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Strategies to reduce the global carbon footprint of plastics

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Over the past four decades, global plastics production has quadrupled[1]. If this trend were to continue, the GHG emissions from plastics would reach 15% of the global carbon budget by 2050[2]. Strategies to mitigate the life-cycle GHG emissions of plastics, however, have not been evaluated on a global scale. Here, we compile a dataset covering ten conventional and five bio-based plastics and their life-cycle GHG emissions under various mitigation strategies. Our results show that the global life-cycle GHG emissions of conventional plastics were 1.7 Gt of CO_2-equivalent (CO_2e) in 2015, which would grow to 6.5 GtCO_2e by 2050 under the current trajectory. However, aggressive application of renewable energy, recycling and demand-management strategies, in concert, has the potential to keep 2050 emissions comparable to 2015 levels. In addition, replacing fossil fuel feedstock with biomass can further reduce emissions and achieve an absolute reduction from the current level. Our study demonstrates the need for integrating energy, materials, recycling and demand-management strategies to curb growing life-cycle GHG emissions from plastics.

Global production of plastics grew from 2 Mt to 380 Mt between 1950 and 2015, at a compound annual growth rate of 8.4% (ref. [1]). Globally, 58% of plastic waste was discarded or landfilled, and only 18% was recycled in 2015[1]. It is estimated that 4.8–12.7 Mt of plastic waste generated by coastal countries entered the ocean in 2010[3]. Growing alongside the volume of global production and consumption of plastics are the diverse concerns on their impacts on the ecosystem and human health[4–7]. However, relatively little attention has been paid to their contributions to climate change. Although the chemical industry as a whole is responsible for about 15% of global anthropogenic GHG emissions[8], the magnitude of global life-cycle GHG emissions from plastics has yet to be quantified.

Various strategies to reduce GHG emissions from plastics have been discussed in the literature, such as replacing fossil fuel-based plastics with bio-based plastics[9–11]. Bio-based plastics generally show lower life-cycle GHG emissions than their fossil fuel-based counterparts[12]. It is estimated that substituting 65.8% of the world's conventional plastics with bio-based plastics would avoid 241–316 MtCO_2-equivalent (CO_2e) yr^{-1} (ref. [13]). Both biodegradable and non-biodegradable forms of bio-based plastics are available on the market[14]. Bio-based non-biodegradable polymers such as bio-polyethylene (bio-PE) and bio-polyethylene terephthalate (bio-PET), also referred to as 'drop-in' polymers, offer virtually identical properties to their fossil fuel-based counterparts. However, bio-based biodegradable polymers, such as polylactic acid (PLA), polyhydroxyalkanoates (PHAs) and thermoplastic starch (TPS), display different mechanical and chemical properties[12]. Strategies to promote bio-based plastics have been initiated by the European Commission and countries such as Japan, Korea and Thailand[15,16]. In 2017, the total global production of bio-based plastics reached 2.05 Mt, and is projected to grow by 20% over the next five years[17].

Low-carbon energy is another strategy to reduce the life-cycle GHG emissions of plastics. Under a 100%-renewable-energy scenario, the GHG emissions from US plastics production could be reduced by 50–75% (ref. [18]). Another strategy to reduce the GHG emissions from plastics is recycling, which reduces, in part, carbon-intensive virgin polymer production[19] while preventing GHG emissions from some end-of-life (EoL) processes such as incineration[20].

However, the literature so far has focused on a subset of plastic types, mitigation options or geographical locations in isolation[18,21]. Here, we develop a dataset that covers GHG emissions from resin production, conversion and EoL processes for ten fossil fuel-based and five bio-based plastics. We then integrate the dataset with projections of global plastics demand and GHG mitigation strategies. We evaluate the following mitigation strategies and their combinations:

(1) Bio-based plastics. Fossil fuel-based plastics are gradually substituted by bio-based plastics until they are completely phased out by 2050. Although bio-based plastics can be derived from a variety of feedstocks, here we model corn and sugarcane given their dominance in the current market[11].
(2) Renewable energy. The energy mix of the plastics supply chain is gradually decarbonized and reaches 100% renewables (that is, wind power and biogas) by 2050. Emissions under the current energy mix are modelled for comparison.
(3) Recycling. Recycling rates of EoL plastics gradually increase and reach 100% by 2050. For comparison, we also model the emissions under a projected EoL management mix scenario and a 100% incineration/composting scenario.
(4) Reducing growth in demand. The current annual growth rate of global plastics demand (4%) is reduced to 2%.

We examine these strategies as illustrative scenarios, rather than as realistic projections of future trajectories, with the purpose of envisioning their potentials for GHG mitigation. We acknowledge that achieving 100% recycling or renewable energy may be neither practical nor economically feasible in reality. Details on these scenarios can be found in Supplementary Table 1.

