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Perspective

The Unintended Side Effects of Bioplastics: Carbon, Land, and Water Footprints

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The environmental impacts of plastics have become an important political and academic topic. One of the main applications of plastics is packaging, a product with a very short service life, leading to a wide range of environmental problems. In this Perspective, we look at the potential environmental consequences (in terms of greenhouse gas emissions and land and water footprints) of substitution of petrochemical plastics used for packaging in Europe with bioplastics. The research is based on a review of life cycle impact assessment studies and additional calculations to assess the footprints of this substitution. The results demonstrate that currently it does not seem feasible to replace all the petrochemical plastic packaging with bioplastic because this will inevitably result in a considerable increase of land and water use. Unless we find ways to decrease plastic demand, most of the efforts to stop plastic pollution are likely to prove temporary and inadequate.

Introduction

Plastics are widely used in different industries. Applications range from transparent flexible food films to durable construction and high-cost medical materials. Most of these plastics and their additives are of petrochemical origin and thus rely on non-renewable resources, such as natural gas, crude oil, and coal, leading to significant environmental impacts.[1,2]

Packaging is the main user of plastics in Europe and globally, accounting for 39% of the demand for plastics[3,4] (Figure 1). Currently, the main plastic resins used in plastic packaging are polyethene (PE), polypropylene (PP), and polyethene terephthalate (PET), covering more than 80% of all plastic packaging.[3] Many of these plastics end up in the environment, slowly turning into nanoplastics[5] and having negative adverse effects on marine[6,7] and terrestrial[8–10] ecosystems as well as human health.[11,12] However, many of the possible effects are still unclear.[10,13,14]

To mitigate these impacts, governments have responded with the introduction of taxes and/or bans on plastic bags, microbeads, and other single-use plastics, which are spreading around the globe, starting with the European Union (EU) to China, Kenya, India, and many other countries.[16] The EU has developed policies[17–19] to improve the recyclability of plastics, increase demand for recycled plastic, reduce the use of single-use plastics and microplastics in products, provide guidance for national authorities and businesses on how to minimize plastic waste at source, and collaborate to devise global solutions and develop international standards. All these limitations on fossil fuel-based plastic use will lead to increased demand for bioplastics, and thus it is necessary to understand the potential environmental impacts of such a substitution.

The shift to biomass is often mentioned as a move toward a circular economy, to minimize greenhouse gas (GHG) emissions and reduce environmental impacts. Circular[17] and bioeconomy[20] strategies are developed in most of EU member states and many other countries. These strategies propose a vision where alternative feedstocks are developed and used for bioplastic production with the aim of replacing fossil-based alternatives.

Substitution is technically possible for almost every conventional plastic material and application, but currently, production costs of bioplastics are still high and land requirements for some substitutes are large and pose limits to substitution.[21–23] For example, according to a study conducted by the University of Utrecht,[24] bioplastics could technically substitute 85% of conventional plastics, and existing refineries can be used for the production of bioplastics with minimal changes to their current production processes.

Understanding the Plastics Market

A first, obvious question to ask is how much and what kind of plastics are currently produced and what is the contribution of bioplastics. It turns out there is not one straightforward answer. According to Plastics Europe, global plastic production keeps on increasing and in 2018 reached 359 Mt,[3] whereas Geyer[4] estimated global plastics production to be 438 Mt in 2017. The EU is one of the biggest plastic producers, accounting for 17% of global plastics production.[3] Packaging is the main user of plastics (mainly PE, PET, and PP) accounting for 44% globally. Most of this plastic is short-lived thereby generating large amounts of plastic waste.

However, plastic products usually consist not only of the basic polymer but also different often environmentally damaging additives incorporated into a plastic compound, such as plasticizers,

