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Sustainable materials alternative to petrochemical plastics pollution: A review analysis

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ABSTRACT

The upward trend of global demand for fossil-fuel energy for non-energy purposes especially for the production of plastics, and non-renewable energy use (NREU) and global warming potential of the plastics life cycle is poorly understood. Alternatives to petrochemical plastics have been researched intensely, but they have not been developed to replace current plastic products at a commercially viable scale. Here, we identify challenges facing to energy intensiveness of plastic production, land use crisis for biomass production, and non-renewable energy use and global warming potential on the life cycle of plastics, and we propose a material lifecycle perspective for bioplastics. Our estimate shows that an average of about 13.8 exajoule (EJ), ranging from 10.9 to 16.7 EJ, of fossil-fuel energy consumed in 2019 was diverted to fossil-fuel feedstock for the production of plastics worldwide, this translates between 2.8 and 4.1% share of the total consumed fossil-fuel energy globally. The life cycle analysis estimate shows that bioplastics produced from 2nd generation feedstock have 25% less NREU than that of 1st generation, while the bioplastics from 1st generation feedstock required about 86% less NREU than that of petrochemical plastics. Similarly, the estimates of the greenhouse gas (GHG) emissions show that the reduction of GHG emission was about 187% more in biomass feedstock than that of petrochemical plastics. We conclude by presenting strategies for improving the recyclability of biological plastics through polymer design, application biotechnology, and by adopting a circular bio-based economy.

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) (Patrício Silva et al., 2021). Until 2019, the global production of petrochemical plastics amounted for nearly 359 million tons annually, consuming an average of 10% of the global petroleum resources (Michaux, 2019). 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 (Singh et al., 2020). The material compositions of PPEs include plastics as major constituent, representing 20–55% by weight, and the plastics used in packaging materials represent nearly 40% of the total plastic production worldwide (Coates and Getzler, 2020). These trends in plastic consumption are responsible for approximately 150–200 million tons of annually discarded plastics worldwide (Tournier et al., 2020).

There are three common routes for the disposal of plastics globally: mechanical recycling, landfilling, and incinerating, with the latter two the major routes used worldwide (Garcia and Robertson, 2017). In many countries, existing facilities for solid waste management (including medical waste) may not be able to sustain the increased inflow due to pandemic related wastes (Singh et al., 2020; Zachary et al., 2020; Singh et al., 2021). Fig. 1 shows the treatment techniques for municipal solid waste (including plastics waste) in the four income groups: high-income, upper-middle-income, low-middle-income, and low-income countries. (Kaza et al., 2018; Zachary et al., 2020). 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

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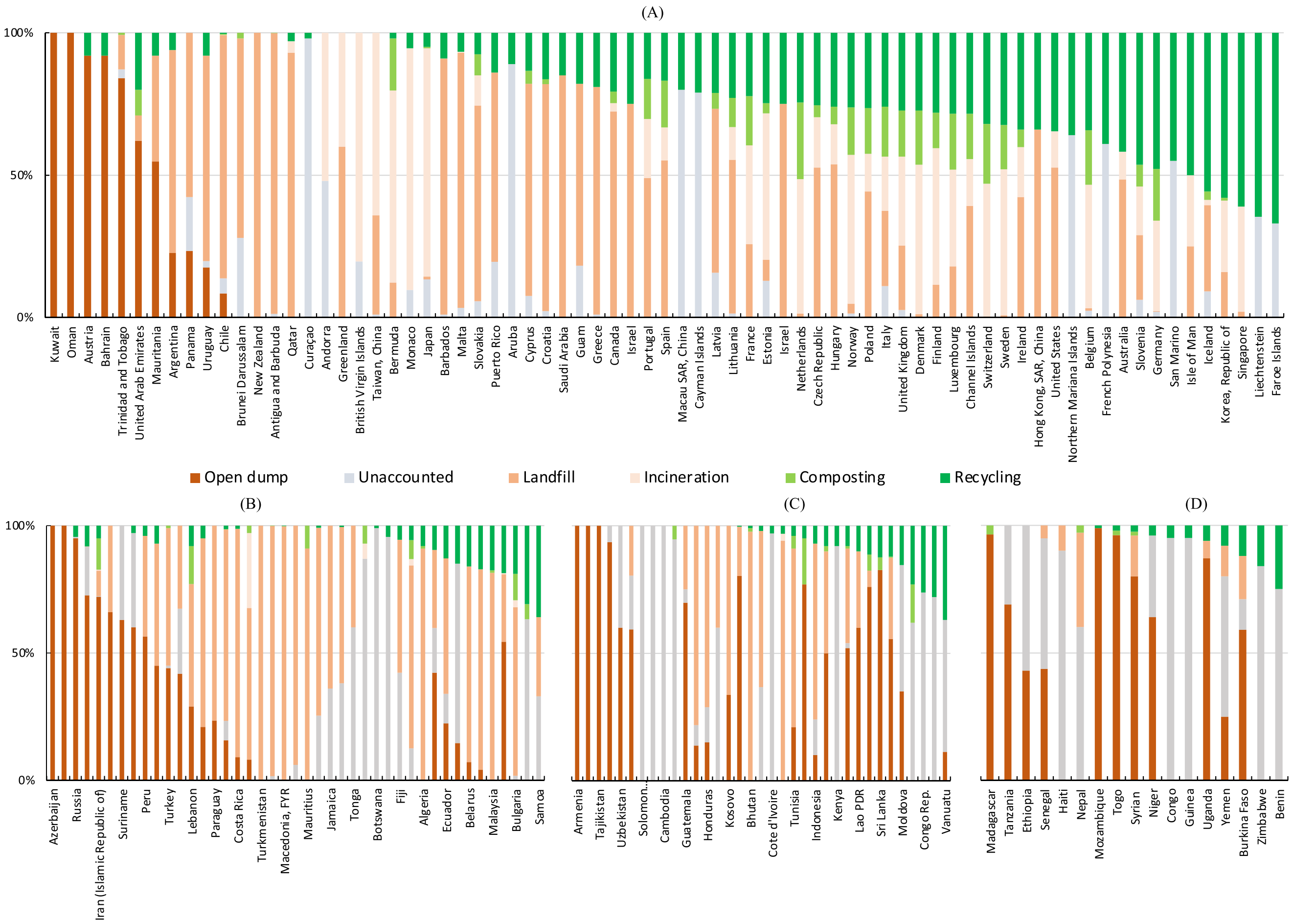

Fig. 1. Municipal solid waste including the discarded plastics treatment and disposal by income groups: (A) high-income countries, (B) upper-middle-income countries, (C) low-middle-income countries, and (D) low-income countries (Kaza et al., 2018).

of the wastes are open dump and unaccounted for management, with a limited amount of waste that is dealt with proper handling.

Many review studies have recently been conducted on biomass-based plastics research covering the topics of bioplastic's types, properties, and disposal mechanism (Nandakumar et al., 2021); overall sustainability of bio-based technologies (Escobar and Laibach, 2021); sustainability of bio-building blocks for the bio-based next-generation polymer (Hwang et al., 2020); biodegradation of bioplastics (Narancic et al., 2020); adverse effects of bioplastics (Brizga et al., 2020); energy demand and emissions for the petrochemical production (Daioglou et al., 2014); and energy sector transitions from oil, coal and natural gas (Lange, 2021). Despite these outcomes, there is a lack of generalizable knowledge and understanding of challenges facing to energy intensiveness of plastic production, land use crisis for biomass production, nonrenewable energy use, and global warming potential on the life cycle of plastics. To understand the above-mentioned issues, we did a compressive literature review on recently published articles on lifecycle analysis of plastics that ensures the identification of source feedstocks in the production system by considering the non-renewable energy use (NREU) and greenhouse gas (GHG) emissions caused by plastics production and then compared the outcomes among the sourced feedstocks of bioplastics and petrochemical plastics. Besides this, we also aimed to quantify the current primary fossil-fuel feedstock energy used to make all the plastics globally and in China and their percent share from the total consumption. We then discussed the scope of the bioplastics and their impacts on the environment and critically assessed the outcomes of life cycle analysis for both the NREU and GHG emissions on the production of the bioplastics and petrochemical plastics.