Our analysis shows that conventional (fossil fuel-based) plastics produced in 2015 emitted 1.8 GtCO_2e over their life cycle, excluding any carbon credits from recycling (Fig. 1). The amount corresponds to 3.8% of the 47 GtCO_2e emitted globally that year[22]. The resin-production stage generated the majority of emissions (61%), followed by the conversion stage (30%). Of all plastic types, polyester, polyamide and acrylic (PP&A) fibres had the highest GHG emissions in both stages. The polyolefin family (polypropylene, PP; low-density/linear low-density polyethylene, L/LLDPE; and high-density polyethylene, HDPE), which accounts for nearly 50% of

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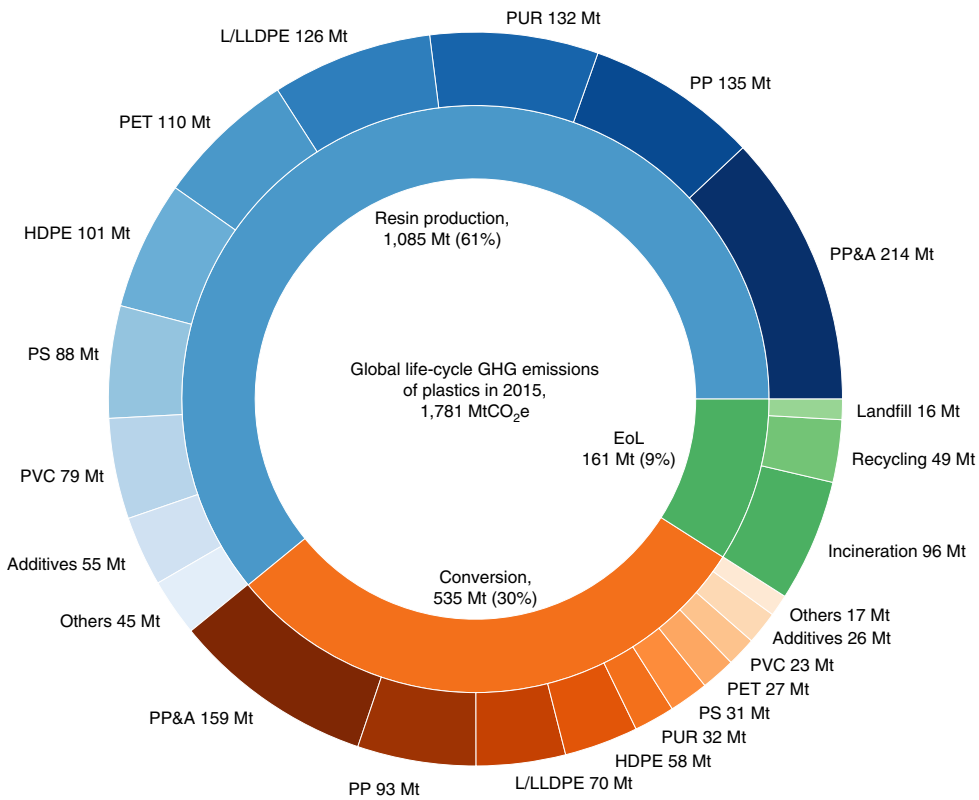

Fig. 1 | Global life-cycle GHG emissions of conventional plastics in 2015 by life-cycle stage and plastic type. Carbon credits generated by recycling are not included. Blue, orange and green represent the resin-production, conversion and EoL-management stages, respectively. The emissions from each stage are broken down by plastic type or EoL-treatment method, indicated with different shades of the corresponding colour. PUR, polyurethane.

the world's plastics consumption, was also a significant contributor. GHG emissions from bio-based plastics are not considered for 2015 given their negligible market share (<1%).

The EoL stage accounted for 9% of total life-cycle emissions, excluding the carbon credits from recycling. Incineration was the dominant source of GHG emissions among EoL processes. Landfill generated the least GHG emissions, although the process handles the largest share of plastic waste (58%). The recycling process itself generated 49 $MtCO_2e$. However, if the displacement of carbon-intensive virgin polymer production by recyclates is considered, the GHG emissions of recycling would go down to negative 67 $MtCO_2e$, and the total emissions from the EoL stage would be reduced from 161 $MtCO_2e$ to 45 $MtCO_2e$. In this case, the total global life-cycle GHG emissions of plastics become 1.7 $GtCO_2e$, or 3.5% of the global annual GHG emissions in 2015.

Under the current trajectory, the global life-cycle GHG emissions from plastics are poised to grow rapidly (Fig. 2a). The global economy produced 407 Mt of plastics in 2015, with an average annual growth rate of 4% between 2010 and 2015[1]. Following this trend, annual plastics production is expected to grow to 1,606 Mt by 2050, and the life-cycle GHG emissions are expected to grow from 1.7 $GtCO_2e$ in 2015 to 6.5 $GtCO_2e$ in 2050, using the projected EoL-management mix change[1], and maintaining the current energy mix (the baseline is the blue solid line in Fig. 2a). If all plastic waste is incinerated by 2050, total annual emissions will reach 8.0 $GtCO_2e$ (a 22% increase from the baseline). Recycling all plastic waste, however, would reduce the emissions to 4.9 $GtCO_2e$ by 2050 (a 25% reduction from the baseline).