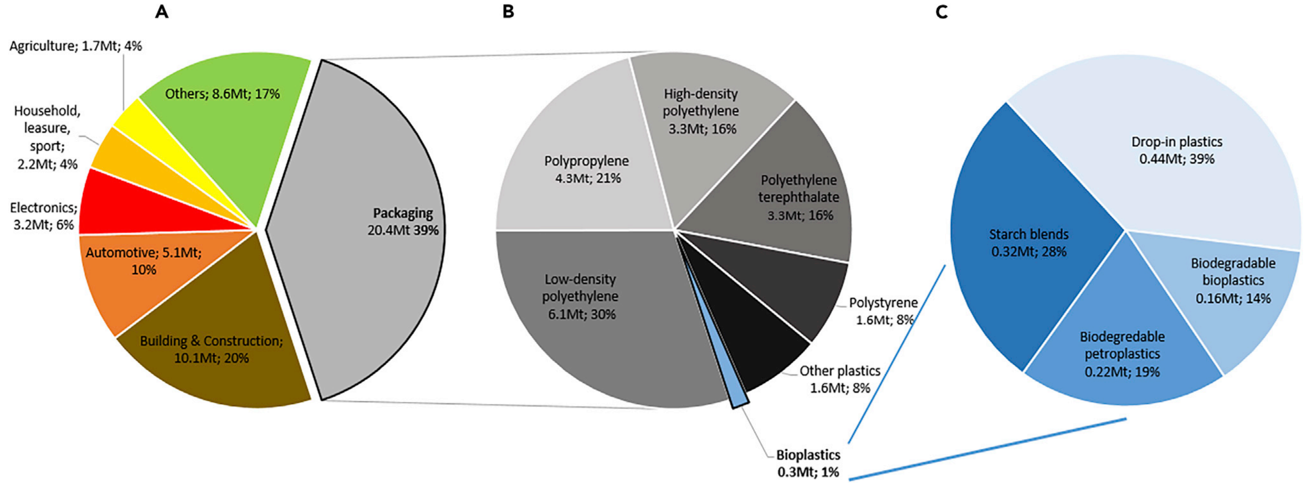

Figure 1. Volume and Share of Plastic Polymers Use in the European Union

(A) Volume and share of plastic polymers use in European consumption.
(B) Volumes and shares of plastic packaging polymers.
(C) Volumes and shares of bioplastics in European plastic packaging.
Values are for 2018, in million tons (Mt) and %.
Sources: PlasticsEurope,[3] European Bioplastics.[15]

flame retardants, antioxidants, acid scavengers, light and heat stabilizers, fillers, lubricants, pigments, antistatic agents, slip compounds, and thermal stabilizers.[2,25,26] These additives can sometimes account for more than 50% of the mass of the final plastic product.

Currently, many different plastic polymers are used, but some of them are dominating the market. All plastics can be classified into two broad subsets:

- Thermoplastics are a family of plastics that becomes moldable when heated and hardened upon cooling. They account for over 90% of the mass of plastics produced.[27] The most commonly encountered thermoplastics are PE, PP, polystyrene (PS), polyvinyl chloride (PVC), acrylic, nylon, and PET;
- Thermosetting polymers are plastics that have been irreversibly hardened in a way that prevents melting. Most popular thermosets are used as the matrix in fiberglass, polyurethanes (PUR), vulcanized rubber, and urea-formaldehyde foam.

For packaging, the most popular plastics are low-density polyethene (LDPE), polypropylene (PP), high-density polyethene (HDPE), and polyethene terephthalate (PET) (Table S3). PVC, another popular plastic, is not used in packaging.

Market Share and Costs of Bioplastics

We also have to clarify the term "bioplastic" because it incorporates several concepts. Bio-based plastic polymers are produced from biomass or by living organisms, and they may or may not be biodegradable. It is also possible, but more expensive, to produce biodegradable plastics of petrochemical or mixed origin. For example, so-called drop-in plastics are often non-biodegradable materials (e.g., Bio-PE, Bio-PET, Bio-PTT [polytrimethylene terephthalate]), obtained from renewable raw materials that have identical technical properties to their fossil counterparts. The term bioplastics also covers novel bio-based plastic polymers, e.g. PLA (polylactic acid), PHA (polyhydroxyalkanoates), PHB (polyhydroxybutyrate), and starch blends as well as microbial polymers such as polynucleotides (nucleic acids), polypeptides (proteins), and polysaccharides (polymeric carbohydrates) (Table 1). However, some of the novel biodegradable plastics, e.g. PBS (polybutylene succinate) and PBAT (polybutylene adipate terephthalate), can be produced from petrochemicals.

Currently, most bioplastics are so-called first generation and derived from carbohydrate-rich plants such as corn, sugar cane, castor oil plant, potato, or wheat that could be used alternatively as food or animal feed. Second-generation bioplastics are produced from feedstock not suitable for food or feed, i.e. non-food crops (e.g., wood cellulose, short-rotation crops such as poplar, willow, or miscanthus) and waste materials from first biomass processing, e.g., food waste or sawdust. Third generation refers to direct production of plastic (or monomer) by (micro)organisms. However, these bioplastics are still at the developmental stage.

According to European Bioplastics,[15] in 2019 the global production of bioplastics was below 1% (2.43 Mt) of the global plastics production. Asia accounted for the largest share of bioplastics production (45%). Europe came next with 25%, but this is expected to grow, thanks to the European Commission's commitment to transitioning to a circular economy. The most popular applications of bioplastics are for food packaging (with 52% or 1.26 Mt of the total bioplastics market in 2019), but they are also used in other sectors, including textiles (10%), consumer goods (10%), automotive (7%), agriculture (7%), coating and adhesives (7%), construction (4%), and other sectors (3%).