In this work, we aimed 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. . It has been demonstrated in our review analysis 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, and the recently developed bio-passed polymers could possibly be a potential substitute to the whole convention plastics. 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. Methodology

2.1. Literature review

A comprehensive literatures review was conducted that identified all relevant full-length articles on life cycle analysis on bioplastics sourced from first- and second-generation feedstocks and petrochemical plastics regardless of language and regions by searching keywords such "plastics", "bioplastics", "petrochemical plastics", "lifecycle analysis of plastics/bioplastics" "energy use in plastics production" "recycling and biodegradability of plastics" "challenges and solution of plastics pollution" etc., in Web of Science and Google Scholar search engine. We aimed for publications assessing the global warming potential and non-renewable energy use in plastics lifecycle from different sourced feedstock materials, the details outcomes are shown in Table S1. To allow a study for all related publications evaluating the sustainable materials alternatives to petrochemical plastics for enhancing performance, degradability, recycling, and circular design of the bioplastics, we did not limit our initial search keywords to bioplastics nor by other means.

2.2. Feedstock energy estimation

In accordance with the estimate of Hamman (2010), we calculated the fossil-fuel feedstock energy diverted as feedstocks for the production of plastics in China and globally. We framed it by multiplying the net heat of combustion for plastic ((J/kg) by the mass of plastic produced in 2019. We estimated the upper and lower value by using the energy content (in J) and mass quantity (in kg) of polyethylene plastic, which accounts for nearly 30% of global plastics production in 2019, for the total fossil-fuel feedstock energy (J/year) used for the plastics production. Calorimetry experiments conducted by Walters et al. (2000), have estimated the net heat of combustion for polyethylene (LHV), which is about 4.5×107 J/kg, used here for the calculation of the total fossil-fuel feedstock energy (in J) diverted to produce polyethylene plastic (in kg), in 2019. For the upper-value estimate of all plastics, the value of polyethylene (LHV*mass quantity) is divided by a factor of 0.36, since about 36% of plastics (by weight) was made of polyethylene plastic in 2019, globally (Table S2). For lower value estimate for the portion of fossil-fuel energy diverted to plastics production is then calculated by multiplying the upper estimate by a factor of 0.65. This is because, the largest share of nearly 65% of all plastics production (by weight) is accounted for by three of the six most widely produced plastics, namely polyethylene, polypropylene, and polystyrene (Table S2). These three types of plastics are pure hydrocarbon polymers and share a similar heat of combustion value as polyethylene (Lide and Haynes, 2010; Walters et al., 2000).

For the estimation of China's fossil-fuel feedstock energy diverted as feedstocks for the production of plastics, the upper and lower value was different than that of the global one due to the different types of polymers production and consumption quantity. For the primary production of the plastics polymers in China, the upper and lower estimate value were 0.18 and 0.46, accordingly (Table S3). The number of plastics consumed in China was higher than that of the primary production, it might be due to the imports of primary resins or could be due to the recycled content of the raw material which was not accounted for in the primary polymer resins production (Table S4). The upper and lower estimated value for consumed plastics in China were 0.28 and 0.53, accordingly.

There are many assumptions in the calculation of fossil-fuel feedstock energy diverted as feedstocks for the production of plastics. For example, plastics contain many chemicals as additives and their quantities vary in different types of plastics, and these additives are non-hydrocarbon feedstocks (Aurisano et al., 2021). Besides the chemicals, the PET is about 33% oxygen by mass while PVC is about 57% chlorine by mass and many other types of plastics contained diversified materials, which may affect the net heat of combustion energy of the plastics (Lide and Haynes, 2010). The loss of feedstocks during the refining process is also not included in this estimation, which may influence the results given the loss of feedstocks during processing. The data for plastics production and energy use are shown in Tables S2–S5.

3. Plastic types, characteristics, and global scenarios

Plastics production including the shared percent of fossil-based and bio-based plastics and their polymers types used in various sectors are shown in Fig. 2. Conventional plastics production and consumption have already been covered by many studies (Geyer et al., 2017; Klemeš, Fan et al. 2020). In the last decade, bio-based polymers (bioplastics) are being developed as an alternative polymer and a sustainable material, determined by the potential they hold to reduce the NREU and anthropogenic GHG emissions, to petrochemical plastics whilst allowing for a transition towards a circular economy by abating fossil resource extraction, and potentially reducing environmental burdens through the utilization of carbon dioxide and biomass which in return helps carbon sequestration from the atmosphere (Garlapati et al., 2020; Moustakas et al., 2020; Escobar and Laibach, 2021; Nandakumar et al., 2021).

The term bioplastic is often perceived as misleading and has been part of confusion due to its partial blends of petrochemicals and non-degradability of polymers that are made from bio-based materials (Lambert and Wagner, 2017). Therefore, bioplastics can be defined as a variety of materials that contain at least partially, bio-based renewable feedstock and are biodegradable depending upon the monomer's characteristics and polymerization processes. Fig. 3 shows the different features of the plastic materials based on the origins of the feedstocks and their biodegradability (European Bioplatics, 2020). The figure revealed that bioplastics refer to polymers that are either bio-based or biodegradable or belong to both parts. The term bio-based refers to material that is at least partially developed from biomass containing organic carbon of renewable origin. Biodegradable refers to materials that can be converted into natural substances such as H_2O, CO_2, and compost by the different naturally occurring microorganisms such as bacteria, fungi, and algae. Degradable plastics refer to polymers that are designed to undergo a significant change in their chemical structure under a specific environmental conditions and time that determines their classification. Polymers refer to a large molecule composed of repeating units of building blocks or monomers and typically connected by covalent bonds (Lambert and Wagner, 2017; European Bioplatics, 2020).

At present, bioplastics production is divided into three types of generation feedstocks, the details are shown in Table S6. The first-generation feedstocks are carbohydrate-rich food plants such as sugarcane, sugar beet, corn, potato, and oily seeds. The sourcing of raw materials for the first-generation feedstocks is considered to be resource-efficient and has been in controversy due to the use of edible food crops and the requirement of the lands for the cultivation (Wellenreuther and Wolf, 2020). Some studies show that the requirements of the lands and utilization of water, fertilizers, and pesticides for crop production cause a significant impact on the environment and have also raised concerns over their sustainability (Brizga et al., 2020). However, many studies outcomes have shown that the overall impacts on the environment and energy use of bioplastics production are significantly less than that of petrochemical plastics production, the details are shown in Fig. 5.

The second-generation feedstocks are sourced from lignocellulose-rich raw material including wood and non-edible by-products of food crops and agricultural wastes such as wheat straw, bagasse, corn stover, or organic waste (Brodin et al., 2017). The third-generation feedstocks for bioplastics production are derived from algae and municipal and industrial waste (Rahman and Miller, 2017). The second and third-generation biomass is considered to be more ecofriendly than the first-generation feedstocks materials but some studies have also revealed that the conversion processes of lignocellulose to building block monomers requires significant energy and longer steps than that of first-generation feedstocks (Singhvi and Gokhale, 2019).

