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Reducing greenhouse gas emissions from polymer processing at end-of-use

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KEYWORDS: Climate change mitigation, polymer, plastic, end-of-use, recycling, landfilling, incineration.

HIGHLIGHTS:

- Polymers account for ~3.5% of the global greenhouse gas (GHG) emissions
- End-of-use treatment of waste is responsible for 13% of the lifecycle emissions
- Incinerating waste polymer would substantially increase lifecycle GHG emissions
- Prioritising recycling and landfilling would reduce lifecycle GHG emissions by 30%
- Recycling and landfilling remain effective with production decarbonization

ABSTRACT: The whole lifecycle of polymers accounts for ~3.5% of global greenhouse gas emissions; however, the way we treat polymer waste can have a large impact on these total emissions. While decarbonisation efforts target polymer production and manufacture, the strategic selection of end-of-use management pathways remains insufficiently explored. Here, we evaluate global end-of-use options for polymers by quantifying their associated greenhouse gas emissions. Under a business-as-usual scenario, polymer-related emissions are projected to reach 3.55 $GtCO_2e$ annually by 2100. Our findings reveal that enhancing recycling and landfilling could substantially reduce emissions by 30%, while mismanagement practices such as open burning and dumping exacerbate environmental pollution and must be avoided. Notably, incineration with energy recovery results in 39% higher emissions compared to the business-as-usual scenario. It should be excluded from polymer treatment strategies because credits for electricity generation become

negligible with decarbonisation efforts. The study provides critical insights to inform policies on sustainable end-of-use polymer management and mitigate the sector's environmental impact.

1. Introduction

The wide use of polymers such as plastics, fibres, and rubbers benefits society but also generates approximately 320 million tonnes (Mt) of polymer waste annually in 2019 (Gao and Cabrera Serrenho, 2025). Such scale and pace of waste generation leads to significant environmental impacts, particularly greenhouse gas (GHG) emissions and ecosystem contamination (Meng et al., 2024; United Nations Environment Programme, 2024; Vidal et al., 2024). End-of-use (EoU) polymers are currently mechanically recycled (7% by mass), chemically recycled (~0% by mass), landfilled (47% by mass), incinerated (18% by mass), or mismanaged (28% by mass), each leading to different environmental impacts.

Previous efforts have assessed the lifecycle GHG emissions of polymers by using material flow analysis or input-output approaches, which may be combined with stock models to estimate EoU flows and emissions factors for each lifecycle stage. The complexity of the global plastics supply chain, data limitations and policy attention increase the challenge of such approaches, with data availability for EoU being particularly sparse, especially in developing countries (Kaza et al., 2018). Previous research, therefore, provides limited detail of the impact of EoU strategies on the full lifecycle emissions of polymers and on their regional variations (Basuhi et al., 2021; Elgarahy et al., 2023; Gracida-Alvarez et al., 2023). Zheng and Suh estimated GHG emissions from waste polymer incineration and mechanical recycling globally but did not evaluate landfilling and chemical recycling (Zheng and Suh, 2019). Similarly, Chen et al. focused on GHG mitigation from

waste polymers in China without addressing chemical recycling (Chen et al., 2019), and the potential impacts of incineration, landfilling and chemical recycling were not quantified in Pottinger et al.'s study (Pottinger et al., 2024). Although current EoU options contribute to only 9% of the total lifecycle GHG emissions (Zheng and Suh, 2019), their potential impact on other lifecycle stages could be far more significant. For example, mechanically recycling polymer waste could avoid the GHG emissions associated with virgin polymer production, which currently accounts for 56% of total emissions; conversely, incinerating polymer waste results in the release of a considerable amount of additional carbon dioxide, despite being widely used to reduce the volume of polymer waste and to recover energy (Kwon et al., 2023).

Three more recent analyses have considered plastic EoU treatment at a global scale, but none provide a comprehensive assessment of GHG emissions associated with future plastic EoU. (Houssini et al., 2025) modelled global plastics trade flow, including waste generation and treatment approaches for 2022, but did not model future flows, nor consider emissions associated with EoU treatment. (Huo et al., 2025), meanwhile, modelled future transition pathways for the global plastic industry, including the potential emissions associated with waste incineration and recycling, but did not consider landfill in the analysis due to the risks of leaching micro- and nanoplastics, as well as harmful monomers, additives, and other chemicals. The data to understand such risks is limited, however, and future work may be needed to consider whether such risks could be justified. The potential to limit demand for polymer products and to increase recycling of polymer waste was found to be limited in a recent global-level analysis (Gao and Cabrera Serrenho, 2025), but a global assessment of the future GHG impacts of other EoU options alongside recycling remains largely unexplored. Click or tap here to enter text.

