries and regions are representing their plastic production and consumption share. B) The plastic content share in the total generated municipal waste and the plastic portions that are managed improperly [35].

3. The current status of bioplastics and future strategies

3.1. Scope of bio-based plastics

The current consequences of plastic use, such as ecological degradation, marine pollution, and littering from fossil fuel-based plastic products have provoked urgent calls for a more sustainable plastic production system [56, 57]. These prerequisites include decoupling plastics production from fossil fuel, prolonging the use of plastics, and a closed-loop recycling system [58, 59]. To adopt a circular and bio-economy system for plastic production, the current linear economy based plastic system requires rethinking of the entire plastics value chain from cradle to grave [60, 61]. Therefore, bio-based plastics could play an important role in decoupling the fossil fuel feedstock. Biomass is not only an important sustainable feedstock for the plastics, but also for biofuel and chemical production [62, 63]. Being approximately 1% of the current market share, bioplastic has plenty of room for innovation and materials development for bioplastic building blocks from complex biomass streams [64]. This is because the current biomass feedstock sourcing and undeveloped infrastructure for recycling and end of life management are additional challenges to bioplastics production [65]. For a sustainable bioplastic system, recyclability and resource recovery from the end of life products are essential components. In this regard, industrial biotechnology would be a key enabler for the production of feedstocks from different sources of biomass and also for the recycling and biodegradation of bioplastics [66, 67].

In 2018, approximately 2.61 million tons of bioplastics were produced globally, of which, 38.5% was biodegradable and the remaining was non-biodegradable [32].

Biodegradable plastics are primarily thermoplastics made of starch and several aliphatic polyesters [32, 68]. These include polyhydroxyalkanoates (PHAs), poly (lactic acid) (PLA), and poly (butylene succinate) (PBS). PLA is the most commercially developed and widespread polymer among biodegradable plastics [69]. Biodegradability is considered to be ecofriendly in nature due to its decomposition to natural building blocks and reduction of waste generation [70]. However, the thermal, mechanical, and rheological properties of the PLA and other biodegradable plastics are not as on par as fossil-based plastics. Due to limited compatibility and the recycling system available now, co-polymerization or blending with additives are required to achieve the required properties for biodegradable plastics [71]. However, not all the bioplastics are biodegradable, as can be seen in Figure 2. Approximately 60% of bioplastics are non-biodegradable, including the poly(ethylene terephthalate) (bio-PET), poly(trimethylene terephthalate) (PTT), bio-poly(ethylene) (bio-PE), and bio-polyamide (bio-PA) [32, 72]. In recent years, these bio-based polymers have been considered to have a renewable origin and are increasingly growing in the market to the substitution in part or in whole of the fossil-based feedstocks of conventional plastics. The details are shown in Table 2 [71]. Notably, the chemical structures of these bio-based materials are identical to those of fossil-based substitutions, and also these greener alternatives can be refined in the existing infrastructure [73, 74]. The final products of the bio-based monomers are also similar to the consumer's familiar plastics in their performance and applications. Additionally, there are various efforts which are underway to improve the quality of other bio-based monomers, such as isoprene, propylene, styrene, acrylic acid, and terephthalic acid, for widely used plastics [71, 75, 76].

The scope of bio-based plastics is not merely based on fossil-based alternatives, but also on a variety of novel structures from renewable sources that are not obtained from fossil resources, e.g., furan-based monomers and isosorbide including 2,5-furan dicarboxylic acid (FDCA). FDCA is a dehydrated product of C_6-sugar oxidized by 5-hydroxymethylfurfural (5-HMF). FDCA is currently used as a building block material for the production of PEF, which is a fully bio-based plastic with excellent thermal properties and superior barrier properties, compared to conventional PET [77, 78]. Furthermore, PEF is considered to be an ideal substitute for the current polymer used in packaging [79]. Bioplastics can also be used in value-added applications, such as in the medicine and cosmetic industries. For example, Evonik, a German chemical company, has developed a chain of biodegradable polymers for use in medical equipment and medicinal packaging [80]. Similarly, L'Oréal, a cosmetic conglomerate, has 100% bioplastic bottles and cosmetic packaging [81].