With a plastics demand growth rate of 4% yr^{-1}, it has been estimated that a complete replacement of fossil fuel-based plastics with corn-based plastics would reduce global life-cycle GHG emissions of plastics to 5.6 $GtCO_2e$ by 2050 under the current energy mix and the projected EoL mix, which is 1.0 $GtCO_2e$ (or 15%) less than the baseline (Fig. 2a). If all EoL drop-in plastics are incinerated and all EoL biodegradable plastics are composted, global life-cycle GHG emissions of corn-based plastics would increase to 6.7 $GtCO_2e$. Recycling all EoL bio-based plastics, however, would reduce the emissions to 4.4 $GtCO_2e$. Sugarcane-based plastics can further reduce global life-cycle GHG emissions of plastics to 4.9 $GtCO_2e$, which is 1.7 $GtCO_2e$ (or 25%) less than the baseline, with a range between 5.8 $GtCO_2e$ (100% incineration/composting) and 4.0 $GtCO_2e$ (100% recycling). A 100% recycling scenario for fossil fuel-based plastics in our model results in similar, or even lower, emissions compared to bio-based plastics with the projected EoL mix (Fig. 2a,b, sidebars). This implies that the recycling of conventional plastics may be as beneficial as using renewable feedstock.

An energy decarbonization scenario shows substantial potential to reduce GHG emissions (Fig. 2b,d). On average, switching to 100% renewable energy would reduce life-cycle GHG emissions from plastics by 62% in 2050, assuming 4% yr^{-1} growth in demand. Even if fossil fuel sources (petroleum, natural gas and coal) serve as the sole feedstock for future plastics production, using 100% renewable energy can achieve 51% reduction (projected EoL mix) compared to the baseline, although the absolute total emissions would double the 2015 level by 2050. However, recycling all EoL plastics under 100% renewable energy allows 77%, 84% and 86% reductions in life-cycle GHG emissions from fossil fuel-, corn- and sugarcane-based plastics, respectively. This result shows that absolute reduction of emissions can only be achieved by combining aggressive deployment of renewable energy and extensive recycling of plastics.

Reducing plastics demand growth rate from 4% to 2% yr^{-1} reduces emissions by 56% (under the current energy mix) to 81%

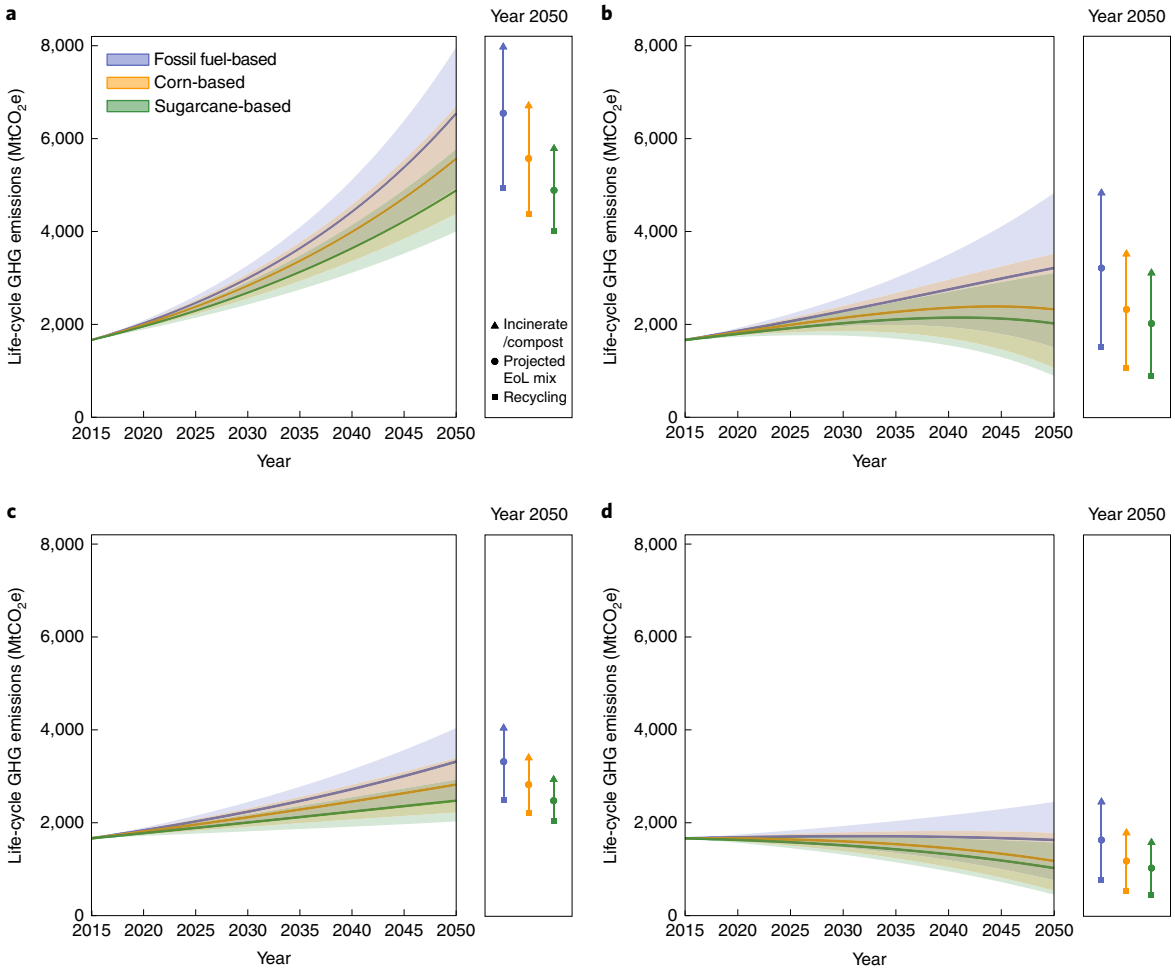

Fig. 2 | Global life-cycle GHG emissions of plastics under scenarios of different feedstock sources, energy mixes, EoL management strategies and growth in plastics demand for 2015–2050. a, Plastics demand grows at 4% yr^{-1} under the current energy mix. **b**, Plastics demand grows at 4% yr^{-1}, and the energy mix decarbonizes by 2050. **c**, Plastics demand grows at 2% yr^{-1} under the current energy mix. **d**, Plastics demand grows at 2% yr^{-1}, and the energy mix decarbonizes by 2050. Solid lines represent the projected EoL-management mix (Supplementary Table 10); whereas shaded areas represent ranges due to EoL options. The bars on the right side of each panel represent ranges due to different EoL options in 2050.