Here we present a comprehensive global assessment of GHG emissions from the full lifecycle of polymers covering all available EoU options using a dynamic material flow analysis model that forecasts polymer demand and waste generation in eight world regions during 2020-2100 (Gao and Cabrera Serrenho, 2025). We then evaluate how global GHG emissions might evolve in the future using different EoU treatment methods by 2100. Regional results and key input variables are presented in the Supplementary Materials (SM).

2. Method

Evaluating the impacts of various EoU options on the global lifecycle GHG emissions of polymers requires reconciling data on the production, consumption, EoU options of polymers and emission factors at different lifecycle stages.

2.1 The mass flow of polymer waste

The estimation and projection of polymer waste from 2010 to 2100 are obtained from our previous mass flow analysis on the global mass flow of polymers (Gao and Cabrera Serrenho, 2025). The model includes the production, consumption and waste generation of 14 polymer groups across eight regions and eight end-use applications. More details can be found in Ref (Gao and Cabrera Serrenho, 2025) and the SM.

Polymer waste trade between regions from 2010 to 2020 is estimated using the Comtrade database (codes 39.15 and 40.04). The amount of polymer waste p processed domestically in region r and year y, $WasteProcessed_{p,r,y,}$ is estimated using Eq. (1). From 2021 onward, polymer waste trade was neglected due to China's 2018 ban on polymer waste imports, which significantly reduced global trade volumes (Wen et al., 2021). As shown in Fig. S2, the ratios between regional import or export and regional waste generation have remained below 3% since 2018.

$$WasteProcessed_{p,r,y} = WasteGen_{p,r,y} + WasteImport_{p,r,y} - WasteExport_{p,r,y} \quad (1)$$

where p stands for the type of polymer, r represents the region, and y is the year of waste generation, $WasteGen_{p,r,y}$ is waste generation of polymer p in region r and year y, $WasteImport_{p,r,y}$ is imported polymer p by region r in year y, $WasteExport_{p,r,y}$ is the amount of exported polymer p by region r in year y.

2.2 The fractions of EoU options

Polymer waste at the EoU today is treated through incineration (with or without electricity recovery), recycling, landfilling, or mismanagement (Pottinger et al., 2024). For this analysis, a business-as-usual (BAU) scenario is chosen to represent a current baseline for all other scenarios; unless otherwise specified, all parameters are set to their BAU values. In the BAU scenario, the mechanical recycling rates of polymers and the fractions of not-recycled waste from 2025 to 2100 are assumed to be equal to the fractions in 2024. The other scenarios are chosen to represent distinct policy proposals, respecting the challenges of increasing recycled fractions. S1-LAND, S2-INCN and S3-INER assume no change to the 2024 mechanical recycling rate but prioritise landfill, incineration with some electricity recovery and incineration with full electricity recovery, respectively, for the residual waste. S4-MECH and S5-CHEM represent the maximum potential for mechanical and chemical recycling against BAU, while S6-RELA is chosen to demonstrate a lowest possible emissions case for plastics EoU.

The amount of mechanically recycled polymers from 2010 to 2024 is extracted from the Independent Commodity Intelligence Service (ICIS) database (Gao and Cabrera Serrenho, 2025). The remaining EoU polymers are treated by incineration, landfilling and mismanagement, whose fractions from 2010 to 2024 are extracted from OECD (OECD, 2022). The fractions of incineration

with and without electricity recovery are estimated from European data (Stegmann et al., 2022a). Among mismanaged EoU polymer waste, 30% is assumed to be burnt, and 70% is randomly dumped (Stegmann et al., 2022a). The assumed fractions of EoU option in different scenarios from 2025 to 2100 are shown in Table 1 and justifications for these values are given in the remainder of this section.