Table 2. Viable bioplastics including biodegradable and non-degradable polymers use for plastic manufacturing and their applications [72]

Name of Polymer	**Biomass content (%)**	**Annual production (tons)**	**Manufacturing company**	**Applications**
PLA- Polylactic acid	100	217 000	NatureWorks, Corbion, Shimadzu Cor., Toyobo	Packaging materials, medical use such as implants, 3D printing polymers, textiles, electronics
PHA- Polyhydroxyalkanoates	100	30 000	Bio-On, Kaneka, Tepha, Danimer Scientific, Newlight Technologies	Packaging materials, agricultural use such as compost bags, laboratory use such as tissue culture engineering

Name of Polymer	Biomass content (%)	Annual production (tons)	Manufacturing company	Applications
PBS- Polybutylene succinate	100	97 000	Mitsubishi Chemical, Showa Denko K.K., SK Chemicals, MCC Biochem	Mulch and sheets for food packaging and agriculture, compost bags, fishing nets, the automotive industry
Starch blend	100	384 000	Novamont	Household use such as food packaging and wrapping, compostable bags, disposable and edible utensils
PBSA- *Polybutylene succinate-co-butylene adipate*	~50	Unknown	Bionolle 3000/Showa Denko K.K.; Skygreen®/SK Chemicals	Household and agricultural use, such as a wrapper, sheets, strings, mulch, fishing net, etc.
PBAT- *Polybutylene adipate-co-butylene terephthalate*	0	152 000	Ecoflex/BASF, Wango Chemical Co., Ecoworld/JinHui, Origo-Bi®/Novamont	Water-resistant coating, cling wraps for packaging, compostable bags, and other household uses.
PCL - *Poly ε-caprolactone*	0	Unknown	Ingevity	Packaging materials, adhesives, footwear, biomedical applications, bags, plastics thread.
Bio-based, nonbiodegradable				
Bio-PE - *Polyethylene*	100	200 000	Braskem/I'm green	Packaging materials, wrapper, and shopper bags
Bio-PET - *Poly ethylene terephthalate*	20	560 000	Coca Cola/Plant Bottle	Packaging materials

Name of Polymer	Biomass content (%)	Annual production (tons)	Manufacturing company	Applications
PEF - *Polyethylene furanoate*	100	Unknown	Corbion/Synvina	An alternative to the PET
Bio-PTT - *Poly trimethylene terephthalate*	30	194 000	Shell Chemicals/Sorona	Use in the textile industry, fine fiber making, doormats and carpets, and nonwoven fabrics.
Bio-PA - *Polyamide*	100	245 000	Evonik, EcoPAXX/DSM	Electronics, automotive, consumer goods, sportswear, and traveling equipment.

3.2.Life cycle analysis studies and challenges

Life cycle assessment (LCA) studies on bio-and fossil-based plastics have revealed that the production and use of bio-based plastics are advantageous in terms of energy-savings and the reduction of GHG emissions [82-86]. For example, approximately 40–50% saving of nonrenewable energy use and approximately a 50% reduction in GHG emissions have been reported in a comparable cradle-to-grave impact study of production between PEF and PET [87]. The environmental impacts of bio-based plastics production are typically dominated by the sourcing of primary materials, which are from first-generation agricultural production (e.g., sugar cane, beat, cornstarch, and potato starch) [88]. The input energy in the form of fossil fuel, the inputs of fertilizers, and water (in the form of irrigation) are the primary sources of GHG emissions, eutrophication, acidification of soil, and stratospheric ozone depletion [89, 90]. In addition, most of the commercial production of bio-based plastics feedstocks require significant agricultural land to grow, which is also an issue for the environment [91, 92]. However, the current production of bioplastics is estimated to translate to approximately 0.82 million ha of land, equivalent to nearly 0.07% of arable land. If, hypothetically, all the plastics became biomass based, there could be an issue due to the land required, and the present level of total plastics production would need roughly 25–30 EJ of biomass feedstocks. This figure is nearly half of all the current biomass used in energy production, despite the global biomass potential of 50–500 EJ [71, 93]. Another problem with bioplastics is limited or no infrastructure for the collection, recycling, and composting to recover the resources at the end of life [94, 95]. In many countries, incineration is the most preferred method for energy recovery [24]. For a cradle-to-grave LCA analysis, the end of life efficiency is vital to assess the overall ecological footprint [90].