(under low-carbon energy) relative to the baseline in 2050 (Fig. 2c,d). Using 100% renewable energy keeps the emissions virtually constant at the 2015 level for fossil fuel-based plastics with projected EoL mix, and replacing them with bio-based ones brings the emission levels down further. Among all the scenarios tested, the global life-cycle GHG emissions of plastics were the lowest under the 100% sugarcane-based plastics with 100% renewable energy combined with 100% recycling and reduced demand growth, which achieved 0.5 $GtCO_2e\,yr^{-1}$, or 93% reduction from the baseline. This demonstrates that a drastic reduction in global life-cycle GHG emissions of plastics would be possible in a technical sense, but it would require implementing all of the four strategies examined at an unprecedented scale and pace.

Figure 3 shows the breakdown of GHG emissions by life-cycle stage, for each kilogram of plastics derived from different feedstock types. The total life cycle GHG emissions for fossil fuel-based, corn-based and sugarcane-based plastics are on average 4.1, 3.5 and 3.0 $kgCO_2e$ per kg plastic in 2050, respectively, under the current energy mix (Fig. 3a). Under a 100%-renewable-energy scenario, however, the average life-cycle emissions will be reduced to 2.0, 1.4 and 1.3 $kgCO_2e$ per kg plastic, respectively (Fig. 3b). Plastics derived from renewable feedstock (assuming projected EoL mix) generate lower GHG emissions over the whole life cycle compared to their fossil fuel-based counterparts regardless of the energy system used.

The resin-production and conversion stages are major contributors to the life-cycle GHG emissions of all feedstock types under the current energy mix (Fig. 3a). However, under the 100% renewable-energy scenario, incineration becomes the largest contributor to the total emissions for bio-based plastics (Fig. 3b). Under the 100%-renewable-energy scenario, recycling generates fewer carbon credits, as the low GHG emissions of renewable energy undercut the carbon benefits of avoiding virgin polymer production.

In summary, our results show that none of the four strategies—namely bio-based plastics, renewable energy, recycling and demand management—can achieve sufficient GHG mitigation for absolute reduction below the current level on their own; only when implemented in concert can these strategies achieve the much-needed absolute reduction. Among them, decarbonization of the energy system—which is an economically more favourable option for GHG mitigation compared to the use of bio-based plastics[18]—shows the greatest potential. Even if fossil fuel feedstock is used as the sole source for plastics production, a 100%-renewable-energy scenario will reduce the average life-cycle GHG emissions by half from the baseline emissions. If combined with extensive recycling or demand management, decarbonization of energy can maintain the current