Table 1. Fractions of end-of-use options for all scenarios used in this analysis

EoU options / Scenarios	Recycling	Mismanagement	Incineration with electricity recovery	Incineration without electricity recovery	Landfilling
BAU	Mechanical recycling rate as of 2024.	As of the regional values in 2024.			
Landfilling (S1-LAND)	Mechanical recycling rate as of 2024.	Decrease to 2% of not-recycled waste by 2034, and be constant thereafter.	Decrease to 0% by 2034	Decrease to 0% by 2034	Increase to 98% of not-recycled waste by 2034.
Current mix incineration (S2-INCN)	Mechanical recycling rate as of 2024.	Decrease to 2% of not-recycled waste by 2034, and is constant thereafter.	Increase to 59/95*98%(Stegmann et al., 2022a) of not-recycled waste by 2034.	Increase to 36/95*98%(Stegmann et al., 2022a) of not-recycled waste by 2034.	Decrease to 0% by 2034.
100% electricity recovery incineration(S3-INER)	Mechanical recycling rate as of 2024.	Decrease to 2% of not-recycled waste by 2034, and be constant thereafter.	Increase to 98% of not-recycled waste by 2034.	Decrease to 0% by 2034.	Decrease to 0% by 2034.
Mechanical recycling (S4-MECH)	Increase to highest realistic mechanical recycling rate by 2034.	Used for not-recycled waste. The ratio of mismanagement/Incineration with and without energy recovery/landfilling is kept constant as of BAU.			
Chemical recycling (S5-CHEM)	Increase to highest realistic mechanical recycling rate by 2034. Fully apply mature chemical recycling to PET, polyester fibre, PU, PS and polyamide by 2050.	The ratio of mismanagement/Incineration with and without energy recovery/landfilling is kept constant as of BAU (as of 2024).			
Recycling + Landfilling (S6-RELA)	As the chemical recycling scenario.	Decrease to 2% of not-recycled waste by 2034 and is constant thereafter.	Decrease to 0% by 2034.	Decrease to 0% by 2034.	Increase to 98% of not-recycled waste by 2034.

In the landfilling scenario (S1-LAND), the mechanical recycling rate is assumed to be as constant as 2024. The fractions of incineration with and without electricity recovery are assumed to drop to 0% by 2034, and the fraction of mismanagement among not-recycled polymer waste is assumed to drop to 2% by 2034 since it is difficult to fully eliminate mismanaged polymer waste (Stegmann et al., 2022b). Thus, the fraction of landfilling among not-recycled polymer waste is assumed to linearly increase from the current value in 2024 to 98% by 2034 in each region.

In the current mix incineration scenario (S2-INCN), the ratio between incineration with and without electricity recovery remains constant. The landfilling fraction will drop to 0% by 2034, and the mismanagement fraction will decrease to 2% by 2034. Incineration fraction for non-recycled waste will increase to 98% by 2034. The 100% electricity recovery incineration scenario (S3-INER) assumes all incineration includes electricity recovery by 2034.

In the enhanced mechanical recycling scenario (S4-MECH), the mechanical recycling rates for thermoplastics in each end-use application are assumed to increase linearly from the current values in 2024 to the highest realistic values by 2034 and to be kept constant thereafter as in our previous study (Gao and Cabrera Serrenho, 2025). The non-recycled waste is assumed to be processed by incineration, landfilling and mismanagement, whose fractions are assumed equal to the fractions in 2024.

The chemical recycling scenario (S5-CHEM) is built on the mechanical recycling scenario, the chemical recycling rate of polymer products made by recycled PET, polyester fibre, PS, PU and polyamide is assumed to increase from the current negligible 0 in 2035 to the highest potential by 2050 and to be kept constant thereafter as our previous study (Gao and Cabrera Serrenho, 2025).

Similarly, the fractions of incineration, landfilling and mismanagement of not-recycled waste are assumed to be equal to the fractions in 2024.

To further reduce the lifecycle GHG emissions, the recycling + landfilling scenario (S6-RELA) is devised, which adopts the amounts of mechanical recycling and chemical recycling in the chemical recycling scenario. The fractions of incineration with and without electricity recovery are assumed to drop to 0% by 2034, and the fraction of mismanagement among not-recycled polymer waste is assumed to drop to 2% by 2034. Thus, the fraction of landfilling among not-recycled polymer waste is assumed to linearly increase from the current value in 2024 to 98% by 2034 in each region.

2.3 The emission factors of polymer production, manufacture and EoU options

The GHG emission factors of polymer production and manufacture are extracted from (Zheng and Suh, 2019), and their uncertainties are estimated using a pedigree matrix as shown in Table S4 in the SM. The use phase emissions, e.g. textile washing, are out of the scope of the study, and are expected to be a minor contribution to overall lifecycle emissions.

In the decarbonised production and manufacture scenarios, the production and manufacture of polymers are assumed to be fully decarbonised by 2050, by applying renewable electricity (Zheng and Suh, 2019). The emission factors of polymer production and manufacture are linearly interpolated from 2024 to 2050 in the decarbonised scenarios.

The landfilling emission factors of waste polymers are extracted from the ecoinvent database (Ecoinvent, 2021). The emission factors of incineration without electricity recovery are calculated based on stoichiometric reactions, while those for incineration with energy recovery in 2019 consider the global average electricity carbon footprint, combustion heat, and energy manufacture

yield, as shown in the SM. Future incineration with energy recovery emission factors for 2050 are based on projected global average electricity carbon footprints in the IEA's sustainable development scenario (International Energy Agency, 2018).