3.3. Opportunities for bioplastics

Bioplastics do have the challenges of the primary feedstocks, water footprint, land use, and limited infrastructure. However, the utilization of by-products and waste flows as raw materials by integrating production in a biorefinery would drastically reduce the ecological footprint [67, 96-99]. Recent studies have shown that wood and other lignocellulosic residues from agroforestry would be more sustainable alternatives due to their polysaccharides and lignin [95, 100]. For example, the production of PHA by utilizing diverse biomass streams, municipal wastewater, CO_2, and CH_4 provides further benefits for the sustainable development of bioplastics [101-103]. Additionally, many refineries that produce only oils operate at very low-profit margins [104, 105]. To overcome these lower profit margins, refineries are integrating fuel and chemical products within a single operation. For example, petrochemical oil refineries distribute their nearly 10% of fuel for chemical production, which in result contributes approximately 25–35% of the annual profits [106, 107]. This integrated production in a single operation would not only be beneficial for the bioplastic production, but also provide incentives for the biorefineries, which are currently operating in loss margins due to the higher production cost than the costs of biofuel output [98, 108, 109].

Generally, biorefineries have greater policy support than the production of bioplastics and chemicals from biomass. Many countries have various incentives for the production of bioenergy and biofuels, and they provide high support to research and development, pilot and demonstration plants, and also offer government subsidies [110-114]. If these biorefineries did not integrate by both chemicals and fuel production in a single operation, the biorefineries not only would lose the profit margin, but also cause negative environmental impacts [115, 116]. To promote an integrated system for biofuel and bioplastics, setting environmental targets, certification, and the labeling of bioplastics products would be effective measures [117-119]. For example, the US Renewable Fuels Standard (RFS2) has set GHG emissions savings targets along with volumetric mandates for biofuels [120]. In this way, environmental targets for bioplastics could also be fully realized. The standard and certifications will not only encourage the development of the bioplastics, but would also reduce the early cost of production that contributes to a higher ecological footprint [121]. Studies have shown that in comparison to their conventional products, an integrated production system of biofuels and biopolymers would save at least 20 MJ (nonrenewable) energy per kg of polymer and avoid at least 1 kg CO_2 per kg of polymer. Overall, this would reduce approximately 20% of negative environmental impacts [122, 123]. The certification of bioplastics would ensure that consumers are aware of the materials that they utilizing. In this way, policymakers can offer harmonious legislation for both producers and consumers clarity for information and choice.

4. Recycling challenges and future designs

Plastic waste management is one of the most challenging global environmental problems, particularly due to its general recalcitrance of plastic polymers [124]. However, not all the plastics are persistent by nature, some of them can be degraded with the assistance of chemicals and living organisms [125]. However, substituting the current plastics system entirely to biodegradable plastics is not a viable option because plastics are used in different applications that have different requirements for their physical and chemical properties [126]. Biodegradable plastics may not be available or suitable for all the applications [127]. Overall, the current plastics economy is not very environmentally sustainable [128]. However, the effective recycling of used plastics could be an effective way to control the leakage of waste plastics into the environment [129, 130]. Yet the effectiveness of the recycling depends on the design of the plastics. If the products are not well designed at the production stage to support proper recycling and degradation, this may lead to further environmental problems in the forms of microplastics and also make recycling very expensive.

There are three types of recycling or transformation of used plastics: mechanical transformation, chemical transformation, and biological transformation (bio-composting), as shown in Figure 4. Mechanical recycling is the most common and economically adopted method for end of life plastics management through sorting, grinding, and recovery of the materials. In this process, the results of polymer degradation vary widely, which makes the mechanical recycling system limited to a number of reprocessing rounds [131]. Based on the cleanliness and known origin of the waste plastics, mechanical recycling operates using two approaches. First, closed-loop or circular recycling, where the waste plastics are returned back to the product used for the same purpose as the original plastic [132, 133]. For example, PET bottle recycling, wherein the used PET bottles are combined with virgin plastics [134].