Drop-in plastics, including bio-PE (polyethene) and bio-PET (polyethene terephthalate), as well as bio-PA (polyamides), are the most popular bioplastics, representing around 42% (0.89 Mt) of the global bioplastic production and are anticipated to

Table 1. Classification of Petrochemical and Bio-based Plastic Polymers

	Petrochemical Plastics	Blended Plastics	Bioplastics
Biodegradable	PBS, PBAT, polyvinyl alcohol (PVA, PVOH), polycaprolactone (PCL), polyglycolic acid (PGA)	starch and PLA blends	PLA, PHA, cellulose-based plastics, lignin-based polymer composites
Non-biodegradable	PE, PP, PET, PS, PVC, PA, PUR, other	drop-in plastics, e.g. Bio-PET, Bio-PA, Bio-PTT	Bio-PA 11, Bio-PE

Based on Shen et al.[24] and Endres and Siebert-Raths.[28]

account for 75% of the bio-based plastics market by 2021.[29] Nevertheless, large growth is also foreseen for PLA (global production in 2019 was about 0.21 Mt) and PHAs (0.29 Mt). Their production capacities are estimated to triple in the next 5 years.

European Bioplastics, which is the association representing the interests of the bioplastics industry, expects rapid development of PEF (polyethylene furanoate) and entrance into the market in 2023.[15] PEF is technically similar to PET but fully bio-based, recyclable, and with a wide range of applications, including packaging. In 2019, bio-PP entered the market on a commercial scale with strong growth potential due to the widespread application of PP in a wide range of sectors. Bio-PUR is another important bioplastic with massive production potential and is expected to grow faster than conventional PUR due to its versatility.

Bioplastics have wide application possibilities. For example, cheaper, biodegradable alternatives (microcrystalline cellulose) can also be used as a good replacement for microbeads in cosmetics.[30] Hemicellulose (polymerized sugars) can be used for films to be used in liquid packaging.[31] It is possible to replace cotton (grown in water-poor areas) with fibers from forests. Wood textiles generally use less energy, water, and chemicals than the conventional cotton industry.[32] It is also possible to use bio-based polymers to produce new textiles with different properties, such as being waterproof.[33]

The competitiveness of bioplastics is closely linked to policy support and the price of oil.[34] Higher oil prices correlate with significant growth in bioplastics and recycling.[35] The current production costs of bio-based materials are heavily dependent on the feedstock. When bio-based products are derived from low-cost sources (such as biomass residues), the competitiveness of bio-based versus fossil-based products is likely to be achieved by means of improved biotechnologies that go beyond the low performance of early research and production phases and market expansion harnessing economies of scale. Bio-ethylene is at least 30% more expensive than its fossil counterpart, and its price is heavily dependent on the price of feedstock.[36] The PLA price is only slightly higher than the average price of all polymers, but prices for starch-based polymers are about 60% higher than LDPE.[37]

Current economic reality prevents replacing all chemicals used in plastic production (e.g., chemicals such as lower olefins, benzene, toluene, and xylenes) with components from biotic feedstocks. Currently, these chemicals can be produced much more cheaply from petrochemical resources.[38] When production of a petrochemical requires more steps and more oxidation, such as for adipic acid, acrylates, and diols, production from biotic feedstocks may already be competitive.[38] The overall situation can certainly improve as bio-based products reach a higher market share, which might introduce cost reductions due to economies of scale, learning curve effects, or policy stimuli, such as a fossil carbon tax creating a level playing field for fossil and bio-based plastics.[39]

Environmental Impacts of Bioplastics

Not only economic aspects of bioplastics are challenging. The production of these polymers also poses a significant threat to the environment, especially if their production is scaled up. There are an increasing number of studies assessing environmental impacts of bioplastics and studies comparing bio-based plastics with their petrochemical counterparts to highlight savings and trade-offs across impact categories.[40–43] The literature, although still limited to a relatively small number of life cycle assessment (LCA) studies, mainly focuses on energy consumption and the global warming potential of bioplastics compared with petrochemical plastics.