The emission factors of burnt polymer waste among mismanagement are equal to the emission factors of incineration without electricity recovery. This is likely to be an underestimate as incomplete combustion (producing methane) is more likely (Guendehou et al., 2006) but is assumed to provide a reasonable approximation in the context of this analysis. The emission factors of dumped polymer waste, meanwhile, are assumed negligible because polymer waste degrades very slowly in the absence of corrosive substances. Polymer degradation to gaseous forms in a dump site could take 100s to 1000s of years. While these simplifications may underrepresent emissions form mismanaged plastic waste, they are sufficient for this analysis, which is primarily focused on the treatment of managed waste.

The emission factors of mechanical recycling of polyethylene terephthalate (PET), polypropylene (PP), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) and their uncertainties are extracted from (Uekert et al., 2023a). The mechanical recycling emission factors of other recyclable polymers are estimated using the averaged emission factors of previous staple polymers. The mechanical recycling of such polymers can be further decarbonised by using renewable electricity, and corresponding emission factors have been estimated by (Uekert et al., 2023a). The mechanical recycling emission factors are assumed to be linearly reduced from the current values in 2024 to reduced values in 2050.

Only five staple polymers can be chemically depolymerised to their corresponding monomers and recycled with mature technologies, namely polystyrene (PS), PET, polyester fibre, PU, and

polyamide. The chemical recycling of PET and polyester fibre is assumed to be implemented by glycolysis, and the average chemical recycling emission factor and its standard deviation are calculated based on (Uekert et al., 2023a). The decarbonisation of chemical recycling of PET by glycolysis is estimated by assuming renewable electricity, and the standard deviation to the decarbonised averaged chemical recycling emission factor of PET ratio is assumed to be equal to the ratio of their non-decarbonised counterparts. The chemical recycling of PS is assumed to be implemented by pyrolysis for the recovery of styrene and repolymerisation. The chemical recycling emission factor of styrene at the lab scale is 37% lower than the production of styrene, with the potential to be 50% lower by upscaling (INEOS Styrolution, 2021). Thus, the current and future chemical recycling emission factors of PS are assumed to be 63% and 50% of the current production emission factor of PS in Europe, respectively. The chemical recycling of polyamide is represented by nylon 6, and its chemical recycling emission factor has been reported by (Aquafil Econyl, 2013). The potential decarbonised chemical recycling emission factor of polyamide is estimated by replacing the fossil-fuel based electricity in the inventory with wind power. All the chemical recycling emission factors are linearly interpolated from the current values in 2024 to decarbonised values in 2050 and are assumed to be constant thereafter.

The emission factors and their uncertainties are all presented in the SM.

2.4 Greenhouse gas emissions

Lifecycle GHG emissions include the production, manufacture and EoU treatment of polymers in each region, as shown in Eq. (2).

$$\mathrm{GHGEM_y} = \sum_{p,r} Production_{p,r,y} \times EFPro_{p,r,y} + \sum_{p,r} Manufacture_{p,r,y} \times EFMan_{p,r,y} + \sum_{p,r,t} EoU_{p,r,y,t} \times EFEoU_{p,r,y,t} \quad (2)$$

where, $GHGEM_y$ is the global GHG emissions from the whole lifecycle of polymers in year y, $Production_{p,r,y}$ is the amount of production and $EFPro_{p,r,y}$ is the production emission factor of polymer p in region r and year y, $Manufacture_{p,r,y}$ is the amount of manufacture and $EFMan,p,r,y$ is the manufacture emission factor of polymer p in region r and year y, $EoU_{p,r,y,t}$ is the amount of EoU treatment and $EFEoU_{p,r,y,t}$ is the EoU treatment emission factor of polymer p by treatment option t in region r and year y. The amount of manufacture of polymer p in a region is assumed to be equal to its consumption in the region.

2.5 Uncertainty analysis

We employ a Monte Carlo approach to estimate the uncertainty of the global GHG emissions from the lifecycle of polymers. The uncertainties from three sources are quantified: polymer waste generation, the fractions of EoU options, and emission factors. After 5000 parameter sets, we calculate GHG emissions to determine the 95% confidence interval.

Polymer waste generation is extracted from our previous study (Gao and Cabrera Serrenho, 2025), and its uncertainties arising from population growth uncertainty, GDP growth uncertainty and stock per capita forecast, are quantified using the same procedure.

The fractions of not-recycled polymer waste treatment options, namely, incineration, landfilling and mismanagement from 2011 to 2024 are extracted from the OECD report (OECD, 2022), and their uncertainties are estimated using the pedigree matrix, as shown in the SM. Randomly

generated fractions are normalised for incineration, landfilling, and mismanagement, as well as for incineration with and without electricity generation.

The distributions of polymer production and manufacture emission factors are estimated using the pedigree matrix as shown in the SM. Current mechanical and chemical recycling emission factor uncertainties are taken from (Uekert et al., 2023a) with future decarbonised ratios assumed based on current data.

The uncertainties of incineration with energy recovery emission factors are estimated considering the lower and upper bound of energy manufacture yield. The calculated lower and upper bounds of emission factors are treated as the corresponding bounds of 95% confidence intervals and used to fit the generalised extreme value distribution parameters. The uncertainties of landfilling emission factors and incineration without energy recovery emission factors are neglected due to their low contribution to the life cycle GHG emissions or their low uncertainty.

3. Results

We estimate the global lifecycle GHG emissions from polymers by reconciling the historical and projected production, consumption and EoU options of polymers and regional emission factors. This provides the basis for quantifying the potential impact of various EoU options on the total GHG emissions.

3.1 Current greenhouse gas emissions from the life cycle of polymers

GHGs are released from the production, use and EoU stages of polymers, which were 1.72 million tonnes CO_2 equivalent ($MtCO_{2e}$) per year in 2019, as shown in Fig. 1. Currently, Northeast Asia has the highest regional GHG emissions from polymers at 615 $MtCO_{2e}$ per year, followed by

Western and Central Europe, North America, and South Asia. Across all regions, production and manufacture are the primary sources of GHG emissions, while EoU treatment contributes between 7% and 18% of lifecycle GHG emissions, with a global average of 13%. This is consistent with Zheng and Suh's estimates (Zheng and Suh, 2019). However, the EoU options have a much larger potential impact on total emissions by affecting production emissions or converting EoU polymers to carbon sinks or emissions sources. Thus, it is essential to explore the impact of different EoU options on future GHG emissions.

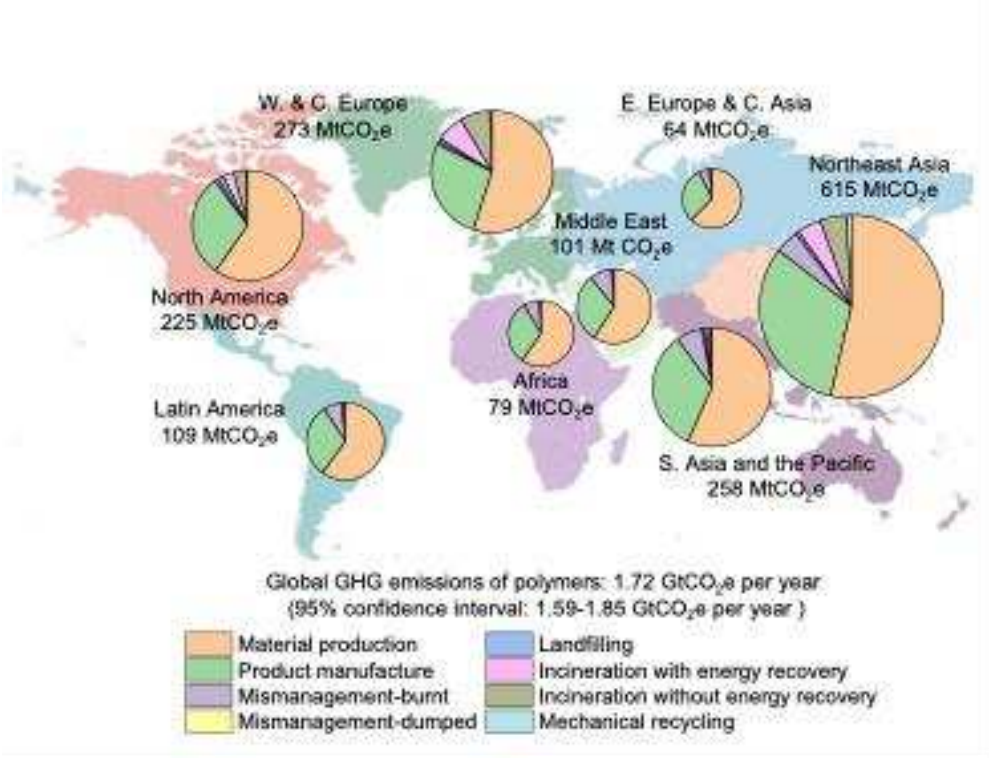


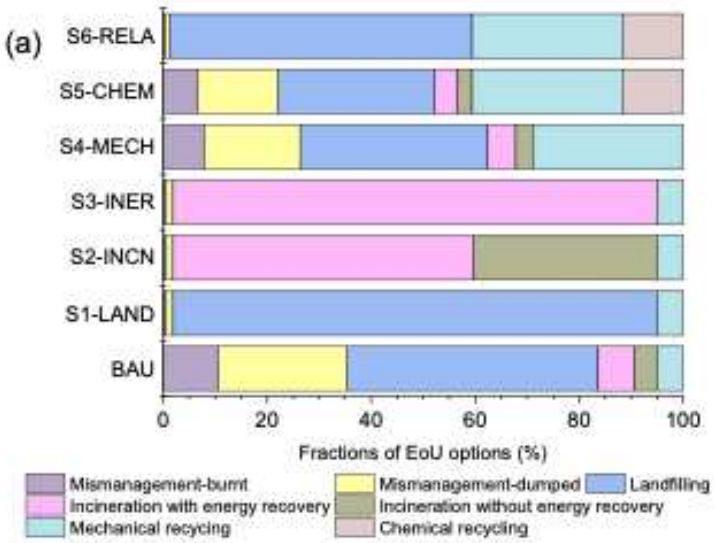
Fig. 1. GHG emissions from lifecycle stages of plastics, fibres and rubbers in 2019 across eight world regions**.** E. Europe & C. Asia stands for Eastern Europe and Central Asia, and W. and C. Europe represents Western and Central Europe. Material production stands for the GHG emissions from the production of polymer pellets, and product manufacture refers to the GHG emissions from the conversion of polymer pellets to final polymer products.

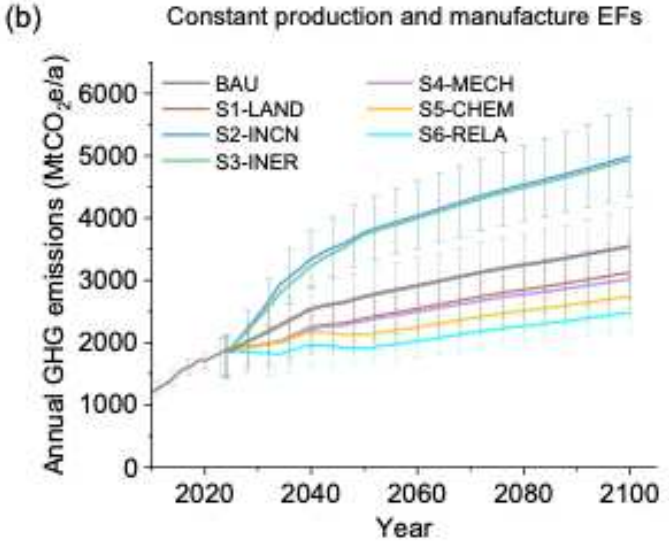
3.2 Polymer greenhouse gas emission mitigation options

The global demand for polymers is projected to rise from 399 Mt per year in 2019 to 821 Mt per year in 2100 using our high-resolution dynamic material flow analysis model (Gao and Cabrera Serrenho, 2025). Consequently, lifecycle GHG emissions are expected to increase from 1.72 $GtCO_2e$ per year (95% confidence interval: 1.59 – 1.85 $GtCO_2e$ per year) in 2019 to 3.55 $GtCO_2e$ per year (95% confidence interval: 3.06 – 4.16 $GtCO_2e$ per year) in 2100, as shown in Fig. 2b. This projection assumes that the fractions of EoU options remain constant as of 2024 and that polymer production and manufacture are not decarbonised in a business-as-usual (BAU) scenario.

The selection of EoU options for polymers affects the lifecycle emissions in different ways. Mechanical recycling and chemical recycling can generate polymers with lower carbon footprints than virgin polymers and reduce the demand for raw materials. Landfilling EoU polymers results in a small amount of emissions, only 0.1 $kgCO_{2e}$/kg landfilled waste (Ecoinvent, 2021), and it sequesters the carbon in waste polymers underground. In contrast, incinerating EoU polymers converts solid carbon to unwanted gaseous CO_2 emissions released to the atmosphere at a rate of about 3.14 $kgCO_2$/kg incinerated polypropylene. Mismanagement of EoU polymers involves either dumping or open burning of waste polymers in the environment (Stegmann et al., 2022a). This results in environmental pollution, and in the case of open burning, generates additional CO_2 emissions without any energy recovery.

To provide guidance about which EoU option is the best for reducing global GHG emissions, we develop six scenarios by modelling various EoU treatment fractions between 2024 and 2100. Fig. 2a shows the breakdown of EoU treatment options in each scenario, which remain constant from 2050 to 2100. Full details of each scenario can be found in the Methods and SM.


(a)
S6-RELA
S5-CHEM
S4-MECH
S3-INER
S2-INCN
S1-LAND
BAU
0
20
40
60
80
100
Fractions of EoU options (%)
Mismanagement-burnt
Incineration with energy recovery
Mechanical recycling
Mismanagement-dumped
Incineration without energy recovery
Chemical recycling
Landfilling


(b)
Constant production and manufacture EFs
Annual GHG emissions (MtCO2e/a)
BAU
S1-LAND
S2-INCN
S3-INER
S4-MECH
S5-CHEM
S6-RELA
0
1000
2000
3000
4000
5000
6000
2020
2040
2060
2080
2100
Year

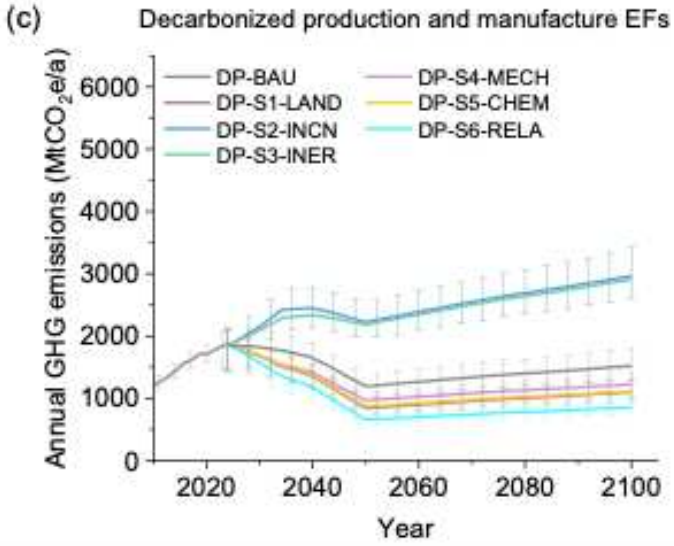

(c)
Decarbonized production and manufacture EFs
Annual GHG emissions (MtCO2e/a)
DP-BAU
DP-S1-LAND
DP-S2-INCN
DP-S3-INER
DP-S4-MECH
DP-S5-CHEM
DP-S6-RELA
0
1000
2000
3000
4000
5000
6000
2020
2040
2060
2080
2100
Year

Fig. 2. The global GHG emissions from plastics, fibres, and rubbers in various scenarios. (a) Fractions of EoU options in 2100 and each scenario. The GHG emissions in scenarios with (b) constant production and manufacture emission factors; and (c) decarbonised production and manufacture emission factors. DP in the legend is the abbreviation of decarbonised production and manufacture of polymers. The error bars represent 95% confidence intervals simulated with 5000 Monte Carlo simulations. S1-LAND = landfilling scenario, S2-INCN = incineration with and without energy recovery scenario, S3-INER = 100% electricity recovery incineration, S4-MECH = mechanical recycling scenario, S5-CHEM = chemical recycling scenario, S6-RELA = recycling + landfilling scenario. Further details can be found in Table 1.

Fig. 2b shows that the landfilling scenario (S1-LAND) can reduce lifecycle GHG emissions by 12% compared to the business-as-usual scenario, reaching 3.13 $GtCO_{2e}$ per year in 2100. In this scenario, the waste polymer is stored in the ground and serves as a carbon sink.

In the 100% electricity recovery incineration (S3-INER) scenario, GHG emissions will rise to 4.93 $GtCO_{2e}$ per year by 2100, as shown in Fig. 2b. If the ratio of incineration with and without energy recovery remains constant (S2-INCN), GHG emissions will be similar due to marginal credits from electricity generation (Cozzi et al., 2020).

Mechanical recycling (S4-MECH), if applied at its maximum potential (Gao and Cabrera Serrenho, 2025), can reduce emissions to 3.02 $GtCO_{2e}$ per year (95% confidence interval: 2.54-3.48 $GtCO_2e$ per year) while adding chemical recycling technologies(Gao and Cabrera Serrenho, 2025) (S5-CHEM) can further reduce emissions to 2.74 $GtCO_{2e}$ per year (95% confidence interval: 2.42-3.25 Gt CO_2e per year).

Given that landfilling, mechanical recycling and chemical recycling all reduce lifecycle GHG emissions, it is important to explore the potential synergy between landfilling and recycling in the Recycling + Landfilling scenario (S6-RELA). Since recycling can reduce the production of virgin polymers and increase resource efficiency, it is prioritised over landfilling. The combined recycling and landfilling scenario (S6-RELA) assumes that maximum mechanical recycling and chemical recycling are implemented as the chemical recycling scenario and 98% of not-recycled waste is landfilled without incinerating the remaining mismanaged 2%. These interventions could result in only 2.48 $GtCO_{2e}$ per year by 2100, 30% less than the BAU scenario.