Chemical recycling of used plastics refers to a chemical process for the degradation of the polymers [131, 135]. In this process, the polymers are degraded into their chemical ingredients or monomers, which ultimately may either be re-polymerized to the same products or converted into other suitable products. For example, the outcomes of a pyrolysis process are normally difficult to separate, where waste plastics are subjected to high temperatures in the presence of a catalyst. Currently, chemical recycling has not been adopted for the large industrial scale due to its high energy input requirement [136]. Bio-degradation or bio recycling is an emerging process in plastic recycling and is primarily focused on plastics with biomass origins [137]. Unlike the current recycling processes, which are primarily based on thermo-mechanical techniques, bio-recycling is based on enzymes. In this process, specific de-polymerization of a single polymer contained in different plastics is recycled, and in the final stage, the obtained monomers are re-polymerization after a purification process [138, 139]. For example, PET polymers are bio-recycled using the Carbios' recycling bioprocess [140]. Lipases and cutinases are the most studied enzymes for bioplastics recycling [141]. Studies have shown that bioplastics including PCL, PLA, PHB, PBS, and PBA, and their copolymers can be possibly recycled using lipase-catalyzed depolymerization to cyclic oligomers and re-polymerization [142-

144]. It has also been demonstrated that the degradation of the polymers can be enhanced by the addition of supercritical CO_2 in the reaction medium [145].

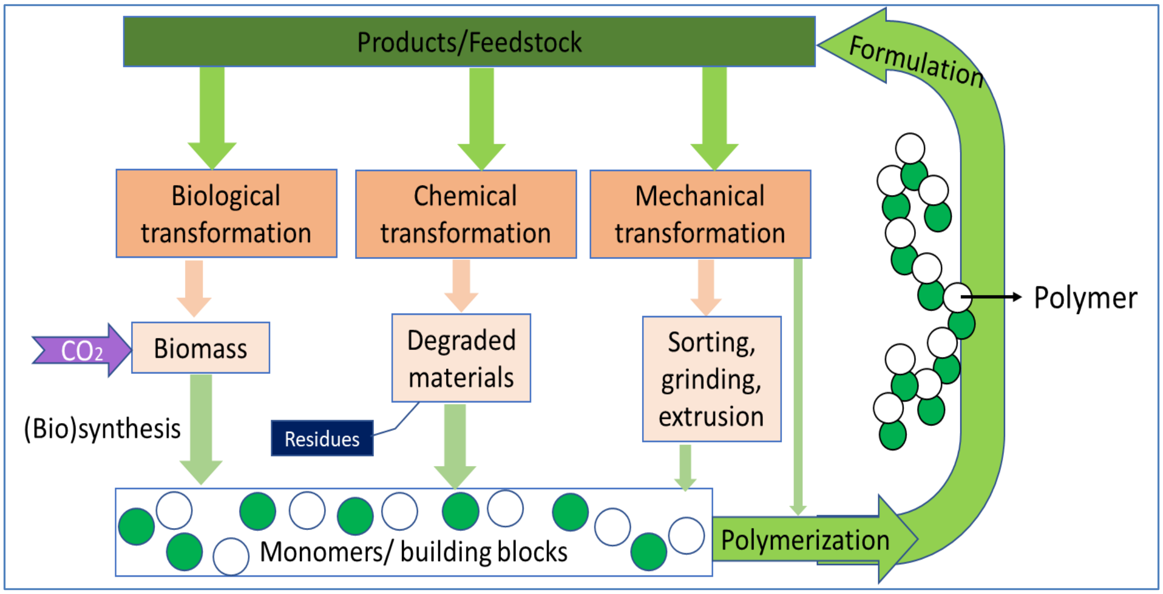

Figure 4. A sketch of the plastic production process including the recycling and material flow.