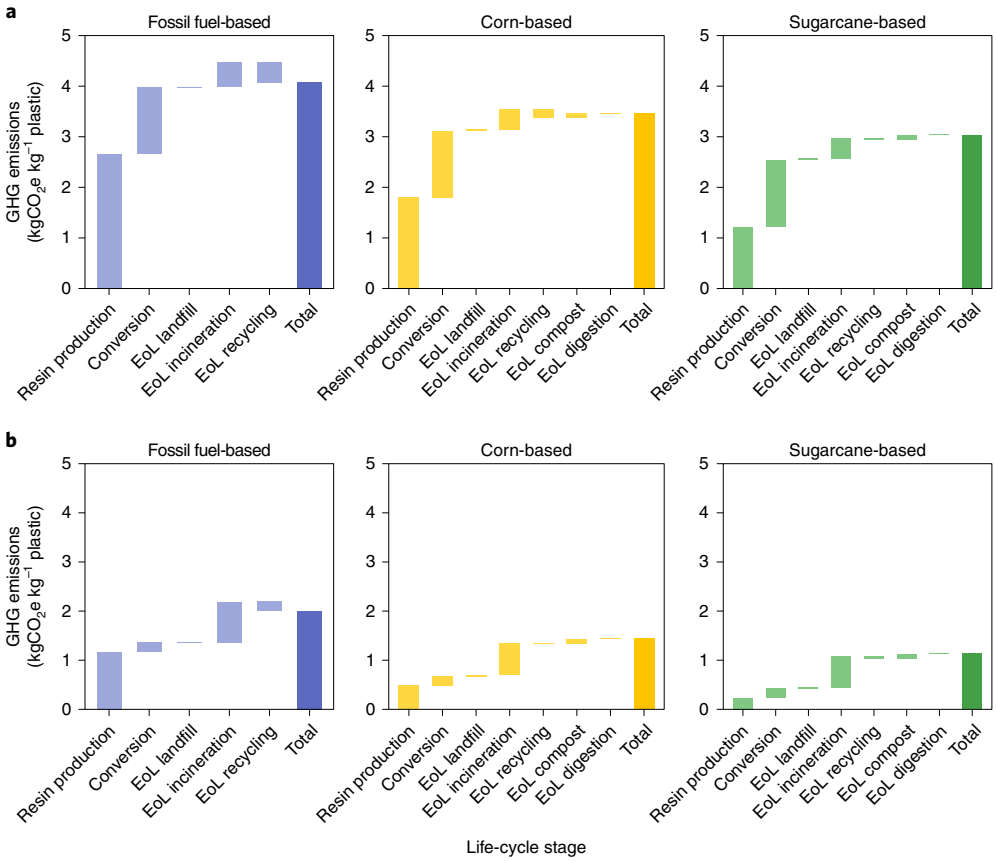

Fig. 3 | GHG-emissions breakdown by life-cycle stage of plastics derived from different feedstock types under two energy-mix scenarios in 2050. **a**, GHG emissions under the current energy-mix scenario in 2050. **b**, GHG emissions under a 100%-renewable-energy scenario in 2050. Emissions results are based on the scenario with a 4% yr^{-1} growth rate for plastics demand and the projected EoL-management mix (Supplementary Table 10). Carbon credits generated by recycling are considered.

level of GHG emissions until 2050. Reducing GHG emissions even further to achieve absolute reduction from the current level requires large-scale adoption of bio-based plastics in addition to implementing all of the other three strategies examined.

Going forward, we see both opportunities and challenges in reducing the life-cycle GHG emissions of plastics. The current global average plastics recycling rate of 18% (ref. [1]) certainly presents substantial room for further improvement. The low price of fossil fuel-based plastics, however, is a key barrier to dramatically increasing recycling rates. Together with technological innovations in plastics recycling, fiscal policies, such as carbon pricing and incentivising recycling infrastructure expansion, should be considered to overcome such barriers[23,24].

Replacing fossil fuel-based plastics with bio-based plastics is shown to play an important role in GHG mitigation. Nevertheless, our results show that the emissions of bio-based plastics are highly dependent on the EoL-management method chosen. Composting or incinerating bio-based plastic waste, for example, showed similar or even higher GHG emissions than the scenario in which 100% fossil fuel-based plastics were used under the projected EoL mix in 2050. Moreover, EoL management of bio-based—especially biodegradable—plastics requires systematic changes such as separate collection and recycling infrastructure, since inclusion of biodegradable plastics in the mix of conventional plastic waste can affect the quality of the recyclates[25]. Furthermore, composting of biodegradable plastics in home composting conditions or natural environments is much less effective than in industrial composting facilities[14]. Finally, the land-use implications of a large-scale shift to bio-based plastics require further research. In 2017, land use for bioplastics was reported to be 0.82 million hectares (or 0.016% of global land area), which would increase to 0.021% in 2022 under the projected market growth[17]. A complete shift of the plastics production of approximately 250 million tonnes to bio-based plastics would require as much as 5% of all arable land[26], which, depending on where they take place, may undermine the carbon benefits of bio-based plastics. The use of lignocellulosic or waste biomass as feedstock, and growing material crops in fallow lands, would alleviate the pressure of cropland expansion and associated GHG emissions from land-use change.

Our study shows that an aggressive implementation of multi-layered strategies would be needed in order to curb the GHG emissions from plastics. GHG-mitigation strategies are often implemented within energy, materials, waste-reduction and management policies in isolation. Our results indicate that absolute reduction in life-cycle GHG emissions of plastics requires a combination of the decarbonization of energy infrastructure, improvement of recycling capability, adoption of bio-based plastics and demand management.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-019-0459-z.

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Author contributions

J.Z. performed the research and analysed the data. S.S. conceived the idea and designed the study. Both authors wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Life-cycle GHG emissions of plastics were compiled for three feedstock types while considering the effects of energy-mix transformation, different EoL-management options and different growth rates of plastics demand. The base year was set as 2015, with GHG emissions modelled until 2050 under different scenarios. GHG emissions data were collected for three life-cycle stages: (1) the resin-production stage, which includes all activities from cradle to polymer-production factory gate; (2) the conversion stage, which covers the manufacturing processes that turn polymers into final plastic products; and (3) the EoL stage, which refers to the treatment and disposal processes of plastic waste. The use stage was excluded. To calculate the total GHG emissions for a certain year, the annual plastics production and waste generation volumes were multiplied with the life-cycle GHG emissions of each plastic type, as shown in Equation (1):

$$\mathrm{GHG}_{s,t} = \Sigma Q_{s,j,t} \times E_{s,i,j,k,t} \quad (1)$$

Where $Q_{s,j,t}$ represents the annual global production or amount of waste generation of plastic of type j, in year t, under scenario s, and $E_{s,i,j,k,t}$ represents the per-unit weight emissions of GHG i by plastics type j, at its life-cycle stage k, in year t, under scenario s. Index i indicates different GHG types such as CO_2, methane and nitrous oxide; j indicates different types of plastic including PP, L/LLDPE, HDPE, PET, polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PUR) and PP&A for fossil fuel-based plastics, and bio-PE, bio-PET, PLA, PHA and TPS for corn- or sugarcane-based plastics; k indicates the life-cycle stage of plastics from the resin-production and conversion stages, to EoL management; t indicates a year between 2015 and 2050, and s indicates scenarios of different combinations of feedstock, EoL options, energy mix and growth of plastics demand.