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 (Hu et al., 2016; PlasticsEurope, 2020). 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(Nandakumar et al., 2021). For example, PLA, bio-PET, bio- PE, and starch blends are mostly used for packaging applications, while bio-based succinic acid is used in sportswear, automotive, agriculture, and textile applications (Chen and Patel, 2012, Dietrich et al., 2017). Typically, the production routes to bioplastics are divided into three main categories: (a) Thermochemical and catalytic

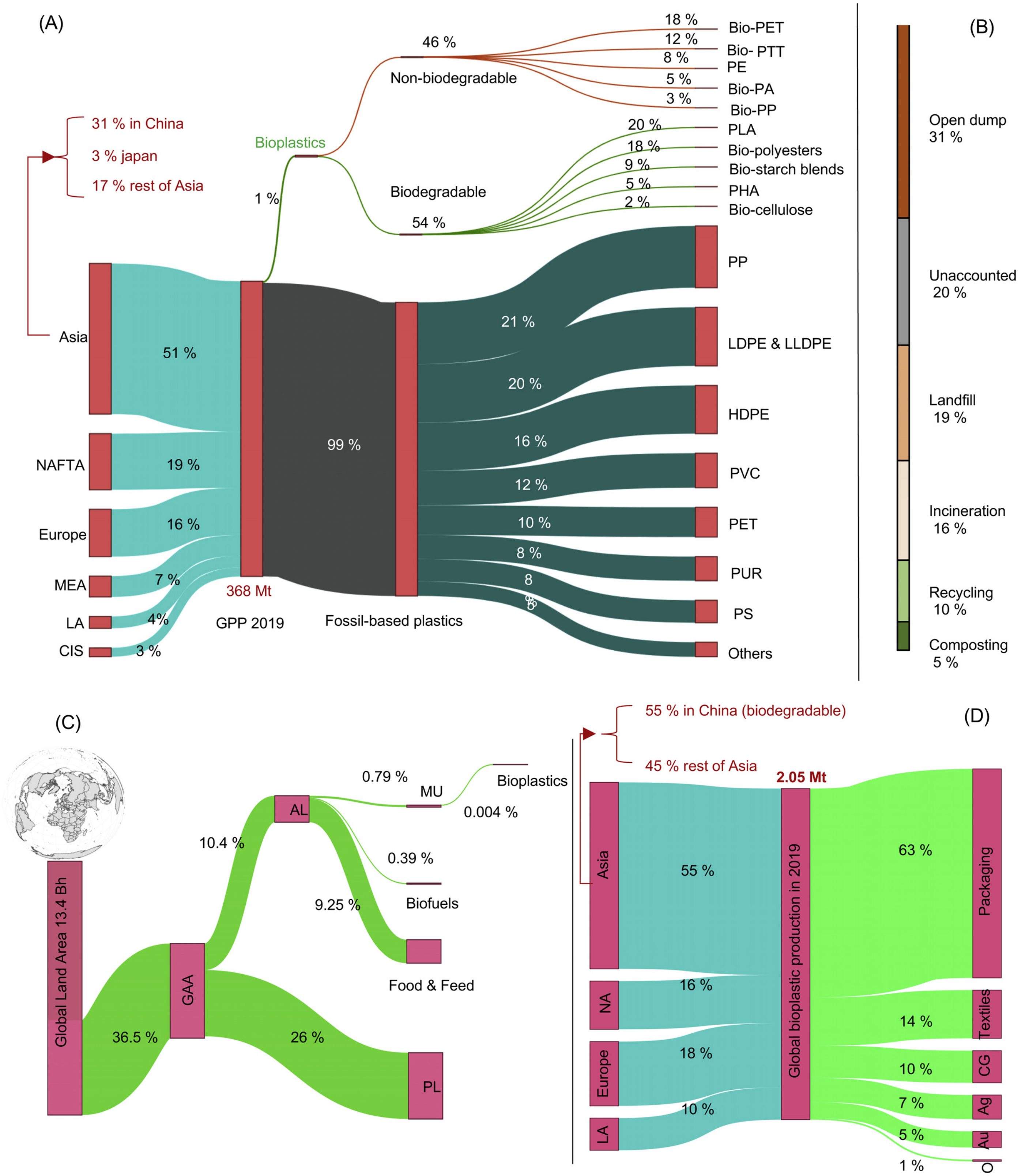

Fig. 2. Global plastic production is based on feedstock and share percentages on the different regions and the end-of -life treatment/disposal system. (A) Plastics production including both fossil-based and bio-based polymers; (B) an average disposal /treatment system of municipal waste management I worldwide, the details are s shown in the Fig.1; (C) global land area and the percent of the land for bioplastics production (percentage compared to total global land area); (D) bio-based plastics production share in different regions and the use of bioplastics in various sectors. (NAFTA = The North American Free Trade Agreement countries. MEA = Middle East Asia; LA = Latin America; CIS = Commonwealth of Independent States; GPP = Global Plastic Production; PP = polypropylene; PE = Polyethylene; PVC = polyvinylchloride, PET = polyethylene terephthalate (polyester), PUR = polyurethane; PS = polystyrene; Bh= billion hectare; GAA = Global Agricultural Land; AL = Arable Land; PL = Posture Land; MU = Material Use; NA = North America; CG = Consumer goods; Ag = agriculture; Au = Automotive; O = Others) (IFBB, 2020; PlasticsEurope, 2020, https://www.jxdjxd.com/843.html).

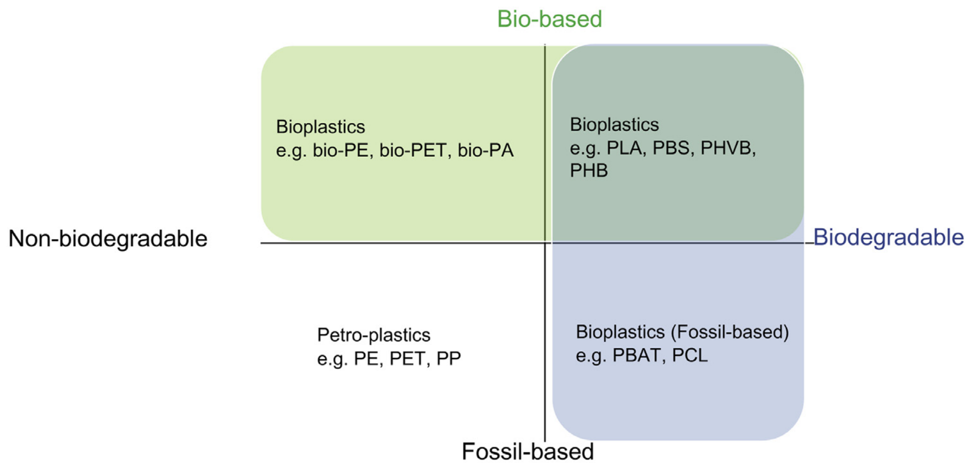

Fig. 3. The illustration of the properties of the plastics based on their origin and biodegradability (European Bioplatics, 2020).

Table 1
Types of plastics and their commercial polymer names, and the origin and biodegradability of bioplastics (Chen and Patel, 2012; Nandakumar et al., 2021).

Petro-plastics		Bioplastics		
Commercial names	Types	Commercial names	Types Bio-based	Biodegradable
Polypropylene (PP)	Thermoplastics	Starch blends	Yes	No
Polycarbonate (PC)		Polylactic acid (PLA).	Yes	Yes
Polyethylene (PE)		Polyhydroxyalkanoates (PHAs)	Yes	Yes
Polystyrene (PS)		Polyhydroxybutyrate (PHB)	Yes	Yes
Polyethylene terephthalate (PET)		Polybutylene succinate (PBS)	No	Yes
Polytetrafluoroethylene (PTFE)		Polyethylene terephthalate (bio-PET)	Yes	No
Polyvinyl chloride (PVC)		Poly trimethylene terephthalate (PTT)	Yes	NO
Polymethyl methacrylate (PMMA)		Bio-polyethylene (bio-PE)	Yes	No
Acrylonitrile butadiene styrene (ABS)		Bio-polyamide (bio-PA)	Yes	No
Expanded Polystyrene (EPS)		Polybutylene adipate terephthalate (PBAT)	No	Yes
Polycaprolactone (PCL)		Bio-polypropylene (bio-PP)	Yes	NO
Polyurethane (PUR)	Thermosets	Polyethylene Furanoate (PEF)	Yes	No
Epoxide (EP)		Polyvinyl alcohol (PVA)	No	Yes
Phenol-formaldehyde (PF)		Polycaprolactone (PCL)	No	Yes
Unsaturated polyester resins (UP)		Polyurethanes (PURs)	Mixed	Mixed
		polyglycolic acid (PGA)	No	Yes
		Cellulose acetate	Yes	Yes
		Casein plastics	Yes	Yes
		Thermoplastic Starch (TPS)	Yes	Yes

process where the biomass feedstocks are converted into monomers in the first step and then polymerization in the next step; (b) Fermentation process where the biomass feedstocks are fermented into monomers first and then converted into polymers in a second step; (c) Modification of naturally occurring polymers without changing its essence (Eerhart et al., 2012).