4.1. Designing plastics for a circular economy

Currently, bioplastics have less than 1% of the total plastic market share and still have a very tough time competing with fossil-based plastics. However, the future of bioplastics is primarily motivated by the regulations and the ecological footprints, rather than market shareholding. In the coming years, the requirements for bio-based plastics will be more stringent, which will be determined by, not only the growth, but also the rational design and technology behind it [71, 146, 147]. The global agreement achieved in 2019 to adopt anti-single-use plastics legislation by 189 countries is a welcoming step toward sustainable plastic management, but a lack of acknowledgment of the potential future role of bioplastics was unsatisfactory [37]. The key plastic problem of the current time is one of design [148]. The current system of plastic manufacturing, distribution, consumption, and trade requires an ultimate change. The linear model of planned obsolescence is one in which plastics are designed to be thrown away after the first use, sometimes after the second use [149]. This model needs to be replaced by a circular model, where the designed plastic after consumption should be returned to the manufacturing stage to make a circular flow of the materials [60]. In 2018, The European Commission recommended an improved design and production system to enable reuse, repair, and recycling through ‘a European Strategy for Plastics in a Circular Economy’ [150]. The strategy also recommended decoupling plastics production from fossil-fuel resources and reducing GHG emissions under the Paris Agreement on Climate Change commitments.

4.2. Designing plastics for improved performance

In the future, designing high-performance biobased polymers with desirable product properties that can be retained, even when subjected to recycling and processing will be a key point for wider applications. For example, the glass transition temperature (Tg) is one of the most important thermal properties used to determine the physical, mechanical, and rheological properties of amorphous plastics materials, and also to decide the various applications [151, 152]. PET, famous as widely recycled plastic, has a Tg of ranging from 67 to 81°C, but during recycling it loses molecular mass [153]. However, commercial biodegradable plastics have a lower Tg value than PET, and the highest value of Tg is 55°C for PLA [154]. The Tg value of PHA with aliphatic monomers varies widely from 5°C to 47°C, depending on the microflora use during the cultivation of the building blocks [155]. However, the Tg value can be enhanced to 10–30 °C in PHA using the introduction of aromatic units such as phenyl, phenoxy, nitrophenoxy, and benzoyl [156]. Aromatic units from lignin and tannins or produced by bio-engineering processes from sugars are made of renewable components that are suitable for biobased polyesters with high Tg values [151, 157-159]. By applying larger aromatic structures, the Tg value can also be increased. For example, polyethylene naphthalate, which has an approximately 120°C Tg and PEF, a fully biobased with a 5-membered furan ring as a monomer unit, has a TG of approximately 86 °C higher than PE [151]. The value can also be enhanced further by the use of an FDCA dimer monomer to 107 °C [160]. Enhancements in the Tg of bioplastics will be an effective strategy for wider applications and sustainable recycling possibilities.

4.3. Designing plastics for improved post-consumer degradation

The biodegradability of plastics is not the most important feature for the wider applications of plastics. Even in most cases, biodegradable plastics are considered to be less advantageous than nonbiodegradable plastics [126, 127]. However, in certain applications, biodegradable plastics are indispensable where recovery of used plastics is difficult or impossible, and leakage into the environment is difficult to evade, e.g., plastic mulch in agriculture, fishing nets, and cosmetics sachets [161, 162]. In some cases, biodegradability can also be used as a sustainable criterion for plastic recycling [163]. However, there are major limitations during the design of degradable polymers that could achieve the required properties of strength and 100 % degradation after the disposal of plastics within a reasonable time frame [164]. Currently, the available biodegradable polymers in the market have a different range of degradation rates. For example, in comparison among PLA, PHB, and PCL, the results showed that their sensitivity to hydrolysis decreased in the order of PLA>PHB>PCL, while the biodegradability rate for PHB was the fastest, followed by the PCL and PLA [165]. This revealed that the biodegradation rate of PHB and PLA polymers and the depolymerization of their products are influenced by the stereochemistry.

Degradation of plastics is a complex process and it depends on different factors, such as the properties of the monomers and their bonds and biotic and abiotic environmental factors [166]. The degree of crystallinity of the polymers is considered to be an important factor for assessing degradability [167, 168]. For example, amorphous polymers undergo a faster hydrolysis reaction and degradation of the semicrystalline polymers, and this begin with water diffusion in unformed amorphous regions followed by the crystalline regions. PLA, a semicrystalline polymer made of 100% L-lactide units, has the longest degradation time, with a half-life of 110 weeks. However, when it was incorporated with 50% of D-lactide unites, it dramatically decreased the degradation time to only ten weeks, and further decreased to three weeks when it was copolymerized with 25% of glycolic acid [169]. Similarly, the degradation rate of PHA is also determined by the building blocks and the degree of crystallinity [170]. PHA depolymerase and lipase enzymes act faster on the amorphous regions of polymers, and the combination of polymers, such as the PHA and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) co-polymer, degrades faster than the homopolymer of PHB [171]. Similarly, a combination of the dicarboxylic acid unit and a longer carbon chain as the monomer makes for higher enzymatic degradability of polymers (butylene succinate adipate) compared to homopolymers of PBS and PBA [172]. Additionally, the copolymerization of isosorbide with renewable monomers provides readily available biodegradation polyesters with a higher Tg value up of to 180°C, which is better than available commercial bioplastics [173].

The rate of degradation of polymers can also be influenced by introducing a functional group that increases the susceptibility of the hydrolysis reaction by altering the molecular weight, resulting in an open flow of water that facilitates both enzymatic and nonenzymatic hydrolysis. For example, the introduction of acetal functionalities in polyesters, which has two additional routes for degradation including regular acid-promoted hydrolysis and light-induced radical decay. Similarly, the polyoxalates group of polyesters also degrades easily under a mildly acidic to a neutral condition caused by the proximity of carbonyl groups, and this results in increased electrophilicity [71, 174].

5. The roles of biotechnological tools and sustainability science

Biotechnological tools for industrial production and waste treatment have been successfully applied in various bio-based polymer and plastic production processes. At the beginning of the 20th century, many industrial products were made from plant residues, such as dyes, inks, paints, medicines, synthetic fibers for clothing, and plastics [107]. However, these productions were severely affected by the discovery of fossil fuel feedstock and the evolution of petroleum-based plastics that declined the bio-based plastic production from nearly 35% in 1925 to nearly less than 16% in 1989 [175]. In 2018, the world produced approximately 2.11 million tons of bio-based plastics that were less than 1% of the total production of plastics. However, the role of the biotechnology process is considered to be an enabling tool for the production and development of a sustainable plastics economy [71].

Biotechnological approaches can play a vital role in the production of bioplastics that can be a greener substitute for the currently used petroleum-based plastics in PPEs and packaging goods [176]. Microbial polyhydroxy-butyrate (PHB) and polyhydroxy-alkenoate (PHA) are already produced on an industrial scale for packaging and other uses, and numerous efforts have also been underway to produce PHA from plants and sugar, which can further reduce the overall production costs. Chitin and chitosan byproducts of marine animals are also produced and used as alternatives to petroleum plastics [177]. The biotechnology process has also been conveniently applied in the waste management of toxic chemicals and oil spills [178].

Polypropylene (PP) and polyethylene-terephthalate (PET) are common constituents of PPEs and packaging materials, responsible for nearly 70 million tons of the global plastics production annually [179]. For the safe and sustainable management of the discarded PPEs and other plastic products, the key is to advance the production efficiency of bio-based products and maximize the reuse of raw materials, which will drastically reduce the materials and energy consumption of new products. This can only be achieved by recycling reusable materials, using biodegradable compounds instead of non-degradable and redesigning the products to avoid single-use products and waste generation [180].

The biotechnological process depends on the capacity of living organisms such as bacteria, algae, fungi, yeasts, and plants, which are primarily responsible for the degradation of the organic materials [179]. Biotechnology-based bioremediation can be 10 to 20 times cheaper than incineration for organic waste, and composting can degrade 90% of certain types of medical waste in 10 days using biotechnology. Also, recent research published in Nature reported that a highly efficient, optimized enzyme PET hydrolase from bacteria could depolymerize nearly 90% of PET into monomers in approximately 10 hours, making this process exemplary for both bio-based PET and petrochemical PET recycling [181].

To achieve sustainability, discarded products should be either recycled or biologically degraded, which is very difficult for current petroleum byproducts. However, biotechnology offers new potential uses for bioproducts, such as fibers, gums, waxes, leathers, and silk. In addition, the new biotechnologies can produce polysaccharides that are widely used as food additives, bio-adhesives, absorbents, and plastics and deliver biodegradable products including polylactic-acid (PLA), polybutylene-succinate (PBS), and PAHs, of which PLA is widely available in the market [182, 183].

6. Conclusions and future perspectives

There is a widespread concern that increasing demand for PPEs and other plastic products, which are predominantly made of petroleum-based plastics, will ultimately lead to severe environmental pollution. In general, discarded plastics are disposed of either in landfills or incinerators that lead to the release of a significant quantity of hazardous pollutants, such as dioxins and heavy metals. In this time of the pandemic and the sudden increase in discarded plastics, a product lifecycle perspective is proposed in this paper that should be integrated into solutions based on industrial biotechnologies. The life cycle assessments of several plastics made of fossil and non-fossil feedstocks have shown that the production of and use of non-fossil-based plastics would be greener in terms of energy consumption and reducing greenhouse gases emissions.

The principles of the circular economy and the bio-economy need urgent rethinking strategies for the entire plastic value chain. The reliance of fossil resources for the production of plastics products, such as PPEs and packaging, should guide policy development for plastic waste management during and after COVID-19. State policies should be designed for competition with cheap petroleum plastics that go untaxed, despite their carbon content, because bioplastic production is still lacking the infrastructure for production and disposal processes, despite being ecofriendly in nature.

The current pandemic and several other concurrent phenomena are shaping the future demand for plastics. To achieve a safe and sustainable plastics system requires not only an alteration from petroleum byproducts to produce the bio-based polymers used in plastics, but also a novel design for the polymers that will be suitable for both the desired materials functionality and the end of life recyclability. In recent years, biotechnology has shown tremendous improvements in the polymer product field based on renewable feedstocks and has also shown great potential for the recycling of discarded plastics. Although great potentials have been achieved, further research needs to be enhanced to achieve the full potential performance and recyclability of discarded polymers [180].

For future studies, it is recommended that the priority should be placed on bio-based aromatic and long-chain aliphatic monomers that have a very limited presence in the market. It is known that these monomers are considered to be toxic and have very complex biological pathways, but their incorporation with the currently available bio-based polymers would be an important development for future bioplastics. To reduce the environmental impacts from the sourcing materials for bioplastics, more focus needs to be given to diversified biomass feedstocks, such as agricultural waste, waste seafood, woods, and the use of renewable energy, including the use of biomethane and carbon dioxide. Most importantly, future work needs to focus on the life cycle analysis of integrated plastic production in biorefineries. This will provide rational outputs regarding the consumption of primary feedstock and provide sustainable techno-economic results using multiple product outputs.

Acknowledgment

This study was supported by the National Natural Science Foundation of China (NSFC) (41977329), the Shenzhen Government Funding (29/K19297523), and the State Environmental Protection Key Laboratory of Integrated Surface Water-Groundwater Pollution Control. Oladele Ogunseitan acknowledges support from Lincoln Dynamic Foundation's World Institute for Sustainable Development of Materials (WISDOM) which he co-directs.

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Highlights:

- Petrochemical plastics are major pollutants disrupting ecosystem health.
- COVID-19 pandemic has exacerbated plastic pollution through the increasing use of single-use personal protective equipment.
- Diversification of biomass feedstocks are important for the wider application of bioplastics
- Integrated production of biofuels and bioplastics are the key for sustainable circular bioeconomy
- Materials Lifecycle analysis for end-of-life plastics should guide the development of bioplastics