Life-cycle GHG emissions of fossil fuel-based plastics. For the resin-production stage of fossil fuel-based plastics, GHG emissions data are from the ecoinvent 3.4 database[27], the European Life Cycle Database[28] and literature sources. Detailed unit processes of resin production are listed by polymer type; emissions data of some polymer types with subtypes were calculated as weighted sums according to their market-share information (Supplementary Table 2). There is a large gap in life-cycle inventory data of plastics additives[29]. Hence, we chose diisononyl phthalate as a proxy for plastics additives, which is frequently used as an all-purpose plasticizer[30]. For the last group (Others), the average GHG emissions values of all plastic types were used.

After resin production, the polymers are transformed into various final products for specific applications. Injection moulding, blow moulding and extrusion are commonly used conversion technologies[31]. There are limited data on the conversion processes of plastic products in ecoinvent 3.4, and additional data were compiled from the literature: ref. [31] and ref. [32] served as the main data sources for this stage. The average GHG emissions from converting various plastic parts for a typical vehicle were taken from ref. [31], and we used the data for GHG emissions from general conversion processes. For the PS conversion process, data were drawn from ref. [33]. For the PUR conversion process, due to the scarcity of data, the average emissions from the PP and PE conversion processes was used. For PP&A fibres, data from ref. [34] was used and the emission values were weighted on the basis of the market share of polyester, polyamide and acrylic. Due to the complex supply chain of textile industry, we cut off at yarn production and exclude the subsequent conversion processes including fabric production and garment production. As the amount of additives added into different types of polymer varies, average emissions data were used for the conversion of all of the other types for Additives and Others.

For the landfill and incineration processes, we used the life-cycle GHG emissions data of mixed plastics from ecoinvent 3.4. For the landfilling process, given that fossil fuel-based plastics barely degrade, only a small amount of GHG emissions is produced during collection and transportation. Incineration of plastic waste generates 3.92 MJ of electricity and 7.66 MJ of heat per kg of plastic, according to ecoinvent 3.4, and these credits were used to calculate GHG emissions for incineration process.

The recycling process includes collection, transportation, sorting, separation and material recovery of the waste. The average emission value from the PET and HDPE recycling processes (906 $kgCO_2e$ per tonne polymer) was calculated and used[35]. To account for the GHG emissions credits from recycling EoL plastics, a substitution ratio of 80% is applied, meaning that 1 kg of recycled plastics avoid producing 0.8 kg of average market-mix plastics[20]. As the recycled content of average market-mix plastics changes over time under some scenarios, GHG credits from displacing them are calculated each year and subtracted from the GHG emissions generated from recycling.

The resulting GHG emissions data for fossil fuel-based plastics at different life-cycle stages can be found in Supplementary Table 3.

Life-cycle GHG emissions of bio-based plastics. The most readily available feedstock for a specific region can vary. For example, Thailand and Brazil have excellent conditions for growing sugarcane, the United States is predominantly growing corn, whereas Europe has good farmland for growing sugar beet[36]. In our study, corn and sugarcane were chosen. The emissions data for bio-PE, bio-PET, PLA, PHAs and TPS production derived from corn and sugarcane were collected separately, with the direct and indirect land-use change (LUC) emissions already included or calculated (see below). A system expansion method was used to handle co-products such as electricity, heat and digestate. The biological carbon sequestration credits were subtracted from corresponding life-cycle GHG emission values for bio-based plastics (for example 3.14 $kgCO_2e$ per kg bio-PE, 1.83 $kgCO_2e$ per kg PLA, 2.05 $kgCO_2e$ per kg polyhydroxybutyrate (PHB)[37] and 1.94 $kgCO_2e$ per kg TPS; ref. [38]).

Bio-PE and bio-PET are two major bio-based non-biodegradable plastics used today[17]. The production processes of bio-PE include corn or sugarcane cultivation and harvest, ethanol fermentation and distillation, and bio-ethylene production through dehydration and polymerization of bio-ethylene to polyethylene[18,39]. To produce bio-PET, instead of directly going through polymerization, bio-ethylene is oxidized to ethylene oxide and hydrolysed to ethylene glycol, which then is polymerized with purified terephthalic acid to obtain bio-PET polymers[40]. For corn-based PE and PET, we averaged bio-HDPE and bio-LDPE emissions data[18]. For sugarcane-based PE, after adding LUC emissions, the net emissions in 2015 under the baseline scenario ranged from −0.7 to 1.8 $kgCO_2e$ per kg bio-PE[40] and an average value was taken. We used the average value of emissions data taken from three geographical locations for bio-PET resin production[40].

PHB, the most common PHA polymer, was selected as a representative PHA type. A typical corn-based PLA/PHB polymer production process covers corn cultivation, corn wet milling, fermentation and polymerization/recovery, successively. The sugarcane-based production follows a similar process, but with sugarcane milling instead of corn milling. The production process for TPS involves corn cultivation, starch production and compounding. The emissions data for resin production for corn-based PLA/PHB and TPS are from ref. [37] and ref. [41], respectively. And the data for sugarcane-based PLA and PHB are from ref. [42] and ref. [43], respectively.