The demand for plastics is growing rapidly worldwide, and in 2019, plastic demand outpaced all other bulk materials, such as cement, aluminum, and steel (Made, 2020). Approximately 70 million tons of thermoplastics are used in the textile industry alone annually (Beckman, 2018). 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 (Iles and Martin, 2013; Reddy et al., 2013; Padil et al., 2019, Tjahjono and Cao, 2020). For example, from July 2019, 7–11 Japan has adopted bio-based plastic wrappers for foods (Kyodo, 2019) and, similarly, Germany has supported the use of certified bioplastic bags since 2015 (European Bioplastics, 2017). 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.

4. Challenges related to energy intensiveness of plastic production

Plastics are mostly derived from hydrocarbons (coal, oil and gas), which contain the primary feedstocks for plastics. A big part of hydrocarbons is processed to become fuel for combustion, the remaining part is used in chemical production, particularly for plastics production (Daioglou et al., 2014). The processes of both the production of plastics and the production of fossil fuels are closely linked to each other. Naphtha - a mixture of flammable liquid hydrocarbons - is made during the distillation process, and is heavier than crude oils that produce the naphtha. Naphtha is one of the key petrochemicals which is used in most plastic production. Besides, Ethylene - used to create polyethylene – is the most widely produced plastics worldwide, Toluene, Propylene, Benzene, Methanol are the key building blocks for polymer production worldwide (CIEL, 2018). The details of the key building blocks and polymers for both petrochemical and bio-based plastics are shown in Table S6. Crude Oil is the main source of feedstocks for plastics production in Asia and Europe, while the importation and use of natural gas liquids are also growing rapidly, especially in America and the middle-eastern

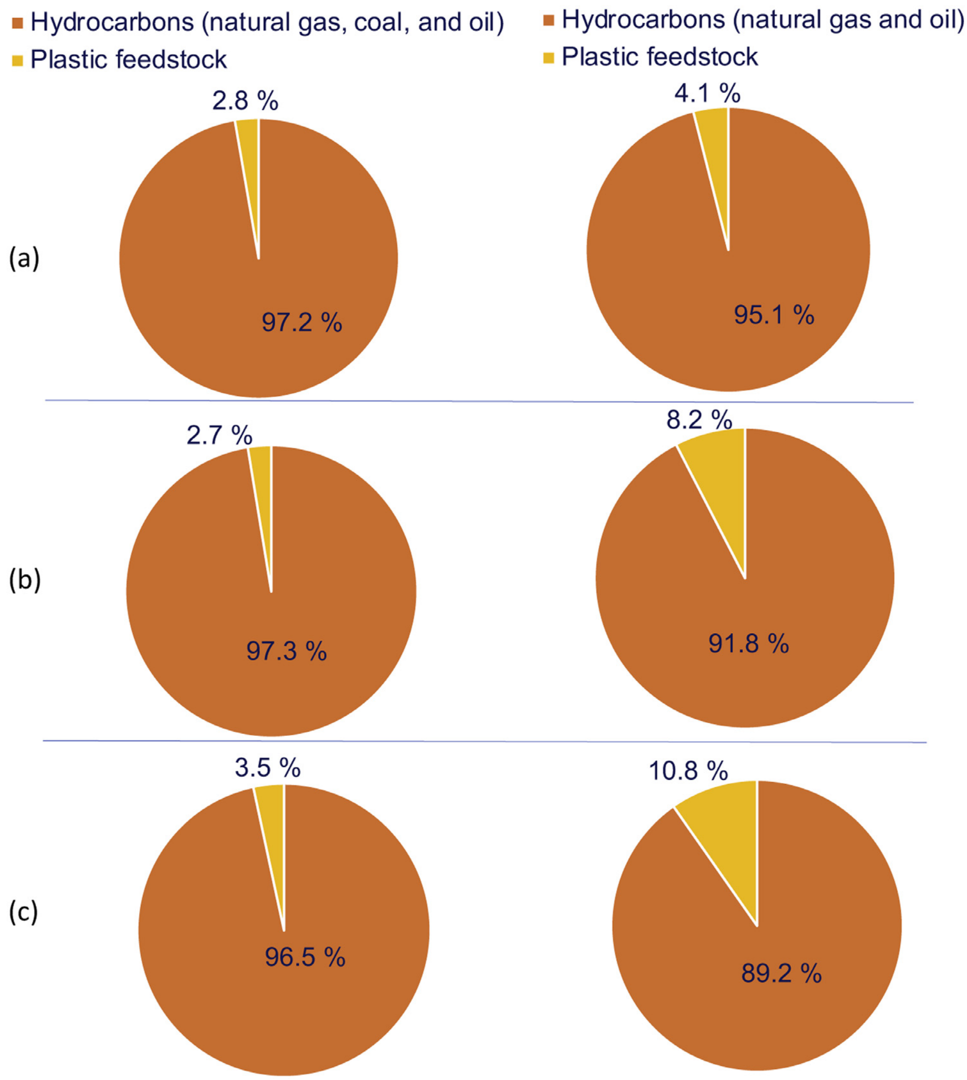

Fig. 4. The estimated outcomes of the fossil-fuel feedstock energy used to make all the plastics globally and in China. a) an average primary share of fossil-fuel energy diverted as feedstocks for the production of plastics worldwide, in 2019; b) an average primary share of fossil-fuel energy diverted as feedstocks for the production of primary plastic resins in China, in 2019; c) an average primary share of fossil-fuel resources diverted as feedstocks for all the consumed plastics in China, in 2019. (Additional data are presented in Tables S2 to S5)

countries. Coal is also used for plastics production but the process is not economically viable as compared to Oil and natural gas (Hurd et al., 2014).

The production of plastics, which required both feedstocks in the form of oil, natural gas and coal, and processing energy from fossil-fuel energy, prompting a great amount of GHG emission and consuming a bulk share of fossil-based energy of countries total fossil-fuel consumption. For example, In 2018, primary petrochemical production caused about 880 million tons of direct CO_2 emissions, a nearly 4% increase compared to the previous year's emission (IEA, 2021). A similar trend of increase (4%) was also observed in the petrochemical demands for plastics production between 2017 and 2018. This increase in demand is large because around half of the fossil-fuel energy input is consumed as feedstock for the production of plastics worldwide. Hamman (2010), estimated that a range from 1.3 to 2.1% of primary fossil-fuel energy is consumed each year (based on 2008 data) is diverted to fossil-fuel feedstocks for the production of plastics worldwide. Whereas, if biomass (first generation) is used for plastics production along with the climate policy implementation, nearly 50% of the emission can be mitigated for plastics production globally (Daioglou et al., 2014).

To identify the current fossil-fuel energy feedstock used to make all the plastics globally and in China, we estimated the primary share of fossil-fuel energy diverted as feedstocks for the production of plastics in 2019 (for estimate details, see supporting information (SI) file). Fig. 4 shows the estimated percent share of fossil-fuel feedstock energy used to make all the plastics from the total consumed hydrocarbons (oil, natural gas and coal), which amounted to about 492.4 EJ globally, and about 120.6 EJ in China, in 2019 (Table S5). The global consumption of hydrocarbons (oil, natural gas and coal) amounted to an average of about 13.8 EJ, ranging from 10.9 to 16.7 EJ, in 2019 for all the plastics production (Table S2). Thus, between 2.2 and 3.4% for the lower and higher estimate, accordingly, of primary fossil-based energy consumed in 2019 are diverted to the plastics production globally (Fig. 4a). If we exclude the coal, as it is mentioned that the coal is not an economically viable process for the feedstocks use due to its energy extensiveness, then the global consumption of oil and natural gas amounted to an average of about 4.1% (between 3.3 and 5% for the lower and higher estimate, accordingly).

In 2019, China produced about 95.7 million tons of primary resins plastics and consumed about 122.9 million tons of plastics comprising five major types of polymers; polyethylene, polypropylene, polystyrene, polyvinyl chloride, and acrylonitrile butadiene styrene (Table S3, S4). We estimated the fossil-fuel energy feedstock used to make all the plastics in China based on the number of primary production polymers and consumption of the polymers, in 2019. For the primary production, we assumed that the primary production of the plastic does not include the imported polymers to China, between 1.7 and 3.6% for the lower and higher estimate, accordingly, hydrocarbons (oil, natural gas and coal), were diverted as feedstocks to the plastics production from the total consumed energy, in 2019 (Fig. 4b). Without coal, it accounted for an average of about 8.2% (between 5.1% and 11.3%). The consumed amount of plastics accounted for between 2.6% and 4.6% for the lower and higher estimate, accordingly, of primary fossil-based energy (oil, natural gas and coal) consumed in 2019 (Fig. 4c). Without coal, it accounted significantly higher percent share than that of the global average, about an average of 10.8% (between 7.5 and 14.1% for the lower and higher estimate, accordingly).

The energy used for process and refining the feedstocks into plastics are not been estimated in this study because the refining process energy required for both the petrochemical and alternatives such as bio-based plastics, and are somewhat the same in range and for bioplastics, it depends on the biomass types and generation of the bio-based feedstocks (Ruiz et al., 2016). The non-renewable energy use and the GHG emissions from the bioplastics and plastics from fossil-fuel-based have been discussed in detail in Section 4.2.

5. The current status of bioplastics and future strategies

5.1. 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 (Kunwar et al., 2016, Nielsen et al., 2020). These prerequisites include decoupling plastics production from fossil fuels, prolonging the use of plastics, and a closed-loop recycling system (Liu et al., 2018; Shogren et al., 2019). 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 (Payne et al., 2019; Blank et al., 2020; Usmani et al., 2020). Therefore, bio-based plastics could play an important role in decoupling the fossil fuel feedstock. Biomass is not only an important sustainable feedstock for plastics, but also for biofuel and chemical production (Saha et al., 2019; Garlapati et al., 2020). 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 (Singh, 2020). This is because the current biomass feedstock sourcing and undeveloped infrastructure for recycling and end-of-life management are additional challenges to bioplastics production (Thakur et al., 2018). For a sustainable bioplastic system, recyclability and resource recovery from the end-of-life products are essential components.

In 2019, approximately 2.05 million tons of bioplastics were produced globally, of which, 54% was biodegradable and the remaining was non-biodegradable (IFBB, 2020). Biodegradable plastics are primarily thermoplastics made of starch and several aliphatic polyesters (Havstad, 2020; IFBB, 2020). PLA is the most commercially developed and widespread polymer among biodegradable plastics (Gere and Czigany, 2020). Biodegradability is considered to be ecofriendly in nature due to its decomposition to natural building blocks and reduction of waste generation (Kubowicz and Booth, 2017). 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, copolymerization or blending with additives are required to achieve the required properties for biodegradable plastics (Hatti-Kaul et al., 2020).

In recent years, the 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 of the potential substitution of bio-based polymers to conventional plastics are distributed in Table 2 (Brizga et al., 2020; Sheldon and Norton, 2020). 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 (Spierling et al., 2018; Luzi et al., 2019). 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 (de Jong et al., 2012; Harmsen et al., 2014; Hatti-Kaul et al., 2020).

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, which contains purified terephthalic acid (PTA) as building block material (Sousa et al., 2015; Svenningsen, 2018). Furthermore, PEF is considered to be an ideal substitute for the current polymer used in packaging (Hwang et al., 2020). Bioplastics can also be used in value-added applications, such as in the medical 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 (Evonik, 2020). Similarly, L'Oréal, a cosmetic conglomerate, has 100% bioplastic bottles and cosmetic packaging (L'Oréal, 2020). Currently available bioplastics including biodegradable and non-biodegradable polymers use for plastic manufacturing and their applications are described in Table S7 (Hatti-Kaul et al., 2020).

5.2. Life cycle analysis studies, challenges, and estimation of non-renewable energy use and greenhouse gas emissions

Life cycle analysis (LCA) is a methodology for quantifying the environmental impacts arising over all the stages of a product, process or services. Analyzing the environmental impacts of plastics with embedded fossil carbon or biomass traced from the extraction of the fossil carbon (raw material and energy inputs/cradle) all the way to its emission into the atmosphere (end-of-life management/grave), in LCA terms, this translates to a cradle-to-grave LCA which takes into account both the fossil or biomass origin of the plastics and the emissions caused by the final disposal management (Finkbeiner et al., 2006). 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 (Gironi and Piemonte, 2011; Weiss et al., 2012; Chen et al., 2016; Zhu et al., 2016; Walker and Rothman, 2020). 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 (Eerhart et al., 2012). 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) (Tsiropoulos et al., 2015). 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 (Yu and Chen, 2008; Narodoslawsky et al., 2015). In addition, most of the commercial production of bio-based plastics feedstocks requires significant agricultural land to grow, which is also an issue for the environment (Piemonte and Gironi, 2011; Escobar et al., 2018). However, the current production of bioplastics is estimated to translate to approximately 0.51 million ha of land, equivalent to nearly 0.04% of arable land (Fig. 2). 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 (Palm et al., 2016; Adegoke et al., 2021). This figure is nearly half of all the current

Table 2
Potential bio-based polymers available in the market to substitute the whole conventional plastics, and their percent renewable carbon in bioplastics (Brizga et al., 2020; Sheldon and Norton, 2020).

Petrochemical Plastics	Market share (%)	Potential substitution of bio-based polymers (both degradable and non-degradable)							
		Bio-based (%)	Bio-PTT (%)	PBAT (%)	PBS (%)	PHA (%)	PLA (%)	TPS (%)	Cellulose-Based (%)
PP	100	10 (bio-PP)	5		10	20	20	15	20
PS	100					20	30	25	25
HDPE	100	50 (bio-PE)		10		15	10	10	5
LDPE	100	55 (bio-PE)		10		15	10	5	5
PET	100	60 (bio-PET)	10			5	20		5
PVC	100	50 (bio-PVC)				20			30
PS expended	100							70	30
PA	100	80 (bio-PA)	20						
PUR	100	80 (bio-PUR)				10		10	
Other thermoplastics	100			10	10	20	20	20	20
other plastics	100			10	10	20	20	20	20

biomass used in energy production, despite the global biomass potential of 50–500 EJ (Bauer et al., 2018; Hatti-Kaul et al., 2020). Another problem with bioplastics is limited or no infrastructure for the collection, recycling, and composting to recover the resources at the end of life (Philp, 2014; Brodin et al., 2017). In many countries, incineration is the most preferred method for energy recovery (Kaza et al., 2018). For a cradle-to-grave LCA analysis, end-of-life efficiency is vital to assess the overall ecological footprint (Yu and Chen, 2008).

However, the studies on GHG emissions to bio-based products including biofuels and bioplastics show that overall GHG emissions can be mitigated compared to petrochemical products by harnessing CO_2 sequestration from the atmosphere through photosynthesis during plants growth (Jiang et al., 2020; Moustakas et al., 2020; Escobar and Laibach, 2021). The land use for agricultural crop production and its concerns are also studied by the researchers and they found that land-use change (LUC) can be distinguished in two forms; first direct land-use change (dLUC) and indirect land-use change (iLUC). The dLUC refers to the direct conversion of virgin land or tropical rainforest to agricultural crop production for bio-based material production, whereas iLUC refers to the conversion of existing cultivated agricultural land into crop production for bio-based materials production (Searchinger et al., 2008). In the past decade, the GHG emissions caused by dLUC and iLUC for the production of bio-based materials for plastics and biofuels have been discussed extensively and recent estimates suggest that the iLUC factor for biomass production are between 0.15 and 0.30, which was roughly 1 when it reported first-time (Edenhofer et al., 2011). Therefore, LUC could potentially be reduced by good governance, land use management, and certification to protect existing carbon stocks. For example, in the US, the state of California has included iLUC into the state's Low Carbon Fuels Standard and adopts a value of 30 g per MJ for corn-based ethanol predation (Wade, 2015). Similarly, other states and researchers have shown the improved value of iLUC between 7 and 14 g per MJ (Tyner et al., 2010).

The recent development on bio-based feedstocks generation materials and transition from first-generation bio-based products to second-generation products derived from lignocellulosic feedstocks has become an attractive source for sustainable biomass production for bioplastics. Many advantages have been observed from the 2nd generation feedstocks (lignocellulosic feedstocks) as compared to 1st generation that including higher yield per hectare, lower GHG emissions, do not compete with food crops, and most importantly, the LUC is non or negligible when non-agricultural lands are used (Wicke, 2011). However, there are still few concerns with lignocellulosic materials that require a large amount of NREU and chemicals for the removal of lignin and the conversion process from biomass material to building blocks (Zeng et al., 2014). Even though, the production of bioplastics from 2nd generation and 3rd generation feedstocks are still in development stages, particularly the 3rd generation, the outcomes of the LCA studies of NREU and GHG emission (both the cradle to gate and cradle to grave) from bioplastics (1st and 2nd generation feedstocks) and petrochemical plastics have significant differences. Fig. 5 shows that the bioplastics produced from 2nd generation feedstocks have 25% less NREU than that of 1st generation, while the bioplastics from 1st generation required about 86% less NREU than that of petrochemical plastics. In the case of GHG emissions results, the reduction of GHG emission was 16% less in 2nd generation feedstocks than that of 1st generation while a significant less about 187% was found in 1st generation feedstocks than that of petrochemical plastics.

5.3. 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 (Ivanov and Christopher, 2016; Zhang et al., 2018; Karan et al., 2019; Tsang et al., 2019; Ummalyma et al., 2020). Recent studies have shown that wood and other lignocellulosic residues from agroforestry would be more sustainable alternatives due to their polysaccharides and lignin (Brodin et al., 2017; Tedeschi et al., 2020). 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 (Ampelli et al., 2015; Dürre and Eikmanns, 2015; Crumbley and Gonzalez, 2018). Additionally, many refineries that produce only oils operate at very low-profit margins (Moraes et al., 2014; Rahimi and Shafiei, 2019). To overcome these lower profit margins, refineries are integrating fuel and chemical products within a single operation (Sadhukhan et al., 2018). For example, petrochemical oil refineries distribute nearly 10% of fuel for chemical production, which in result contributes approximately 25–35% of the annual profits (Bozell, 2008; Philp et al., 2013). 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 (Snell and Peoples, 2009; Zahari et al., 2015; Ivanov and Christopher, 2016).

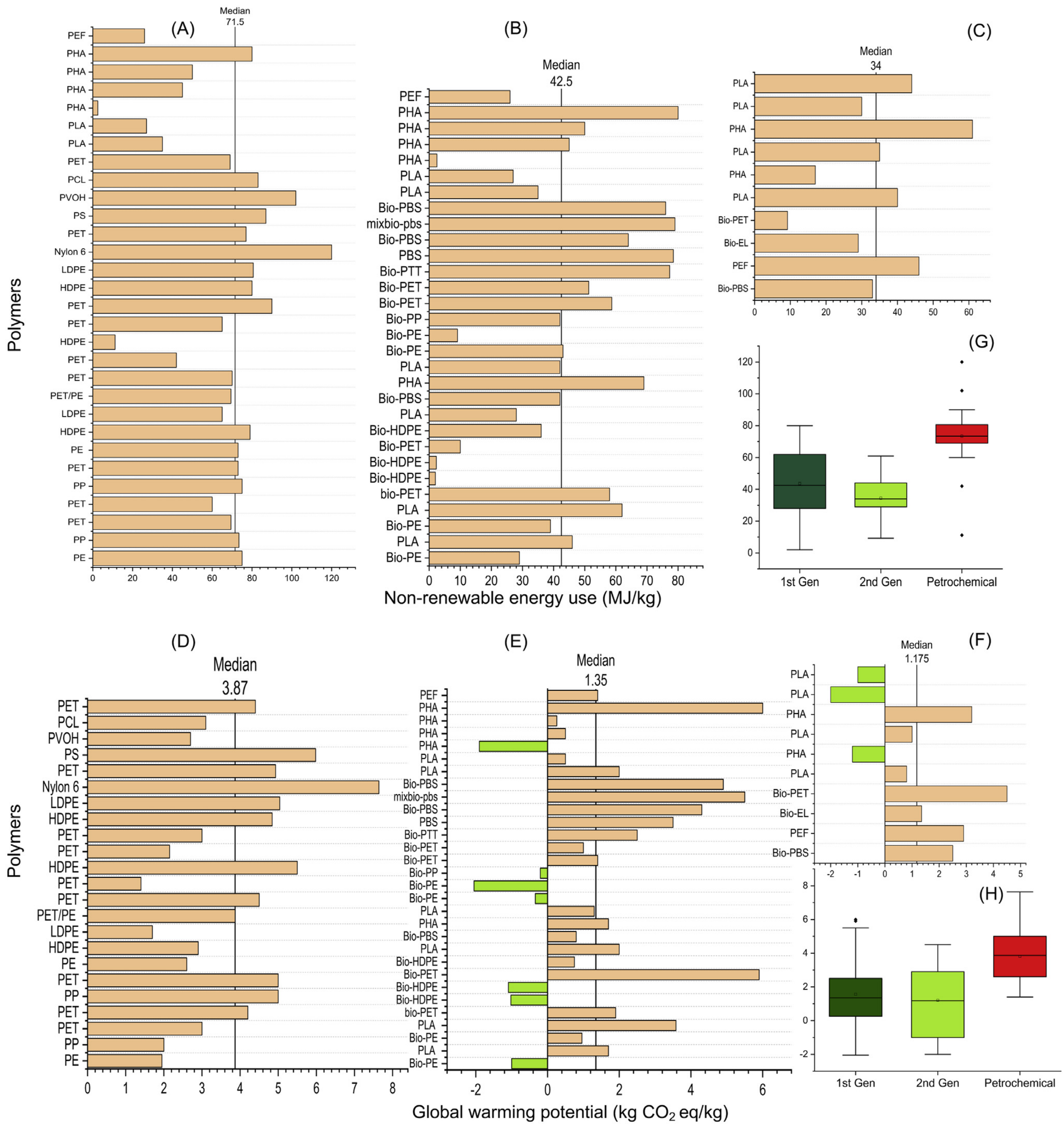

Fig. 5. Results of life cycle analysis (LCA) studies (both the cradle to gate and cradle to grave) on environmental impacts of Non-renewable energy use (NREU) and greenhouse gas (GHG) emissions on production of bioplastics (1st generation feedstocks and 2nd generation feedstocks) and petrochemical plastics. (A) Results of LCA studies on NREU of petrochemical plastics; (B) Results of LCA studies on NREU of 1st generation feedstocks bioplastics; (C) Results of LCA studies on NREU of 2nd generation feedstocks bioplastics; (D) Results of LCA studies on GHG emissions of petrochemical plastics; (E) Results of LCA studies on GHG emissions of 1st generation feedstocks bioplastics; (F) Results of LCA studies on GHG emissions of 2nd generation feedstocks bioplastics; (G) a box plot description of medium values of LCA studies on NREU of bioplastics (1st generation feedstocks and 2nd generation feedstocks) and petrochemical plastics; (H) a box plot description of medium values of LCA studies of GHG emissions of bioplastics (1st generation feedstocks and 2nd generation feedstocks) and petrochemical plastics. (Additional data are presented in Table S1)

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 (Germany, 2012; Valdivia et al., 2016; Kedron and Bagchi-Sen, 2017; Voegele, 2017; USDA, 2019). 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 (Chagas, Bordonal et al., 2016; Rajendran and Murthy, 2017). To promote an integrated system for biofuel and bioplastics, setting environmental targets, certification, and the labeling of bioplastics products would be effective measures (Horvat and Kržan, 2012; You et al., 2015; Yu et al., 2018). 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 (Narayan and Patel, 2003; Mori et al., 2013). 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.

6. 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 (Andrady, 2015). However, not all the plastics are persistent by nature, some of them can be degraded with the assistance of chemicals and living organisms (Goldberg, 2011). 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 (Tokiwa et al., 2009). Biodegradable plastics may not be available or suitable for all the applications (Berkesch, 2005). Overall, the current plastics economy is not very environmentally sustainable (Pazienza and De Lucia, 2020). However, the effective recycling of used plastics could be an effective way to control the leakage of waste plastics into the environment (Rahimi and García, 2017; Chandrasekaran et al., 2018). 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 Fig. 6. 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 (Ragaert et al., 2017). 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 (Ragaert, 2016; Christensen et al., 2019). For example, PET bottle recycling, wherein the used PET bottles are combined with virgin plastics (Qin et al., 2018).

Chemical recycling of used plastics refers to a chemical process for the degradation of polymers (Ragaert et al., 2017; Jiang et al., 2020). 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 (Himebaugh and Rebecca, 2020). Bio-degradation or bio recycling is an emerging process in plastic recycling and is primarily focused on plastics with biomass origins (Bano et al., 2017). Unlike the current recycling processes, which are primarily based on thermomechanical 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 (Matsumura et al., 2000; Alaerts et al., 2018). For example, PET polymers are bio-recycled using the Carbios' recycling bioprocess (Maille, 2019). Lipases and cutinases are the most studied enzymes for bioplastics recycling (Koshti et al., 2018).

6.1. Designing plastics for a circular economy and bio-based 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 (Barbi et al., 2019; Hatti-Kaul et al., 2020; Zwetsloot, 2020). 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 (UNEP, 2019). The key plastic problem of the current time is one of design (Narancic et al., 2020). 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 (Penca, 2018). 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 (Payne et al., 2019). 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' (European Commission, 2018). The strategy also recommended decoupling plastics production from fossil-fuel resources and reducing GHG emissions under the Paris Agreement on Climate Change commitments.

Recently, there is a discussion about creating a bio-based economy for the production of bio-based chemicals and products including bioenergy/ biofuels, a slightly different definition from bioeconomy which also includes the food and feed sectors (Kardung and Wesseler, 2019; Hu and Gholizadeh, 2020; Antar et al., 2021; Mobtaker et al., 2021; Mulvaney et al., 2021). In general terms, a sustainable (if implemented properly) bio-based economy could offer opportunities to local farmers through a diversified crop production for food, feed, and industrial demands which in return can provide more security and stability to locals (Hamelin et al., 2019; Karan and Hamelin, 2020). Through the local supply chains of feedstocks for bio-based products and bioenergy, the farmers can adopt better precision agriculture that can mitigate the GHG emission through better land use, and therefore, it would be beneficial for the socio-economic development of countryside areas (Machado et al., 2021). Besides, through the cascading use of biomass and coupled production strategies, which are a part of a bio-based economy, the substitution of most of the fossil-based products can significantly mitigate the GHG emissions and increase resource efficiency (Sadhukhan et al., 2018; Hamelin et al., 2021). The flow of the biomass and cascading strategies that are also aligned with the principles of the circular economy could be a very prolific concept for the entire value chain of the bioeconomy (Escobar and Laibach, 2021; Wang et al., 2021; Wu et al., 2021), as described in Fig. 7 (Carus, 2017). The concept also promises to introduce new biomaterials with innovative functionalities which opens a window of opportunities to develop new process technologies. For example, industrial biotechnology (discussed in Section 6) delivers a solution for a green and sustainable circular economy for bio-based materials.

6.2. Designing plastics for improved performance

In the future, designing high-performance bio-based 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

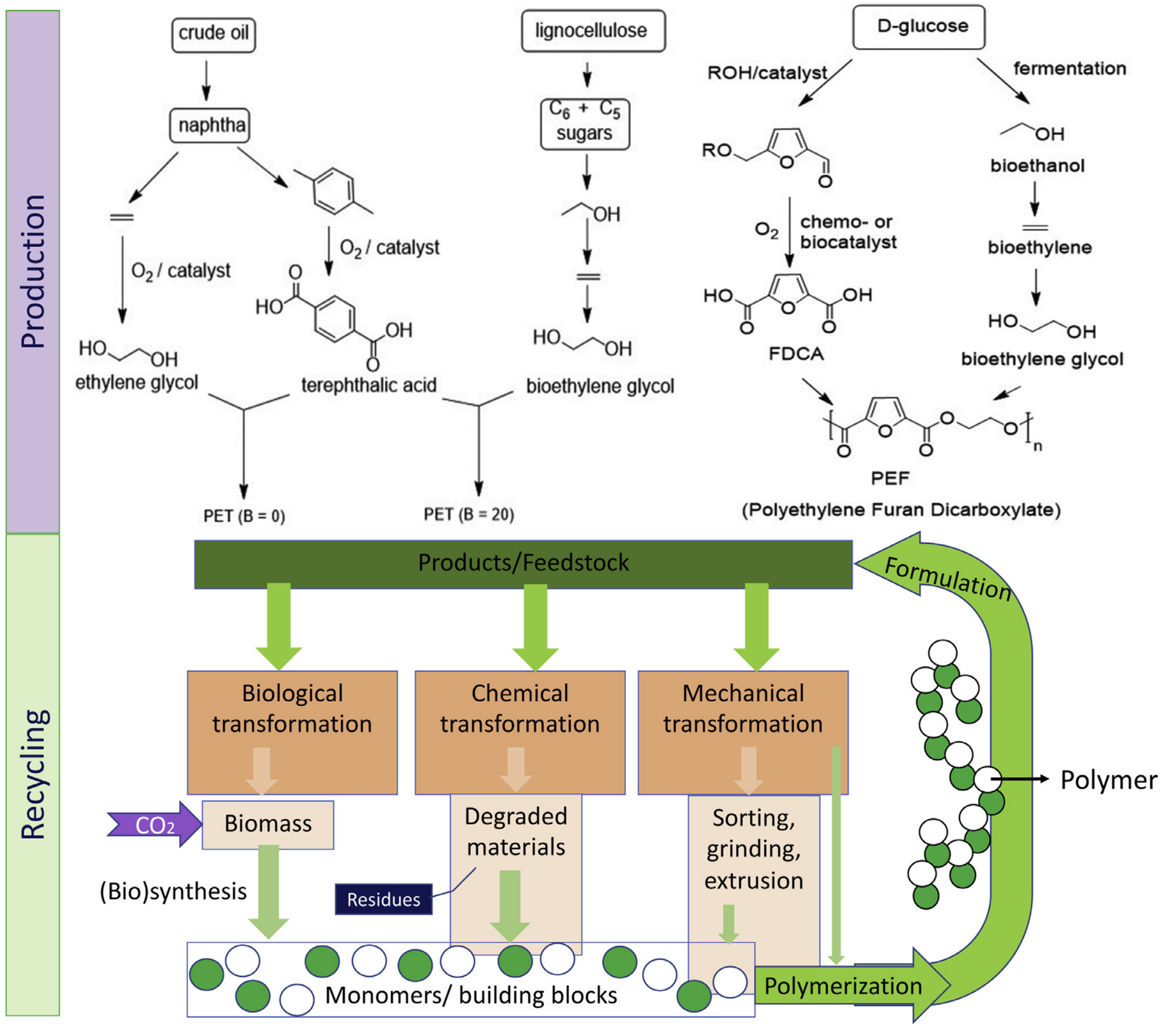

Fig. 6. A sketch of the plastic production process of bioplastics and petrochemical plastics and the recycling and material flow (Sheldon and Norton, 2020).

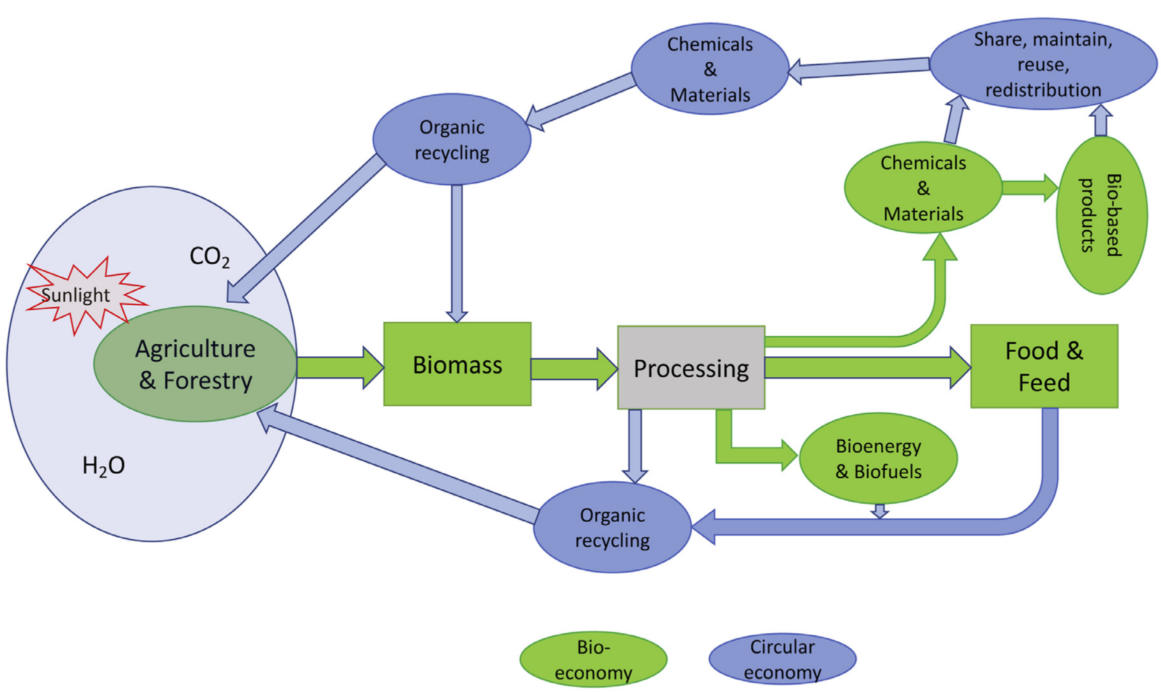

Fig. 7. A comprehensive approached for circular and bioeconomy (Carus, 2017).

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 (Farah et al., 2016; Nguyen et al., 2018). PET, famous as widely recycled plastic, has a Tg of ranging from 67 to 81 °C, but during recycling, it loses molecular mass (Demirel et al., 2011). However, commercial biodegradable plastics have a lower Tg value than PET, and the highest value of Tg is 55 °C for PLA (Benabdillah et al., 2000). The Tg value of PHA with aliphatic monomers varies widely from 5 to 47 °C, depending on the microflora use during the cultivation of the building blocks (Koller and Braunegg, 2015). 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 (Ishii-Hyakutake et al., 2018). 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 (Suvannasara et al., 2014; Goto et al., 2018; Nguyen et al., 2018; Short et al., 2018). 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 (74 °C) and holds lower T_m value than PET (235 °C vs. 265 °C). The lower melting temperature (T_m) provides suitability for blow molding and extrusion processes of plastics (Nguyen et al., 2018). The value of T_g can also be enhanced further by the use of an FDCA dimer monomer to 107 °C (Kainulainen et al., 2018). Enhancements in the Tg of bioplastics will be an effective strategy for wider applications and sustainable recycling possibilities.

6.3. *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 (Berkesch, 2005; Tokiwa et al., 2009). 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 (Corbin et al., 2013; Pazienza and De Lucia, 2020). In some cases, biodegradability can also be used as a sustainable criterion for plastic recycling (Reichert et al., 2020). 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 (Hakkarainen, 2002). 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 (Sanford et al., 2016). This revealed that the biodegradation rate of PHB and PLA polymers and the depolymerization of their products are influenced by the stereochemistry. The outcomes of different studies on the biodegradation of plastics including bioplastic and petrochemical plastics are shown in Table S8.

The 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 (Saini, 2017). The degree of crystallinity of the polymers is considered to be an important factor for assessing degradability (Migliaresi et al., 1991; Wei et al., 2020). For example, amorphous polymers undergo a faster hydrolysis reaction and degradation of the semicrystalline polymers, and this begins 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 (Li et al., 1990). Similarly, the degradation rate of PHA is also determined by the building blocks and the degree of crystallinity (Yean et al., 2017). 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 (Iwata et al., 1999). 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 (Mergaert et al., 1993). 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 (Lavilla et al., 2012).

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 (Kwon et al., 2013; Hatti-Kaul et al., 2020).

7. 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 (Philp et al., 2013). 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 (Van Wyk, 2001). In 2018, the world produced approximately 2.1 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 (Hatti-Kaul et al., 2020).

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 (Hauenstein et al., 2016). 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 (Sen et al., 2016). Chitin and chitosan byproducts of marine animals are also produced and used as alternatives to petroleum plastics (Qaseem et al., 2021). The biotechnology process has also been conveniently applied in the waste management of toxic chemicals and oil spills (Fox, 2011).

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 (Palm et al., 2019). 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 (Liang et al., 2020). 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.

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 (Palm et al., 2019). 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 h, making this process exemplary for both bio-based PET and petrochemical PET recycling (Tournier et al., 2020).

8. 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 leading 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, 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 current study revealed the following main outcomes;

1 Bioplastics produced from 2nd generation feedstock have 25% less NREU than that of 1st generation, while the bioplastics from 1st generation feedstocks required about 86% less NREU than that of petrochemical plastics.
2 The GHG emissions results show that the reduction of GHG emission was 16% less in 2nd generation feedstocks than that of 1st generation while a significant less about 187% was found in 1st generation feedstocks than that of petrochemical plastics.
3 Our estimate shows that an average of about 13.8 EJ, ranging from 10.9 EJ to 16.7 EJ, of fossil-fuel energy consumed in 2019 was diverted to fossil-fuel feedstocks for the production of plastics worldwide, this translates between 2.8 and 4.1% share of the total consumption of fossil-based energy. In China, it shows between 2.7 and 10.8% share of the total consumption of fossil-based energy depending upon the production and consumption amount.
4 Diversification of biomass feedstocks and precision crop cultivation with better land utilization is important for the wider application of bioplastics

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.

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.

CRediT authorship contribution statement

Narendra Singh: Conceptualization, Data curation, Writing – review & editing. **Oladele A. Ogunseitan:** Conceptualization, Writing – review & editing. **Ming Hung Wong:** Conceptualization, Writing – review & editing. **Yuanyuan Tang:** Conceptualization, Writing – review & editing.

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Supplementary materials

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