For example, Eerhart et al.[44] compared fossil-based PET and cornstarch bio-PET in terms of fossil energy use and GHG emissions. Sugarcane bio-LDPE and bio-PVC from bio-based ethylene were assessed throughout their life cycle, also accounting for direct and indirect land-use change,[45–47] whereas Hottle et al.[48] performed a sustainability assessment of PLA, PHA, and thermoplastic starch (TPS), highlighting the importance of the end-of-life phase of these polymers. Full bio-HDPE and partial bio-PET from Brazilian and Indian sugarcane ethanol were compared with their petrochemical counterparts produced in Europe.[41] HDPE was chosen as the polymer reference for an assessment of environmental impacts of its production process from sugarbeet and wheat bio-based ethanol as well as from conventional fossil fuels.

Many of the studies are looking not at the bioplastics themselves but at their main building blocks (platform chemicals). Cok et al.[49] evaluated the environmental impacts of three different production processes of succinic acid, which is used to produce PBS. Fiorentino[43] focused on the impacts generated by ethyl levulinate (used in biodegradable polymers: polyesters, PUR, and thermoplastics) not only in terms of energy use and global warming potential (GWP) but also in terms of human toxicity, acidification, eutrophication, and photochemical oxidation potentials. Moreover, many assessments refer to bioethanol as a biofuel rather than as a bio-based building block for bioplastics.

Bioplastics have been shown to lead to savings in non-renewable energy use and GHG emissions in comparison with conventional materials.[50] In particular, Weiss and Haufe[51] calculated that bio-based materials save, on average, 55 ± 34 GJ/t and 127 ± 79 GJ/ha of non-renewable energy and 3 ± 1 t CO_{2e}/t and 8 ± 5 t CO_{2e}/ha of GHG emissions relative to

Table 2. Technical Substitution Potential of Bioplastics (in %)

Non-biodegradable				Biodegradable					
	Bioplastics (Drop-in)			Petrochemical Plastics		Bioplastic			
Petrochemical Plastics			Bio-PTT	PBAT	PBS	PHA	PLA	TPS	Cellulose-Based
LDPE	Bio-PE	55		10		15	10	5	5
PP	Bio-PP	10	5		10	20	20	15	20
HDPE	Bio-PE	50		10		15	10	10	5
PET	Bio-PET	60	10			5	20		5
PS						20	30	25	25
PVC	Bio-PVC	50				20			30
PS expended								70	30
PA	Bio-PA	80	20						
PUR	Bio-PUR	80				10		10	
Other thermoplastics				10	10	20	20	20	20
Other plastics				10	10	20	20	20	20

Source: Based on our estimates and data from Shen et al.[24] and Spierling et al.[53]

Some of the drop-in bioplastics are not 100% bio-based, e.g., the bio-based content of bio-PET is currently ~30% because terephthalic acid is not produced from bio-based feedstocks.

conventional materials, in line with results by Patel et al.[52] Globally, bioplastics could potentially save 241 to 316 Mt of CO$_{2e}$ per year by substituting 65.8% of all conventional plastics (which represents the current technical substitution potential). However, assessment results for GWP of bioplastics can be significantly affected by the chosen accounting method of biogenic carbon, which is either accounted for as carbon storage or considered to be carbon neutral.[40] In the case of carbon storage, biogenic carbon contained in the product is deducted when calculating GWP, but in the case of carbon neutrality, biogenic carbon is excluded from the analysis. Many of the studies also fail to account for GHG emissions occurring from land-use change, including changes in soil carbon. Therefore, the GWP for the same bioplastic could lead to very different results (Table 2). Other important determinants of the impact of plastics on climate are premature material deterioration during service life, the extent to which materials are recycled, and the share of fossil or biogenic carbon in the product.

There is also the risk of burden shifting, when benefits achieved in one impact category may be accompanied by increased impacts in other categories. Assessments only focusing on GHGs and non-renewable energy consumption may miss potential unintended consequences, such as toxicity to humans and ecosystems and land and water use. Unfortunately, toxicity aspects of bioplastics are not sufficiently studied and thus excluded from this review, but apart from GWP, we have looked at land and water footprints of plastic polymers.

Competition for land has to be included in bioplastic LCAs in order to account for the potential loss of biodiversity and ecosystem services.[21,54,55] For example, Khoo et al.[56] defined the land footprint as the total land area required to grow crops necessary to produce 1 kg of bioplastics. Because of the differences in yield factors in different countries and conversion factors for different feedstocks, land footprints can vary significantly (Figure 2), e.g., sugarcane required for bio-PET from Brazilian ethanol is 5 kg cane/kg bio-PET, while it is only 2.6 kg cane/kg bio-PET from Indian ethanol.[41] These differences are the result of the different yield factors and production processes as well as byproducts included in the analysis influencing the magnitude of impacts.

Substitution Potential of Bioplastics

Bioplastics can replace petrochemicals directly by replacing chemical feedstocks from crude oil with feedstocks from biorefineries, and indirectly through the increased use of bio-based materials as substitutes for petroleum-based materials, such as natural fibers for packaging and insulation materials as an alternative to synthetic foams that have been in widespread use.

First-generation biopolymers are the dominant near-term biopolymer option. In this Perspective, we estimated the technical substitution potential of petrochemical plastic polymers with bioplastics using information from Shen[24] and Spierling and Knüpffer.[53] We have expanded their estimates and separated non-biodegradable and biodegradable plastics and provided updated substitution potentials for different bioplastics based on interviews with industry experts. Over the last years, some of the bioplastics have undergone significant technical developments and market uptake (e.g., PLA, PHA, bio-PP), which is reflected in our new estimates of technical substitution potential.

Concerning the material properties required for packaging, the almost complete substitution of petrochemical plastics by bioplastics (not all are biodegradable) is technically feasible. Therefore, in Table 2, we assume 100% substitution of all the plastic polymers currently used in packaging with bioplastics, including two biodegradable petrochemical plastic polymers (PBAT and PBS). This table shows that, for example, it is technically possible to replace petrochemical LDPE with bio-PE (55%), PHA (15%), PBAT and PLA (10% each), TPS (5%), and cellulose-based bioplastics (5%) (for more details, see Table S1).

To identify land and water footprints of different bioplastics, we used the FAO's average yield factors from 2009 to 2018[57] (Table S2) multiplied by the conversion factors provided by the

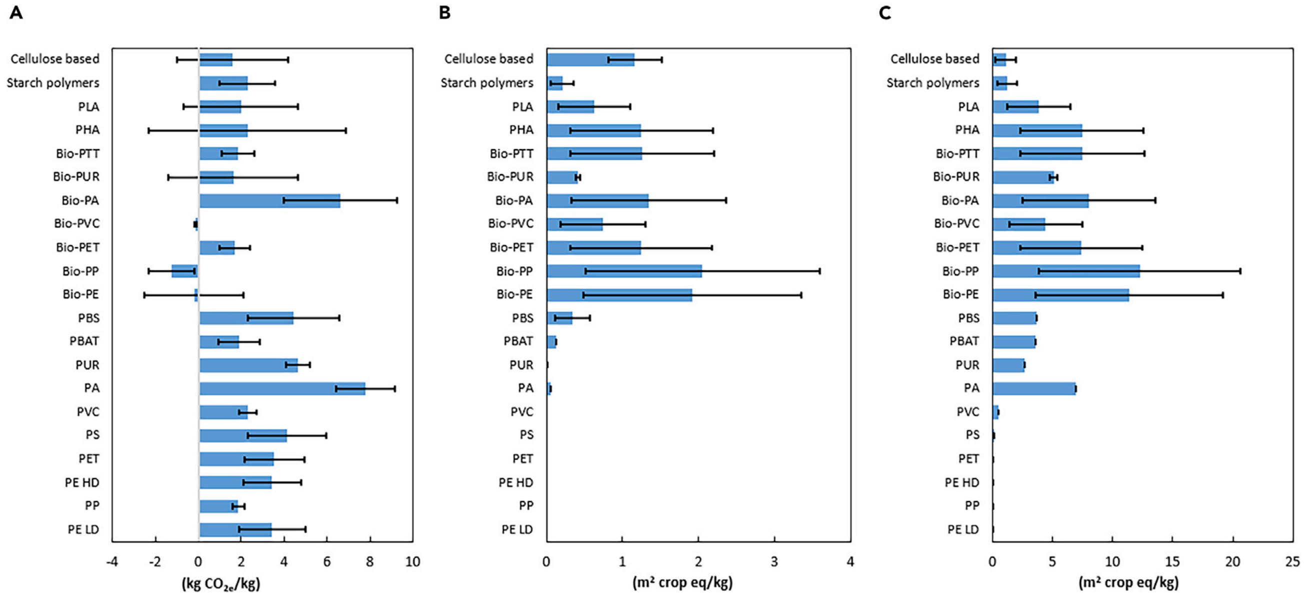

Figure 2. Global Warming Potential, Land and Water Use for Plastic Production
(A) Global warming potential.
(B) Land use.
(C) Water use.
Full bars show means and error bars show maximum and minimum levels. For more details on the calculations of maximum and minimum land and water use of bioplastics, see Experimental Procedures.

Institute for Bioplastics and Biocomposites[58] (Table 3, land and water use). The calculated land use is fully allocated to the production of specific bioplastics. Most of the water and land footprint is associated with the agricultural production of feedstock; the lowest land footprint is for sugar beet-based glucose production and the highest is associated with wheat; the lowest water footprint is associated with sugar beet-based glucose production and the highest is associated with potato.

Impact factors for plastics were gathered from the Ecoinvent database, and results from other LCA studies were added. We should note that the reviewed LCA studies differ from each other in functional units, cutoff criteria, system boundaries, methods, allocation procedures, and impact categories used. In this study, we refrained from correcting these differences, which can be justified[51] by the limited availability of the necessary information to make corrections. However, if available, we used the LCA results based on economic allocation and the ReCiPe method midpoint indicators, focusing on the plastic polymer production and not the product itself. If necessary, we recalculated environmental impacts per kilogram of a polymer. All the impact factors are summarized in Figure 2 showing maximum, minimum, and mean GWP, land use and water footprints, but a more detailed overview of the LCA studies covered is available at https://doi.org/10.17632/gsfp9c3zyy.1).

LCA studies on bioplastics demonstrate significant differences in selected environmental impacts, depending on the feedstock, geographical region, energy source used in refineries, as well as end-of-life fate of final products. Evidence suggests that environmental impacts of bioplastics could potentially be reduced by maximizing the exploitation of biomass throughout the combined production of chemicals and energy carriers, in line with the concept of an integrated biorefinery.

Results demonstrate that to substitute European consumption of petrochemical plastics used in packaging alone, global bioplastic production would need to increase by 8.4 times. For some of the bioplastics, the required increase in production would be close to 100 times (Figure 3). However, this represents only technical substitution potential and factors such as economic feasibility and resource availability are not taken into account.

To replace EU plastic packaging with bioplastic, 20.4 Mt of bioplastic would be needed, requiring 70.3 Mt of corn (or 6% of current global production[57]), 0.08 Mt of castor beans (i.e., 30% of current global production[57]), and 3.1 Mt of wood (around 0.1% of current global roundwood production[57]). However, corn can also be substituted with other feedstock, e.g., sugarcane, sugar beet, wheat, potato, all of which have different feedstock efficiencies and yield factors. Therefore, we estimate that satisfying these land-based inputs would require a minimum of 7.4 million ha of land (which is larger than the total area of Ireland) and at least 45 billion m^3 of water (the equivalent to almost a fifth of the EU's total freshwater withdrawal) (Figure 4). However, the results of the bioplastic environmental impacts have a significant range, depending on the differences in yield factors, underlying production processes, and other factors. The results for the GHG emissions when comparing plastic packaging production from petrochemical and bioplastics are overlapping: current GHG emissions to produce petrochemical polymer packaging for Europe are estimated to range between 41.5 and 90.1 Mt of CO_{2e} (with a mean across all studies of 56 Mt CO_{2e}), and estimated GHG emissions from bioplastic substitution range

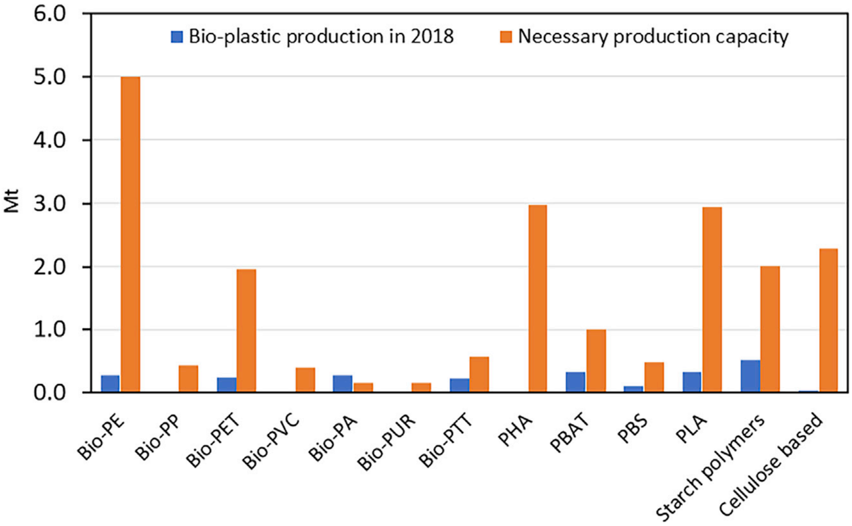

Figure 3. Current Bioplastic Packaging Production versus Necessary Production Capacity Source

For more details on the calculations, see Experimental Procedures.

between −17.5 and 80.1 Mt of CO_{2e} (with a mean of 15 Mt CO_{2e}). This difference mostly depends on different assumption used in the LCA studies, e.g., depending on how the biogenic carbon (avoided emissions) is accounted for, which feedstocks are used, and the energy mix used in production processes. Calculation details are described in the Experimental Procedures.

On a global level, not surprisingly, this picture looks worse. Globally, around 170 Mt of plastic is used for packaging purposes annually (44% of global plastic consumption). Substituting these petrochemical plastics with bioplastics would require 613 Mt of corn (54% of the current global production[57]), 1.8 Mt of castor beans (12 times current global production[57]), and 21.3 Mt of wood (around 0.8% of current global roundwood production[57]). To satisfy these land-based inputs would require a minimum 61 million ha of land (which is larger than the total area of France) and at least 388.8 billion m^3 of water (60% more than the EU's annual freshwater withdrawal).

Outlook

The results demonstrate that currently the replacement of petrochemical plastic packaging with bioplastic increases the risk of burden shifting of environmental impacts. In other words, the increased use of bioplastics will result in additional significant amounts of land and water use. This would increase competition for different land uses and have a negative effect on biodiversity.

Some other environmental impacts of bioplastics, e.g., leaching of toxic chemicals from plastic during decomposition, PM10 pollution from sugar cane conversion, and biodiversity impacts of microplastics, are poorly studied and not well integrated into current LCA methodologies. The same applies to the impacts caused by agrochemicals used in agricultural production of bioplastics feedstocks. For example, the impact of bio-HDPE on human health is estimated to be 50 times higher and on ecosystem quality two times higher than conventional HDPE.[41] The agricultural phase has been shown to be more impactful than the industrial conversion of biomass to platform chemicals within a biorefinery.[41,51,59]

Thus, there are many limitations with current assessments of environmental impacts of bioplastics, and more research is needed to overcome the knowledge gaps on critical methodological aspects such as (1) missing information for environmental impacts of some bioplastics, (2) a lack of standardized accounting approaches of biogenic carbon and direct and indirect land-use change, (3) data uncertainties regarding changes in soil organic carbon, as well as (4) lack of common guidelines for LCA studies on bio-based and fossil-based plastics leading to problems in comparing results.[40,53]

To reduce environmental impacts of bioplastics, we need technological advances such as (1) improved yields and decrease of agrochemical use for feedstock production, (2) switching to second- and third-generation feedstocks, (3) improvements in energy efficiency and use of renewable energy in biorefineries, (4) higher conversion efficiencies in biorefineries, and (5) further improvement of end-of-life management (e.g., recycling of bioplastic wastes).[37,41,47,60,61] Nevertheless, it is also clear that technological solutions alone will not be enough. Even if packaging materials differ significantly in their environmental impacts, it is hard to say which packaging is best for the environment because it depends on factors such as reuse and end-of-life management of packaging, energy use in material production, and so on. The use of lighter packaging material has been identified previously as a good choice to decrease the environmental impacts of packaging.[62] Currently, more and more efforts are being made to increase reuse and recyclability of packaging as highlighted in the EU Circular Economy plans.[17,18]

To a large extent, plastic is embedded in our daily lives, thus any reduction of plastic requires behavioral changes as much as technological solutions. In order to significantly decrease the environmental impacts, we will have to change and dematerialize our consumption patterns, which can be achieved only through transformational change across spheres including policy, lifestyles, culture, technology, education, research, and product design. Some encouraging examples do exist, such as the global zero-waste movement providing good examples in zero-waste lifestyles, business, community, and city contexts.[63,64] Numerous, unconventional, exciting, potentially highly effective technical solutions are being put forward and tested at the local level but require support to be scaled up to be able to move beyond small-scale experiments.[65] Also governments are becoming increasingly active in this arena by implementing taxes and bans on plastic packaging and other single-use plastics in parts of the EU,[66] Kenya, India, and other countries,[67] as well as introducing labeling for certain single-use plastic products (e.g., food containers, cigarettes, wet

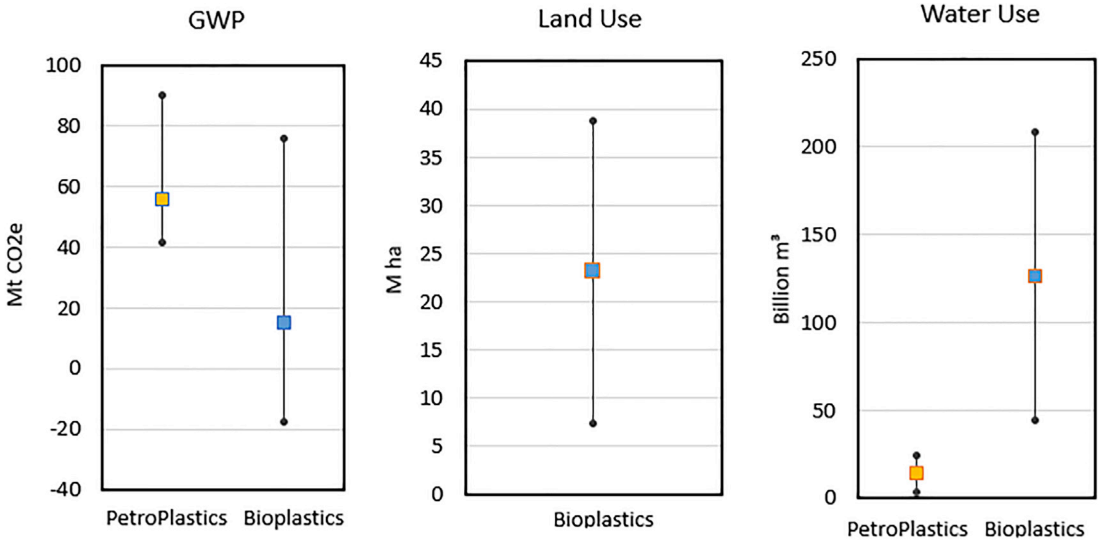

Figure 4. Global Warming Potential, Land and Water Use of Petrochemical versus Bioplastic Packaging Production

Boxes show means and error bars show minimum and maximum global warming potential, land and water use to support current plastic packaging production for Europe. For more details on the calculations, see Experimental Procedures. The land use associated with petro-plastics is zero.

wipes) and producer responsibility schemes to stimulate better design, separate collection, and recycling of plastic polymers.[68] These initiatives need to tackle the problems at different scales, providing local solutions and alternatives as well as expanding producer responsibility globally. However, at this point, the outcomes of many of these attempts are still not sufficiently analyzed and understood. Moreover, it becomes clear that unless we find ways to use less, most of the efforts to stop plastic pollution are likely to prove temporary and inadequate.

Experimental Procedures

Resource Availability

Lead Contact. For queries related to this article, please contact janis.brizga@lu.lv.

Materials Availability. This study did not generate new unique materials.

Data and Code Availability. The LCA data used in this study are available at Mendeley: https://doi.org/10.17632/gsfp9c3zyy.1.

Calculation of Necessary Bioplastic Production Capacity

Calculation of necessary bioplastic production capacity to substitute EU petrochemical packaging demand (Figure 3) is based on the technical substitution potential of bioplastics (Table 3) using the following equation:

$$\sum_i Pc = B_i \times C_i, \qquad \text{(Equation 1)}$$

where Pc is the necessary bioplastic polymer production capacity (Mt) to substitute EU petrochemical packaging demand; B is the current petrochemical plastic polymer production (Mt) to satisfy EU packaging consumption; C is the share of the bioplastic technical substitution potential; i is a type of bioplastic polymer. The results are presented in Table S1 and Figure 3.

Bioplastics Packaging: GWP, Land and Water Use Analysis

The amount of CO_{2e} emissions to support Europe bioplastic packaging production to substitute petrochemical plastics (Figure 4) was calculated using Equation 2:

$$\sum_i CO_{2e} = Pc_i \times GWP_i, \qquad \text{(Equation 2)}$$

where GWP is bioplastic global warming potential (kg CO_{2e}/kg bioplastic), and i is a type of bioplastic polymer. Maximum, mean, and minimum values were calculated using respective impact factors. The results are presented in Figure 4.

To identify the land footprints (LF) of different bioplastics (Figure 4), we used the following equation:

$$\sum_i LF = Pc_i \times Y_i \times CF_i, \qquad \text{(Equation 3)}$$

where Y is an average yield factor for respective feedstock from the last 10 years[57] (Table S2); CF is a conversion factor provided by the Institute for Bioplastics and Biocomposites[58] (Figure 2B, land use); i is a type of bioplastic polymer. Maximum, mean, and minimum values were calculated using respective impact factors. The results are presented in Figure 4.

To calculate the water footprints of different bioplastics (Figure 4), we used the following equation:

$$\sum_i WF = Pc_i \times W_i, \qquad \text{(Equation 4)}$$

where W_i is the average water use per unit of bioplastic production (L/t of bioplastic) provided by the Institute for Bioplastics and Biocomposites[58] (Figure 2C, water use); i is a type of bioplastic polymer. Maximum, mean, and minimum values were calculated using respective impact factors. The results are presented in Figure 4.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.06.016.

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AUTHOR CONTRIBUTIONS

All authors conceived the original idea and contributed to the analysis, development, and writing of the paper. J.B. collected the data and led the writing.

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