For corn-based plastics, LUC emissions data of 89 $kgCO_2e$ per tonne corn were used[37]. We used ref. [18] for the amounts of corn required for bio-PE, bio-PET, PLA, PHB and starch production. For sugarcane-based plastics, LUC emissions range between 0.16–2.38 $kgCO_2e$ per kg for bio-PE and 0.03–0.4 $kgCO_2e$ per kg for bio-PET[40]; we used an average value for each plastic type. For sugarcane-based PLA, 63.6 $kgCO_2e$ per tonne PLA was used for LUC emissions[44].

Regardless whether the feedstock is fossil fuels or plants, further conversion of ethylene to bio-PE or bio-PET polymers remains the same[40]. Therefore, the emission values for the bio-PE/PET conversion process are the same as fossil fuel-based ones. The manufacturing technologies for plastics conversion into final products do not differ much between biodegradable plastics and conventional plastics[37,45]. For example, PLA is usually processed by existing methods such as extrusion, thermoforming, injection moulding, blow moulding or cast film and sheet[45]. One slight difference is that before melt processing of PLA, the polymer must be dried sufficiently to prevent excessive hydrolysis, which can compromise the physical properties of the polymer[46]. However, no specific life-cycle inventory data could be found for biodegradable plastics processing so far. Therefore, we assumed that the emission values for biodegradable polymers conversion are the same as conventional polymers.

The EoL treatments of bio-PE and bio-PET are no different from their fossil fuel-based counterparts, given that they have identical properties and appearances. Therefore, they follow the same EoL mix of fossil fuel-based plastics including recycling, incineration and landfill. In comparison, EoL-management methods for biodegradable plastics can include recycling, incineration, landfill, industrial composting or anaerobic digestion. Credits were given for generation of electricity, heat and digestate during incineration and composting processes. The efficiency of waste plastics to substitute virgin polymers was assumed to be 80% for all recycling processes, except 74% for TPS, which undergoes higher quality loss during recycling[38]. Recycled contents were assumed to replace an average market-mix of plastics for that year with an 80% substitution rate, as explained earlier.

The resulting emission values for bio-based plastics at different life-cycle stages can be found in Supplementary Table 4.

Life-cycle GHG emissions under the low-carbon energy scenario. Building on the methodology in ref. [18], we explored the emissions under the low-carbon energy scenario (100% wind power for electricity and 100% biogas for heat). We performed a contribution analysis of the life-cycle emissions data wherever possible. By closely examining the references, the amount of electricity and heat used in the production, conversion and EoL-treatment processes were parsed out for different plastic types. We then recalculated the emissions from the electricity and heat from low-carbon energy sources in 2050, and assumed a linear increase of low-carbon energy in the energy mix from 2015 to 2050 to model a gradual energy decarbonization process. The GHG emissions of each plastic type in 2050 under the low-carbon energy scenario were calculated by Equation (2):

$$E_{\mathrm{lc2050},j,k} = E_{j,k} - (E_{\mathrm{elec}} + E_{\mathrm{heat}}) + (E_{\mathrm{elec_lc}} + E_{\mathrm{heat_lc}}) \quad (2)$$

Where $E_{\mathrm{lc2050},j,k}$ is the GHG emissions of plastic type j in its life-cycle stage k under the low-carbon energy scenario in 2050; $E_{j,k}$ is the GHG emissions of plastic type j in its life-cycle stage k under the current energy mix; E_{elec} and E_{heat} are the emissions produced from the generation of electricity and heat under the current energy mix,

respectively; E_{elec_lc} and E_{heat_lc} are the emissions from the generation of electricity and heat under the low-carbon energy scenario, respectively. All of the emissions values are based on one unit of weight (that is 1kg).

For fossil fuel-based plastics resin-production stage, the ratios between the emissions under a low-carbon energy scenario and that under conventional energy scenario in ref. [37] were applied. For the conversion stage, blow moulding, injection moulding and extrusion processes from ecoinvent 3.4 were selected as representative conversion processes to calculate the average contributions of electricity and heat to GHG emissions (81.3% and 9.5%, respectively). For the EoL stage, the electricity and heat generation credits from incineration were calculated using low-carbon energy emission values. In addition, we calculated the process emissions from recycling by using the energy profile of recycling depicted in ref. [35]. It was assumed that the diesel used for vehicles in waste collection in the recycling process is replaced with electricity from wind. Supplementary Table 5 lists the GHG emission data for energy sources used to calculate our results under the low-carbon energy scenario.

For corn-based bio-PE and bio-PET resin production, emissions data in the low-carbon scenario were from ref. [18]. For corn-based PLA and PHA resin production, the low-carbon emissions data from ref. [22] were used, and the LUC emission data from ref. [12] were applied. For TPS production, the maize starch production process in ecoinvent 3.4 was used as a proxy process, and the contributions of electricity and heat to the GHG emission were 24% and 17%, respectively. For sugarcane-based bio-PE, 3.09 kWh electricity and 10.5 MJ diesel were used for per kilogram of bio-LDPE produced[39], and they served as representative data for bio-PE and bio-PET due to unavailability of detailed energy use data for bio-HDPE/PET production. For sugarcane-based PLA, the emissions from electricity and steam were 600 kg and 675 kgCO_2e per tonne polymer, respectively[42]. For sugarcane-based PHB, the electricity and steam production were 1.1 kWh and 14.8 MJ per kg polymer, respectively[43].