With decarbonised polymer production and manufacture by 2050 (Zheng and Suh, 2019), global GHG emissions under different EoU scenarios show similar trends in Fig. 2c. The combined recycling and landfilling scenario (DP-S6-RELA) leads to the lowest emissions amongst the options tested at 0.85 $GtCO_{2e}$ per year by 2100.

4. Discussion

By 2100, the projected global demand for polymers is expected to result in 3.55 $GtCO_2e$ of GHG emissions per year, highlighting the urgent need for significant interventions across all stages of the polymer lifecycle to mitigate the severe impacts of climate change. Our findings underscore the substantial influence of different EoU strategies. While incinerating waste polymer could increase the lifecycle GHG emissions by 39%, maximising recycling and landfilling has the potential to reduce the total emissions by 30%. Meanwhile, decarbonising polymer production and manufacturing of polymers remains essential and unavoidable.

From a GHG emissions mitigation perspective, Figure 2 shows that recycling and landfilling should be prioritised over incineration, even with electricity generation. Although landfilling is

less costly and requires less advanced technology than incineration and recycling, it must be managed carefully to avoid negative environmental impacts, such as air contamination, dust, and hazardous leachates. Sanitary landfilling practices, such as impermeable liners, leachate collection, and covering layers, are essential to prevent leachate from contaminating the underground water (Patrício Silva et al., 2021). Regulations, such as the European Union Landfill Directive (1999/31/EC), mandate such approaches alongside long-term monitoring of gas emissions and leachate collection and treatment for known pollutants, such as heavy metals. Nascent research also suggests that leachate can be a source of other pollutants, such as microplastics, but data availability is sparse and uses inconsistent approaches (Dehal et al., 2024). Current data, however, suggests that microplastic concentration in treated leachate can be significantly reduced (Kabir et al., 2023). These risks can be mitigated with modern, well-controlled landfill sites and could be further reduced if polymers were cleaned and stored separately from other waste streams, where they would remain inert. Segregating plastics from organic wastes would similarly limit leaching of monomers and additives, such as BPA, which have also been found in mixed-waste landfill leachates(Kwan and Takada, 2016).

The risks of plastic-specific pollutants, such as microplastics and additives, are not unique to landfill. Mechanical recycling has been shown to be a significant microplastics source (Suzuki et al., 2024), while microplastics have also been detected in both bottom-ash (Yang et al., 2021) and flue gases(Su et al., 2025) from solid-waste incinerators. Incineration is often used to eliminate polymer additives but it produces bottom-ash containing toxic metals, which must be landfilled. Chemical recycling approaches, meanwhile, are essential for maximizing recycling rates but are associated with much higher toxicity than virgin production for most technologies and polymer types(Uekert et al., 2023a). Non-GHG environmental and health impacts of waste treatment

strategies are difficult to compare because existing studies do not provide comprehensive or consistently reported data. A systematic comparative review of non-GHG impacts across plastic waste treatment options is therefore needed to enable the potential ~30% emissions savings identified in this analysis, through maximising recycling and landfilling.

Maximising the potential of recycling and landfilling to reduce the lifecycle GHG emissions and pollution requires the collective efforts of all stakeholders across the value chain. Thoughtful product design that facilitates recycling (Ding and Zhu, 2023), such as replacing non-recyclable thermosets with thermoplastics or incorporating easily separable components, can significantly streamline the recycling process and enhance recycling rates. Customers' preferences and taxation policies can also drive this shift. Technology innovation, such as methods for removing additives and dyes, is pivotal to expanding recycling capability and minimizing landfill risks. Additionally, knowledge sharing, dissemination of best practices, and the provision of technological and financial support to developing countries should be prioritised in international negotiations on ending plastic pollution (United Nations Environment Programme, 2024).

5. Conclusion

We have built a high-resolution model to quantify the global GHG emissions across the supply chain of polymers, from production to end-of-use, which enables the comparison of various end-of-use treatments. While incinerating waste polymer could substantially increase GHG emissions, combining recycling and landfilling could reduce the lifecycle GHG emissions by reducing production emissions and increasing carbon sink. The study is expected to guide the policy on sustainable waste polymer treatment.

Supplementary materials

Supplementary materials associated with this article can be found in the online version.

CRediT authorship contribution statement

Yunhu Gao: Conceptualisation, Data Curation, Investigation, Methodology, Writing.

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Declaration of competing interest

The authors declare no competing interest.

Data and code availability

The code used for the analysis is generated by Matlab 2022a and is available from https://doi.org/10.17863/CAM.111126 upon request.

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