Bio-PE and bio-PET were assumed to produce the same amount of GHG emissions as their fossil fuel-based counterparts during EoL stage. As for biodegradable plastics, GHG emissions were assumed to stay unchanged for landfilling process; for incineration, industrial composting and anaerobic digestion, electricity and heat generation data from ref. [47] were used.

The GHG emissions values for fossil fuel-based plastics and bio-based plastics under the low-carbon energy scenario can be found in Supplementary Tables 6 and 7, respectively.

Plastics demands. Beginning with the amount of plastics produced in 2015[1], two scenarios were evaluated up to 2050, assuming annual resin-production growth rates of 4% (an average annual growth rate of 2010–2015) and 2% (a slower growth trend of plastics production). For a 100%-fossil fuel-based plastics scenario, the market share of each plastic type was assumed to remain unchanged. For a corn- and sugarcane-based plastics scenario, the market share of bio-based plastics was assumed to linearly grow from zero in 2015 to 100% in 2050, given that the global market share of bio-based plastics in 2017 was less than one percent[17]. It was also assumed that bio-based plastics substitute for conventional plastics on a 1:1 scale by weight.

Substitution assumptions. Today, there is a bio-based plastic alternative for almost every conventional plastic and its corresponding application[17]. A report regarding the technical substitution potential of bio-based polymers concludes that 90% of the conventional polymers can be replaced worldwide[48]. Considering biopolymer technology advancement, it is assumed that all fossil fuel-based plastics can be replaced with bio-based plastics scenarios by 2050.

In 2017, bio-based non-biodegradable plastics accounted for 56% of the global bioplastics market. These so-called drop-in solutions have the same properties, conversion processes and disposal methods as their fossil fuel-based counterparts and therefore serve as perfect substitutes. Bio-PEs were assumed to replace the majority of fossil fuel-based PEs, PVCs and PURs, while bio-PETs look to replace PETs and PP&A fibres. Other types of bio-based, non-biodegradable plastics were not considered in this study as they are not yet available at a commercial scale, or there is a lack of data in the literature.

Bio-based biodegradable plastics make up the remaining 44% of the bioplastics market, with PLAs and PHAs driving the growth[17]. PLA is the most versatile biodegradable plastic type and has wide applications across food packaging, medical devices and agriculture films, among others[49–51]. It has comparable mechanical and thermal properties to PS and PET, and can also replace PE, PP and PVC in some applications[37]. The use of PLA to replace nylon and PET in the textile industry is also increasing[45]. PHAs have been used in fibres, non-woven materials, disposable products[52] and cosmetic and food containers[51]. Commercialized PHAs can frequently replace PE, PP and PS, and may also substitute for PET and PVC[37]. The high price of PHAs is a major barrier to its large-scale commercialization[52]. TPS is used in specialized agricultural applications, as filler in plastic composites, or in single-use items such as bags, containers, diapers and tampons[51,53]. Pure TPS has poor mechanical properties and is susceptible to water, which limits its potential product applications[54]. However, it is a common practice to blend starch with other polymers such as PLA, PCL, and PHAs to obtain composites to improve its properties[50].

On the basis of the technical substitution potential, comparable properties, common application areas and the market growth reviewed above, a substitution plan was developed for bio-based plastics to replace conventional plastics (see Supplementary Table 9).

EoL management. The projected EoL-management mix change of all plastic types (fossil fuel-based and bio-based) between 2015 and 2050 is shown in Supplementary Table 10. The mix in 2050 is determined on the basis of the projections of future EoL change[1], as well as the historical changes of plastic waste EoL management in Europe and the United States. A linear rate of change for each EoL method was assumed between 2015 and 2050.

Limitations. There are uncertainties and limitations associated with the data and the model used in this study. We made various assumptions to simplify the processes involved in a plastic's life cycle. For example, we assumed that the indirect LUC, and the GHG emissions from agricultural expansion for bio-based plastics, would remain at the current level. We also extracted and combined emissions data from multiple sources. Conventional plastics data are from ecoinvent 3.4, which were originally eco-profiles of the European plastics industry (PlasticsEurope). The dataset contains outdated numbers and uses extrapolation for the regions other than Europe. Therefore, the temporal and geographical representation of the data was identified as a weakness, but no better data sources were identified. The methods used to calculate LUC emissions associated with bio-based plastics production vary in the literature and warrant further research.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The authors declare that the main data supporting the findings of this study are available within the Letter and Supplementary Information. Additional data are available from the corresponding author on reasonable request.

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Reporting Summary

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection.
Data analysis	We used Microsoft Excel 2016 for data analysis, and we used Python 2.7.13 (matplotlib) and R 3.4.1 (ggplot) to visualize the research results.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Ecological, evolutionary & environmental sciences study design

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Study description	We aimed at quantifying the global carbon footprint of plastics by combining the global production and waste generation amounts data of plastics with the life cycle greenhouse gas emission data collected from various sources. We performed scenario analysis to evaluate different mitigation strategies, i.e., replacing conventional plastics with bio-based ones, use of low carbon energy, recycling, and slower plastics demand growth. Our results show only by combining these strategies can we achieve absolute reduction of global life cycle GHG emissions of plastics from current level.
Research sample	NA
Sampling strategy	NA
Data collection	NA
Timing and spatial scale	NA
Data exclusions	NA
Reproducibility	NA
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

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☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging