Global Assessment of the Emission Impacts of Chemical Recycling Technologies for Plastics

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Abstract

Chemical recycling is gaining global attention as a solution to plastic pollution, yet understanding of its environmental impacts remains limited. This study quantitatively evaluates emissions from major chemical plastic recycling technologies—solvent-based, depolymerization, pyrolysis, and gasification—under closed-loop scenarios for common plastics. Contrary to prevailing assumptions, when assessed across the full production value chain, closed-loop chemical recycling pathways could increase emissions by 3-84% compared to continued primary plastic production by 2050, depending on implementation scenarios. These increases result from high energy demands, upstream chemical production, and intensive sorting requirements. Even with optimal recovery rates, emissions remain higher due to upstream impacts. The findings highlight the need for significant technological innovation and system-wide improvements before chemical recycling can deliver genuine environmental benefits and serve as a viable plastic pollution strategy. A globally competitive plastics recycling sector must minimize environmental impacts to succeed.

Introduction

Global plastic production and consumption reached approximately 460 million metric tons in 2019, having increased at an average annual rate of 3.6% since 2000 *(1)*. This rapid expansion has created a global plastic pollution crisis, with end-of-life waste accumulation highlighting the urgent need for innovative recycling solutions. While mechanical recycling has historically dominated, it suffers from high material loss rates, inefficient processing, and significant degradation of material quality, ultimately failing to achieve true closed-loop circularity *(2)*. These limitations have contributed to persistently low global recycling rates—just over 6% of all plastic waste is effectively recycled *(1)*—and have spurred growing interest and investment in chemical recycling technologies as an alternative approach.

As the second part of the fifth session of the Intergovernmental Negotiating Committee to develop an international legally binding instrument on plastic pollution, including in the marine environment, (INC-5.2) approaches, chemical recycling has become a focal point in discussions on technological solutions for plastic circularity and waste management. Policy frameworks such as the EU Circular Economy Action Plan of 2020 and the U.S. Accelerating a Circular Economy for Plastics and Recycling Innovation Act of 2024, also point out in exploring the potential of chemical recycling[1]. However, despite this growing interest, most environmental assessments of chemical recycling technologies remain qualitative or limited to laboratory-scale case studies, leaving a critical gap in our understanding of their broader environmental and public health impacts *(7)*. Before widespread adoption, a rigorous quantitative analysis of the environmental and health impacts of chemical recycling is essential to ensure these technologies are truly beneficial without introducing unintended consequences.

This research addresses this gap by evaluating global recycled plastic production and the environmental impacts of various chemical recycling scenarios, with a specific focus on greenhouse gas (GHG) emissions. The need for such analysis is particularly critical given the projected growth in GHG emissions from plastic production. Karali et al. *(4)* projected that GHG emissions from primary plastic production could more than double by 2050, to 4.75 Gigatonne carbon dioxide equivalent ($GtCO_2e$) under a plastic demand growth scenario of 2.5% per year; or almost triple by 2050, to 6.78 $GtCO_2e$ under a 4% annual growth scenario.

We model six chemical recycling technologies applicable to common plastics and capable of contributing to closed-loop circularity: solvent-based recycling, depolymerization (glycolysis, methanolysis, enzymatic hydrolysis), and thermochemical recycling (pyrolysis and gasification). These technologies operate under specific temperature and pressure conditions and often employ solvents and catalysts to break down plastics into constituent parts such as gaseous, liquid, and solid mixtures of hydrocarbons, monomers, and oligomers *(2,5)*. Solvent-based recycling use solvents and antisolvents to separate additives from polymers *(6)*. The resulting products can then be used to manufacture new plastics, or serve as alternative chemicals or fuels. All of these processes often require significant energy inputs and can generate substantial GHG emissions, including carbon dioxide (CO_2) from combustion of energy sources for process heat and electricity, and direct process emissions such as CO_2, carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and other process chemical gases *(7)*. Building upon our original bottom-up energy and GHG emissions framework for primary plastic production (Karali et al. *(4)*), we investigate global GHG emissions associated with chemical recycling of different plastic polymers compared to primary plastic production under four implementation scenarios using these six processes.

European Commission (2020), A new Circular Economy Action Plan: For a cleaner and more competitive Europe', COM (2020) 98 final, Brussels. ;. H.R.9676 - Accelerating a Circular Economy for Plastics and Recycling Innovation Act of 2024.

Our implementation scenarios are based on varying collection rates, with projections extending to 2050. We compare the scenario results against a Reference scenario in which the current primary plastic production structure remains unchanged. While mechanical recycling can achieve some GHG emission reductions, the progressive and significant quality degradation of polymers through repeated recycling cycles means the final products may not provide equivalent functionality to primary (virgin) materials. Therefore, this study focuses exclusively on closed-loop chemical recycling processes where recycled outputs are used to produce new plastic products, including only technologies that are commercially available or at small-scale or pilot stage.

Our analysis pays particular attention to contamination and sorting requirements, as most chemical recycling processes demand high-purity plastic streams to achieve efficient recycling and produce materials that can substitute for primary plastics. This research expands the system boundaries of previous recycling studies by applying a comprehensive production value chain approach—from extraction and collection of fuels and waste materials through to final product formation—that also includes the production of all chemical inputs required for recycling. Through this holistic approach, we provide a more accurate assessment of the GHG emissions from chemical recycling of plastic polymers.

Results

Defining Scenarios for Chemical Recycling GHG Emissions Assessment

Chemical recycling encompasses several distinct technological approaches, each typically tailored to single or limited types of plastic. As mentioned previously, our modeling integrates six chemical recycling processes as alternatives for producing hydrocarbons, monomers, and polymers in plastic production: *solvent-based recycling* for multiple polymers (including low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), and acrylonitrile butadiene styrene (ABS)); *three types of PET depolymerization* (enzymatic hydrolysis, glycolysis, and methanolysis); and thermochemical recycling including *pyrolysis* (for multiple polymers—LDPE, LLDPE, HDPE, PP, PS) and *gasification* followed by either Fischer-Tropsch (F-T) or methanol synthesis (for mixed plastics of LDPE, LLDPE, HDPE, PP, PS, and PET).

To evaluate the potential environmental impact of these technologies at scale, we developed four implementation scenarios that vary collection rates and contamination thresholds. In the chemical recycling scenarios, recycled products replace a share of primary production, while the remaining plastic demand is met through primary plastic production. Table 1 summarizes the scenarios, including contamination thresholds and collection rates assumed by 2050. While some scenarios are based on current collection rates, it is important to note that not all collected plastics currently enter recycling streams *(7,8)*.

These scenarios do not reflect a definitive future path, but rather serve as analytical tools to investigate the impact of chemical recycling technologies on GHG emissions under various collection rates. Additionally, inevitable process losses occurring from collection to chemical recycling mean that final recycling rates differ from collection rates. Please see Supplementary Methods section of Supplementary Information for process losses used for the processes and polymers, and detailed collection rates over time (2025-2050) assumed in the scenarios.

Table 1. Chemical recycling scenarios evaluated in this analysis

		Collection Rates in 2050 by Scenarios[2]			
	Contamination threshold[1]	Realistic	Ambitious	High-Ambitious	Extreme
Solvent-based recycling					
L(L)DPE	<12%	2%	5%	35%	55%
HDPE	<10%	5%	13%	45%	55%
PP	<12%	5%	15%	35%	55%
PET	<4%	10%	33%	43%	55%
PVC	<1%	2%	6%	15%	45%
PS	<12%	2%	5%	30%	60%
ABS	<12%	5%	5%	30%	55%
Depolymerization of PET[3]					
Glycolysis	<30%	33%		42.5%	55%
Enzymatic Hydrolysis	0%>	33%		42.5%	55%
Methanolysis	<30%	33%		50%	85%
Pyrolysis[4]					
L(L)DPE/HDPE/PP	0%>	18%	30%	50%	85%
PS	0%>	5%	30%	50%	85%
Gasification of Mixed plastic of L(L)DPE, HDPE, PP, PET, PS[4]	0%>	18%	30%	50%	85%

Realistic** *Uses current global average collection rates but assumes only some single-type plastic bales meet contamination thresholds. Therefore, modeled collection rates represent a fraction of the current collection.* ***Ambitious***** *Assumes all currently collected plastics meet contamination thresholds.* ***High Ambitious***** *Assumes higher collection rates with all collected material below contamination thresholds.* ***Extreme***** *Assumes maximum collection rates with all collected material meeting contamination thresholds. Maximum rates are based on the estimated availability of recyclable plastic waste, considering current product applications per polymer, their respective lifespans, and the exclusion of products degraded below acceptable quality after repeated recycling.*

Notes:

1. Source for contamination thresholds: (7).

2. Collection rate data: Current collection rates for mixed plastic waste streams are sourced from major plastic consumers for 2019 (1). Polymer-specific collection and contamination rates are compiled from recent data spanning 2019-2023, primarily from U.S. and EU sources including United Nations (UN) and industry association reports.

3. PET depolymerization scope: Depolymerization technologies are assumed to apply only to PET plastics. The current PET bottle collection rates reflected in our Realistic scenario are already ambitious when extended to cover all PET plastic products. Therefore, we do not define an Ambitious scenario for PET depolymerization.

4. Pyrolysis and gasification scope: We exclude pyrolysis for PET, PVC, ABS, and PU plastics, and gasification for PVC, ABS, and PU from mixed plastic collections. Collection rates in gasification scenarios apply to both F-T synthesis and methanol synthesis pathways.

Emissions Impact

Our modeling shows that all closed-loop chemical recycling scenarios analyzed in this study, except glycolysis of PET, increase GHG emissions from global plastic production compared to the Reference scenario. Over 95% of these emissions originate as CO_2 from fuel combustion for heat and electricity. The remaining emissions are direct process emissions and a combination of both CO_2 and non-CO_2, including CO, NO_x, SO_x, and other process chemical gases. The extent of the increase varies by technology and implementation scenario.

For solvent-based recycling, total emissions from the polymers included in our scenarios exceed the Reference scenario by 0.33 $GtCO_2e$ in the Realistic scenario, 1.04 $GtCO_2e$ in the Ambitious scenario, 1.87 $GtCO_2e$ in the High Ambitious scenario, and 3.0 $GtCO_2e$ in the Extreme scenario by 2050, representing increases of 9% to 84% compared to the Reference scenario without chemical recycling (Fig. 2A). Recycled plastics account for 9% of total emissions in the Realistic scenario (despite only a 3% average recycling rate), rising to 55% in the Extreme case (with a 34% average recycling rate) in 2050 (Fig. 2B). The largest emission increase is observed in PET production, which rises by 21% in the Realistic scenario and more than doubles in the Extreme scenario by 2050 (Supplementary Table S1). This is primarily due to the use of benzyl alcohol and methanol as solvent and antisolvent, both of which are highly energy-intensive to produce. PET is followed by PVC, PS, and ABS recycling, all of which use solvent/antisolvent pairs that are highly energy and emission-intensive compared to other polymers.

The majority of emissions (69% for all polymers included in the Realistic scenario (Fig. 2C), ranging from 51% to 76% in 2050, depending on the individual polymer (Supplementary Figs. S1 and S2) originate from solvent/antisolvent recovery and additional production. Although unit emission intensity decreases over time in all the scenarios as recovered solvent/antisolvent pairs begin meeting most of the demand (Fig. 2D and Supplementary Fig. S3), by 2050, the production of new solvent and antisolvent still accounts for about 19% of emissions for LDPE, LLDPE, HDPE, and PP, and 45–63% for PET, PVC, PS, and ABS in the

Realistic Scenario. Similar results are observed across other scenarios, though with slightly lower additional production and slightly higher recovery shares in High Ambitious and Extreme scenarios (Supplementary Fig. S4). This underscores that the majority of emissions are tied to solvent and antisolvent use, including both recovery and new production, and highlights the need for comprehensive modeling boundaries.

Sensitivity analysis reveals that emissions levels rise and fall in tandem with the loss rate and amount of solvent/antisolvent use (Supplementary Tables S2 and S3). However, even with perfect recovery (0% loss rate), total global emissions from plastic production with chemical recycling in 2050 remain higher than in the Reference scenario across all solvent-based scenarios. This emphasizes the importance of innovation on solvent-based recycling technologies that minimize solvent/anti-solvent input requirements while maximizing recovery efficiency, and/or identifying less energy and emission-intensive solvent/antisolvent pairs. It is important to note that these results are based on the solvent/antisolvent pairs commonly used in the solvent-based literature for specific polymers; the results would be different with alternative solvent/antisolvent pairs.

Both enzymatic hydrolysis and methanolysis of PET scenarios result in higher emissions than the Reference scenario. By 2050, emissions for PET production increase by 2% to 3% with enzymatic hydrolysis scenarios and 5% to 14% with methanolysis scenarios, translating to an additional 0.02–0.03 $GtCO_2e$ and 0.05–0.14 $GtCO_2e$, respectively, in the Realistic and Extreme scenarios, compared to the Reference Scenario (Fig. 3A and 3B and Supplementary Table S4).

Enzymatic hydrolysis has lower emissions than methanolysis in all scenarios, but remains slightly higher than primary PET production, with the hydrolysis process and chemicals production accounting for 61% of production emissions and waste plastic feedstock preparation for 16% (Fig. 3D). For methanolysis, the process itself (including premelting, catalyst synthesis, methanolysis reactor, clarification, crystallization, and EG/DMT recovery) is the main emissions driver (35%) in 2050 in the Realistic scenario (Fig. 3E). Similar results across other scenarios are observed (Supplementary Figs. S5-S7). Similar to solvent-based recycling, unit emission intensity decreases over time as recovered solvent (methanol) begins meeting most of the demand (Supplementary Fig. S8). However, by 2050, the production of new solvent (methanol) still accounts for about 12% of emissions from methanolysis. The recovered DMT and EG from the methanolysis is insufficient to polymerize a tonne of PET. The additional production of virgin monomers, including the production of hydrocarbons and other chemicals, account for 9% of the total GHG emissions. Both technologies are sensitive to energy consumption rates, including sorting and pretreatment in Material Recovery Facilities (MRFs), which are heavily influenced by feedstock contamination (Supplementary Tables S5 and S6). While separate collection of PET bottles is common in many regions, other PET products such as textiles and carpets generally lack separate collection infrastructure, complicating efficient depolymerization and increasing emissions due to additional sorting and pretreatment needs. A substantial portion of PET waste is currently collected as mixed plastics *(9)*, highlighting the need to prioritize infrastructure for single-stream collection for PET depolymerization.

Glycolysis offers some emissions reduction, but the resulting recycled PET is often not a direct substitute for virgin material due to contaminants in recovered monomers and lower material quality (See Methods for more details), necessitating further purification steps that may not be technically or economically feasible *(10)*. Our analysis assumes glycolysis-recovered PET can be used for all PET product applications, though this is not the case in practice. Thus, glycolysis results from this study should be interpreted with caution depending on the intended use case.

All pyrolysis scenarios show increased GHG emissions compared to the Reference scenario, with a projected 0.06–0.47 $GtCO_2e$ rise by 2050 (a 3.1% to 22.8% increase from the total emissions from the polymers included in pyrolysis scenarios) (Fig. 4A and Supplementary Table S7). Fig. 4B shows the production stages share of the closed-loop pyrolysis production chain for the polymers analyzed in this study in the Realistic scenario, which remains consistent across other scenarios. The pyrolysis process itself contributes an average of 30% of emissions for production of recycled polyolefins and PS, while plastic waste feedstock preparation accounts for about 14%.

Closed-loop pyrolysis recycling shows higher emissions than primary production for all polymers analyzed, except PS, which has lower emission intensity than primary PS when the recycled styrene serves as a perfect replacement for its primary counterpart (Supplementary Table S8 and Supplementary Fig. S9 for polymer-specific data). Even if pyrolysis oil could fully replace virgin naphtha, emissions would remain higher, indicating that pyrolysis oil is not a low-emission alternative to primary naphtha in steam crackers (Supplementary Tables S9-S11). Additionally, extra efforts to sort and clean plastic and purify pyrolysis oil to achieve a 1:1 replacement rate would require even more energy, potentially further increasing emissions.

Gasification is the most energy-intensive chemical recycling process evaluated. Both F-T and methanol synthesis routes significantly increase energy input for the closed-loop process. All gasification scenarios result in GHG emissions increases compared to the Reference scenario (Figs. 5A and 5B). When methanol synthesis is used instead of F-T synthesis, emissions increase further, as recycled methanol alone cannot meet process demand, requiring large amounts of virgin methanol or substantially more mixed plastic feedstock.

By 2050, emissions rise by 0.17–2.4 $GtCO_2e$ (a 5.5% to 79% increase from the total emissions from the polymers included in the closed-loop gasification scenarios), depending on scenario conditions. In the F-T synthesis case, about 60% of emissions from closed-loop gasification come from the combined gasification and F-T process, including chemicals (i.e., oxygen and nitrogen) needed for gasification (Fig. 5C), while additional virgin methanol production contributes the bulk of the emissions in the methanol synthesis route (Fig. 5D). Detailed polymer results are provided in Supplementary Tables S12-S19 and Supplementary Figs. S10 and S11.

It is important to note that this analysis assumes that the theoretical recovery rates from the experimental studies would be realized in commercial applications. In reality, feedstocks are often more contaminated and less well-characterized than in laboratory studies, potentially leading to lower recovery rates. Current pilot and commercial operations typically achieve lower efficiencies than theoretical values *(10,11,12,13,14,15)*.

The broader system boundaries used in this analysis yields higher emission estimates than previous studies that focus solely on the recycling process and either exclude the production of solvents, antisolvents, and/or other necessary chemicals or do not use a production value chain approach from extraction and collection of fuels and waste plastics to final product formation. Most previous literature for the energy, emissions, and other environmental or economic estimates only accounts for chemical replacements resulting from recycling losses (e.g., 7,15,16,17). However, including chemicals production is crucial for assessing the scalability of chemical recycling, as demand for process chemicals will only increase to achieve global scale-up, and recovered chemicals will not be sufficient.

Our results reflect global conditions, such as global average grid GHG emission factors and collection rates, and would not be reflective of specific case studies or plants in particular regions. The results are also limited to the polymers and chemical recycling technologies included in the analysis, and are not representative of other recycling technologies or polymers. Additionally, our findings are based on the assumption that global primary production technology infrastructure and electricity grid emission intensity remain at current levels through the modeling period. Karali et al. *(4)* provide insights on how emissions from primary plastic production change under different grid emissions intensity conditions.

While we primarily examine chemical recycling technologies from a GHG emissions perspective, most solvents and process chemicals used, such as benzyl alcohol, dichloromethane, and zinc chloride, are also toxic, posing risks to human health, water systems, and other ecosystems *(18,19,20,21)*.

Discussion

This study provides the first comprehensive, quantitative assessment of the GHG emissions impacts from major chemical recycling technologies for plastics, examining closed-loop scenarios where recycled outputs directly substitute for primary plastic production. Our analysis, which integrates detailed material flow modeling that spans the entire production value chain—from fuel extraction and waste collection to final product formation—and incorporates contamination and collection constraints, finds that all modeled chemical recycling scenarios-including solvent-based recycling, depolymerization of PET, and thermochemical recycling (pyrolysis, gasification), except glycolysis, result in higher GHG emissions than maintaining current primary plastic production practices through 2050. GHG emissions from plastic production are already set to grow dramatically, with Karali et al. (4) projecting those emissions from primary plastic production could more than double by 2050 to 4.75 $GtCO_2e$ under a 2.5% annual demand growth scenario. Our findings indicate that widespread adoption of current chemical recycling technologies could further exacerbate these emissions.

The magnitude of these emissions increases varies by technology and implementation scenario but follows consistent patterns. Solvent-based recycling shows the most dramatic increases, with emissions rising 9–84% above reference levels depending on collection rates in the scenarios. Depolymerization technologies, while more modest in their impact, still increase emissions by 2–14% for PET production. Thermochemical approaches—pyrolysis and gasification—similarly drive emissions higher, with increases ranging from 3–79% depending on the specific process and scenario. These emissions increase stem from energy and chemical requirements inherent to current chemical recycling processes. The substantial energy needed for plastic recycling and recovery of solvents, antisolvents, and other process chemicals drives the majority of emissions, along with the energy intensity of essential sorting, pretreatment, and purification steps. Over 95% of these emissions originate as CO_2 from fuel combustion for heat and electricity, with the remainder consisting of direct process emissions including CO, NO_x, SO_x, and other process chemical gases.

Our findings underscore the critical importance of proper system boundary definition in environmental assessments of recycling technologies. Many previous studies have underestimated emissions by excluding the production of necessary chemical inputs or feedstock preparation processes. Our modeling reveals that by 2050, production of additional solvents and antisolvents could account for 19–63% of emissions from solvent-based recycling, depending on the polymer. Similarly, chemicals production for PET enzymatic hydrolysis could represent 20% of total GHG emissions, while additional methanol production could account for 12% of PET methanolysis emissions. Including these components is essential for scalability assessments, as global adoption of chemical recycling would require significant chemical production scale-up.

Glycolysis could offer some emissions reduction, but the resulting recycled PET often cannot directly substitute for virgin material due to contaminants in recovered monomers and reduced material quality. This limits glycolysis applications to a narrow subset of PET products, substantially constraining its real-world emissions benefits.

As plastic waste management policies evolve, including the ongoing negotiations for a Global Plastic Treaty, these findings suggest that even though chemical recycling technologies offer the potential to process a broader range of plastic waste than mechanical recycling, they face significant obstacles to becoming viable environmental solutions to the plastic crisis without substantial improvements. Current technologies struggle with substantial energy and chemical demands, high contamination sensitivity, and process losses that prevent them from delivering true environmental benefits. Technological innovation on these ends is essential for true circularity and widespread deployment without unintended consequences. Furthermore, a comprehensive transition to chemical recycling necessitates a holistic approach, focusing on not just innovation, but systemic improvements such as enhanced global collection infrastructure and optimized product design for recyclability that eliminates hazardous chemicals use and reduce material degradation. Additionally, different polymers and waste compositions are better suited to specific chemical recycling technologies, indicating a careful consideration for tiered system design for proper recycling types—incorporating mechanical recycling where appropriate—will be essential once current technical challenges are addressed.

It is important to note that this analysis focuses exclusively on closed-loop chemical recycling that aims to substitute primary plastic production. Incineration is excluded from direct comparisons because it represents a terminal disposal method rather than a circular pathway for production.[2] Additionally, chemical recycling only delays incineration or other end-of-life disposal (e.g., landfilling). Plastics can typically undergo 3 to 4 recycling cycles before reaching material degradation limits (except methanolysis-recycled PET, which retains near-virgin quality), after which they still require incineration or other disposal methods. For short-lived products like packaging, this delay may be minimal. This limitation further emphasizes the need to carefully evaluate the true environmental benefits of chemical recycling technologies in a complete value-chain context.

Methods

Current State of Chemical Recycling Technologies

This section provides detailed definition of the chemical recycling technologies used in our modeling (summarized in Table 2).

Table 2. Chemical recycling technologies used in this analysis

Type	To	Applicable	“Problematic”
Solvent-based recycling	Polymer	PEs, PP, PET, PS, ABS, PVC	PU
Depolymerization	Monomer	PET, PU	PEs, PP, PS, ABS, PVC
Thermochemical recycling			
Pyrolysis	Mix of gases, liquids (pyrolysis oil), monomers, aromatics, and solid char	PEs, PP, PS	PET, PVC, ABS, PVC, PU
Gasification	Syngas (Synthesis gas)	PEs, PP, PET, PS	PVC, ABS, PVC, PU

Problematic means either not applicable or very challenging.

Solvent-based recycling

Solvent-based recycling—also known as purification or dissolution/precipitation—is considered a "polymer-to-polymer" technology, as it recovers polymers that can be used to manufacture new plastic products. The process involves dissolving target polymers in a compatible solvent, and then recovering them by precipitation using an antisolvent with different polarity and solubility *(7, 11)*. Solvents and antisolvents are partially recovered and reused. This technology can process a variety of polymers, including polyethylenes (PEs—LDPE, LLDPE, HDPE, and others), PP, PET, PVC, PS, and ABS. However, it requires highly pure, single-polymer streams due to low contamination tolerance *(7)*. Exposure to solvents, heat, and mechanical stress can cause polymer chain scission or other degradation, reducing the mechanical properties of recovered material. Solvent-based recycling of polyurethane (PU) faces challenges due to the cross-linked molecular structure of thermoset PUs, which makes complete dissolution in most solvents difficult, and the mechanical properties of the recovered PU are often inferior to virgin material, limiting its potential applications *(22,23)*. Although some literature names this process as physical recycling, we consider it chemical recycling due to its reliance on chemical methods and inputs.

Depolymerization

Depolymerization breaks down polymers into their basic building blocks (monomers or oligomers) using heat, chemicals, enzymes, and/or catalysts *(10)*. Polymers with carbon-carbon backbones (PEs, PP, PS, PVC) require extremely high temperatures and yield low monomer selectivity, making them less suitable for depolymerization *(24)*. In contrast, polymers with carbon-heteroatom bonds, such as PET, PU, polyamides (PAs), and polycarbonates (PCs), are more amenable to selective cleavage under milder conditions *(25)*. Most research, therefore, focuses on depolymerizing PET, PU, PA, and PC. PET depolymerization uses various solvents such as hydrolysis, glycolysis, and methanolysis *(26)*. Hydrolysis uses water, glycolysis uses glycols (e.g., ethylene glycol (EG)), and methanolysis uses methanol, typically under elevated temperatures and pressures, often with catalysts. Enzymatic hydrolysis employs biological catalysts for lower-temperature operation. PET depolymerization has seen the most commercial interest, while PU, PA, and PC processes remain at the experimental or small-scale commercial stage. Contaminants carry through to the monomer stream, requiring additional purification steps that may not be technically or economically viable *(10)*. For example, methanolysis catalysts optimized for PET will be ineffective or can be damaged by exposing other polymers *(27)*. Recycled PET from glycolysis often suffers from a yellowish tint due to thermal degradation and residual contaminants *(24)*, and typically has lower molecular weight and weaker mechanical properties than virgin PET *(28)*. Additionally, the presence of oligomers and chemical residues limits its use in food-contact applications without further purification *(29)*, restricting its overall applicability.

Thermochemical recycling

Thermochemical recycling (also known as feedstock recycling or thermolysis) primarily uses high heat to break down plastics into small molecules. It is largely nonselective regarding plastic type and, depending on process conditions, produces a mix of hydrocarbons, monomers, and/or oligomers. Pyrolysis and gasification are the most prominent examples. Pyrolysis operates at 400° to 600°C in the absence of oxygen, with or without catalysts *(30)*. Product yield and composition depend on feedstock type and process conditions. Pyrolysis of PEs and PP yields oils, gases, and chars, while PS mainly yields styrene monomers *(31)*. Challenges include handling chlorinated plastics (e.g., PVC) and oxygenated plastics (e.g., PET), which can contaminate products and damage equipment. Similarly, ABS produces a wider variety of compounds, including potentially hazardous nitrile-containing substances *(32)*, and the presence of butadiene in ABS complicates purification, whereas PS pyrolysis typically yields more readily usable styrene monomers. Pyrolysis of PU can lead to significant char (solid residue) formation, reducing overall efficiency *(33)*. In addition, pyrolysis oil cannot easily be used as a 'drop-in' feedstock for naphtha steam crackers due to contaminants and unsuitable hydrocarbon chemistry, which can cause corrosion, coke formation, or catalyst deactivation *(34)*. The literature shows that the replacement rate of virgin naphtha with pyrolysis oil ranges from 0.5% to 20%, depending on the contamination levels *(7, 35)*.

Gasification uses a controlled amount of oxygen, air, or steam at 700° to 1100°C *(36)*, breaking polymers down into CO, CO_2, water, and hydrogen (together called syngas). Raw syngas requires purification to remove contaminants that could poison downstream catalysts. Purified syngas can be converted via F-T or methanol synthesis into fuels and chemicals for new plastics. PVC and PU in mixed plastic streams are problematic: PVC generates corrosive hydrogen chloride gas, and PU can produce NO_x compounds *(37)*. Similarly, ABS produces potentially hazardous nitrile-containing substances *(32)*.

Some examples of small-scale commercial and pilot operations are provided in Supplementary Table S20. Most chemical recycling processes are designed for specific polymers. Without adequate sorting and cleaning, target reactions cannot proceed efficiently, and product quality or equipment integrity may be compromised. Most consumer plastic waste typically contains a mixture of polymers and numerous additives *(8,11)*. Contaminants such as metals, halogens, inorganics, and cellulosic material can cause severe or irreparable equipment damage *(38)*. Even when processes tolerate contaminated feedstock (e.g., pyrolysis), product quality suffers, requiring further treatment *(34)*. Nearly all chemical recycling technologies require pretreatment to separate polymers and remove extraneous materials, which may involve screening, sorting, washing, drying, flotation, grinding, extrusion, and filtration *(7)*.

Defining Modeling and System Boundaries for Chemical Recycling Emissions Assessment

Our existing modeling is a comprehensive bottom-up model for GHG emissions from global primary plastic production that captures detailed polymer-specific value chains *(4)*. The model encompasses all production stages, from fossil fuel extraction through final product formation, incorporating the diverse processes and technologies employed throughout polymer production. Given its polymer- and process-specific granularity, this existing framework provides the most suitable foundation for the chemical recycling analysis, enabling targeted assessment of how recycling technologies integrate into and impact existing production pathways. Alternative global studies have limitations for this purpose:

Zheng and Suh *(39)* estimated global plastic production emissions (including recycling) at 1.6 $GtCO_2e$ in 2015, but this study relied primarily on European data and did not account for regional variations in production technologies, process energy demand and yields. These factors depend on location-specific variables, hydrocarbon availability (e.g., crude oil vs natural gas or coal) and regional economics. Cabernard et al. *(40)* provided broader global coverage (1.9 $GtCO_2e$ in 2015, excluding recycling) but lacked polymer- or process-level detail, making it difficult to differentiate emissions related to specific plastic polymers and production processes—a critical limitation for analyzing polymer-specific recycling scenarios. Our original work estimated 2.24 $GtCO_2e$ from primary plastic production in 2019 *(4)*. This estimate aligns closely with Cabernard et al.'s *(40)* findings: when applied to 2015 plastic production volumes, our model generates an estimate of approximately 2.01 $GtCO_2e$.

For the recycling expansion, we maintain consistent system boundaries and adopts a comprehensive production value chain approach for both recycling technologies and associated chemicals, including solvents, antisolvents, and other chemical inputs. System boundaries extend from waste collection and fossil fuel extraction—used for heat and electricity generation—to final product shaping, covering the entire production value chain. The modeling tracks material flows, energy demand, and direct process emissions (CO, CO_2, NO_x, SO_x, and other process chemical gases) for each process. Total GHG emissions are calculated as the sum of combustion-related CO_2 and process emissions, converted to CO_2 equivalent (CO_2e).

For processes where recycled output alone cannot meet a full tonne of input demand in subsequent production chain steps, primary production supplements the remainder. For example, EG monomer recovered from enzymatic hydrolysis of PET is insufficient for a tonne of PET polymer production, requiring additional virgin monomer inputs. The model assumes recycled products are fully utilized in new plastic production until they reach degradation limits (typically 3 to 4 cycles), after which they are excluded from the modeling (and become waste). Detailed polymer degradation charts used in this analysis for solvent-based and depolymerization technologies are provided in Supplementary Fig. S21 of Supplementary Information. For pyrolysis, we assume pyrolysis oil (from PEs and PP) is used as a naphtha substitute in steam crackers at a 5:95 ratio (i.e., 5% pyrolysis oil vs 95% virgin naphtha), while pyrolysis styrene directly replaces virgin styrene production. Syngas from gasification is used in both F-T and methanol synthesis to produce oil and methanol, with no degradation assumed in final plastic products. The initial stage of each modeled recycling process is collection and pretreatment, with process losses, combustion energy, and process emission intensity tracked throughout.

Detailed modeling charts and parameters used for each recycling process and chemicals used are provided in Supplementary Methods of Supplementary Information.

Additionally, Supplementary Fig. S32 display the detailed GHG emissions from primary plastics in 2050 under the Reference scenario.

Collection modelling

In this study, maximum collection rates are determined based on the estimated availability of recyclable plastic waste. This estimation considers current plastic product applications for each polymer type, their respective service lifespans, and excludes products that have degraded below acceptable quality standards after repeated recycling cycles.

The timing of waste generation varies significantly across application sectors. For packaging applications, nearly all waste generated within a given year originates from plastics produced in or after that same year due to short service lives. In contrast, for long-term applications such as construction materials and automotive components, there is a temporal lag between production and waste generation that corresponds to the extended lifetime of these products.

$$\mathit{Maximum\ plastic\ waste}\ (Mt) = \sum_x \mathit{Maximum\ plastic\ waste\ per\ application}\ (Mt) \qquad \text{[Eq.1]}$$

$$\mathit{Maximum\ plastic\ waste\ per\ application}\ (Mt) = \sum_p \sum_t^{t<lifetime_{p,x}} \mathit{Plastic\ waste\ from\ primary\ production}_{p,t} + if\left(\#\ of\ recycling_{p,tech} < maximum\ \#\ of\ recycling_{p,tech}\right), \sum_p \sum_t^{t<lifetime_{p,x}} \mathit{Plastic\ waste\ from\ recycled\ plastics}_{p,t}, 0) \qquad \text{[Eq.2]}$$

p is polymer, t is year, and x is application.

Detailed plastic product application share and lifetime assumptions are provided in Supplementary Methods of Supplementary Information.

Declarations

Data availability

All data are available in the main text or the Supplementary Information document.

Acknowledgments

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References

1. Organization for Economic Co-operation and Development (OECD) (2022) Global Plastics Outlook: Policy Scenarios to 2060. OECD Publishing, Paris. https://doi.org/10.1787/aa1edf33-en
2. Davidson MG, Furlong RA, McManus MC (2021) Developments in the life cycle assessment of chemical recycling of plastic waste – A review. J Clean Prod 293:126163
3. Nordahl S, Scown CD (2024) Recommendations for life-cycle assessment of recyclable plastics in a circular economy. Chem Sci 15:9397–9407
4. Karali N, Khanna N, Shah N Climate impact of primary plastic production, (Report #: LBNL-2001585, Lawrence Berkeley National Laboratory, 2024). https://escholarship.org/uc/item/12s624vf

5. Martínez-Narro G, Hassan S, Phan AN (2024) Chemical recycling of plastic waste for sustainable polymer manufacturing – A critical review. J Environ Chem Eng 12:112323
6. Klotz M, Oberschelp C, Salah C, Subal L, Hellweg S (2024) The role of chemical and solvent-based recycling within a sustainable circular economy for plastics. Sci Total Environ 906:167586
7. Uekert T, Singh A, DesVeaux JS, Ghosh T, Bhatt A, Yadav G, Afzal S, Walzberg J, Knauer KM, Nicholson SR, Beckham GT, Carpenter AC (2023) Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. ACS Sustain Chem Eng 11(7):965–978
8. Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3:e1700782
9. Cecon VS, Curtzwiler GW, Vorst KL (2023) Evaluation of mixed #3–7 plastic waste from material recovery facilities (MRFs) in the United States. Waste Manag 171:313–323
10. Coates GW, Getzler YD (2020) Chemical recycling to monomer for an ideal, circular polymer economy. Nat Reviews Mater 5:501–516
11. Ügdüler S, Van Geem KM, Roosen M, Delbeke EIP, De Meeste S (2020) Challenges and opportunities of solvent-based additive extraction methods for plastic recycling. Waste Manag 104:148–161
12. Tournier V, Topham CM, Gilles A, David B, Folgoas C, Moya-Leclair E, Kamionka E, Desrousseaux ML, Texier H, Gahlot S, Cot D, Guémard E, Dalibey M, Nomme J, Cioci G, Barbe S, Chateau M, André I, Duquesne S (2020) Marty, An engineered PET depolymerase to break down and recycle plastic bottles. Nature 580:216–219
13. Jehanno C, Pérez-Madrigal MM, Demarteau J, Sardon H, Dove AP (2019) Organocatalysis for depolymerisation. Polym Chem 10:172–186
14. Solis M, Silveira S (2020) Technologies for chemical recycling of household plastics – A technical review and TRL assessment. Waste Manag 105:128–138
15. Meys R, Frick F, Westhues S, Sternberg A, Klankermayer J, Bardow A (2020) Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling. Resour Conserv Recycling 162:105010
16. Wiprachtiger M, Hellweg S (2024) Circularity assessment in a chemical company. Evaluation of mass-based vs. impact-based circularity. Resour Conserv Recycling 204:107458
17. Schwarz AE, Ligthart TN, Godoi Bizarro D, De Wild P, Vreugdenhil B, van Harmelen T (2021) Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. Waste Manag 121:331–342
18. Plum LM, Rink L, Haase H (2010) The essential toxin: impact of zinc on human health. Int J Environ Res Public Health 7:1342–1365
19. Environmental Protection Agency (EPA), EPA-740-R1-8012 (2020) Risk Evaluation for Methylene Chloride, (https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-evaluation-methylene-chloride-0

20. National Institute for Occupational Safety and Health (NIOSH) Criteria for a Recommended Standard: Occupational Exposure to Benzyl Alcohol, (CAS#: 100-51-6, 2020). https://www.osha.gov/chemicaldata/36
21. Agency for Toxic Substances and Disease Registry (ATSDR) (2005) Toxicological Profile for Zinc. U.S. Department of Health and Human Services, Public Health Service,, Atlanta, GA. (CAS#: 7440-66-6
22. Simón D, Borreguero AM, de Lucas A, Rodríguez JF (2018) Recycling of polyurethanes from laboratory to industry, a journey towards the sustainability. Waste Manag 76:147–171
23. Wieczorek K, Bukowski P, Stawiński K, Ryłko I (2024) Recycling Polyurethane Foams via Glycolysis: Rev Materials 17:4617
24. Ragaert K, Delva L, Van Geem K (2017) Mechanical and chemical recycling of solid plastic waste. Waste Manag 69:24–58
25. Rahimi A, García JM (2017) Chemical recycling of waste plastics for new materials production. Nat Reviews Chem 1:1–11
26. Clark JH, Shaver MP (2024) Advances in PET depolymerization for closed-loop recycling. ACS Sustain Chem Eng 12:1234–1245
27. Vollmer I, Jenks MJF, Roelands MCP, White RJ, van Harmelen T, de Wild P, van der Laan GP, Meirer F, Keurentjes JTF, Weckhuysen BM (2020) Beyond mechanical recycling: Giving new life to plastic waste. Angew Chem Int Ed 59:15402–15423
28. Khoonkari M, Haghighi AM, Sefidbakht Y, Shekoohi K, Ghaderian A (2015) Chemical recycling of PET wastes with different catalysts. *International Journal of Polymer Science*, 124524, (2015)
29. Awaja F, Pavel D (2005) Recycling of PET. Eur Polymer J 41:1453–1477
30. Lopez G, Artetxe M, Amutio M, Alvarez J, Bilbao J, Olazar M (2018) Recent advances in the gasification of waste plastics. Renew Sustain Energy Rev 82:576–596
31. Qureshi MS, Oasmaa A, Pihkola H, Deviatkin I, Tenhunen A, Mannila J, Minkkinen H, Pohjakallio M (2020) Laine-Ylijoki, Pyrolysis of plastic waste: Opportunities and challenges. J Anal Appl Pyrol 152:104804
32. Kim S, Lee J, Park YK (2019) Pyrolysis of ABS: Kinetics and product distribution. J Anal Appl Pyrol 138:283–291
33. Oenema J, Liu H, De Coensel N, Eschenbacher A, Van de Vijver R, Weng J, Li L, Wang C, Van Geem KM (2022) Review on the pyrolysis products and thermal decomposition mechanisms of polyurethanes. J Anal Appl Pyrol 168:105723
34. Kusenberg M, Eschenbacher A, Djokic MR, Zayoud A, Ragaert K, De Meester S, Van Geem KM (2022) Opportunities and challenges for the application of post-consumer plastic waste pyrolysis oils as steam cracker feedstocks: To decontaminate or not to decontaminate? Waste Managemant 138:83–115

35. Gracida-Alvarez UR, Benavides PT, Lee U, Wang M (2023) Life-cycle analysis of recycling of post-use plastic to plastic via pyrolysis. J Clean Prod 425:138867
36. Lee U, Chung JN, Ingley HA (2014) High-Temperature Steam Gasification of Municipal Solid Waste, Rubber, Plastic and Wood. Energy Fuels 28:4573–4587
37. Dogu O, Pelucchi M, Van de Vijver R, Van Steenberge PHM, D'hooge DR, Cuoci A, Mehl M, Frassoldati A, Faravelli T, Van Geem KM (2021) The chemistry of chemical recycling of solid plastic waste via pyrolysis and gasification: State-of-the-art, challenges, and future directions. Prog Energy Combust Sci 84:100901
38. Kaminsky W (2021) Chemical recycling of plastics by pyrolysis and gasification: Status, challenges, and prospects. Chem Ing Tech 93:1461–1472
39. Zheng J, Suh S (2019) Strategies to reduce the global carbon footprint of plastics. Nat Clim Chang 9:374–378
40. Cabernard L, Pfister S, Oberschelp C, Hellweg S (2022) Growing environmental footprint of plastics driven by coal combustion. Nat Sustain 5:139–148

Footnotes

1. European Commission (2020), A new Circular Economy Action Plan: For a cleaner and more competitive Europe’, COM (2020) 98 final, Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN;. H.R.9676 - Accelerating a Circular Economy for Plastics and Recycling Innovation Act of 2024. https://www.congress.gov/bill/118th-congress/house-bill/9676
2. Some thermochemical processes like pyrolysis are classified as incineration in regulatory frameworks in some countries. In this study, we evaluate them strictly as feedstock-recovery technologies.

Figures

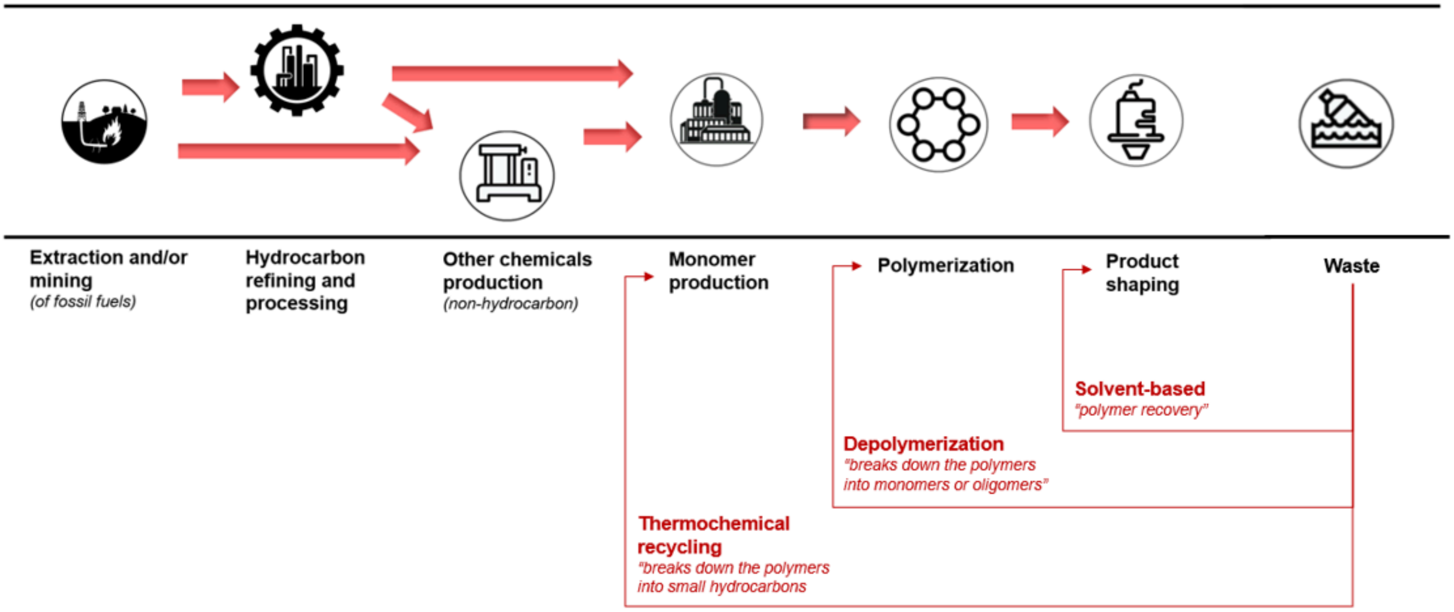
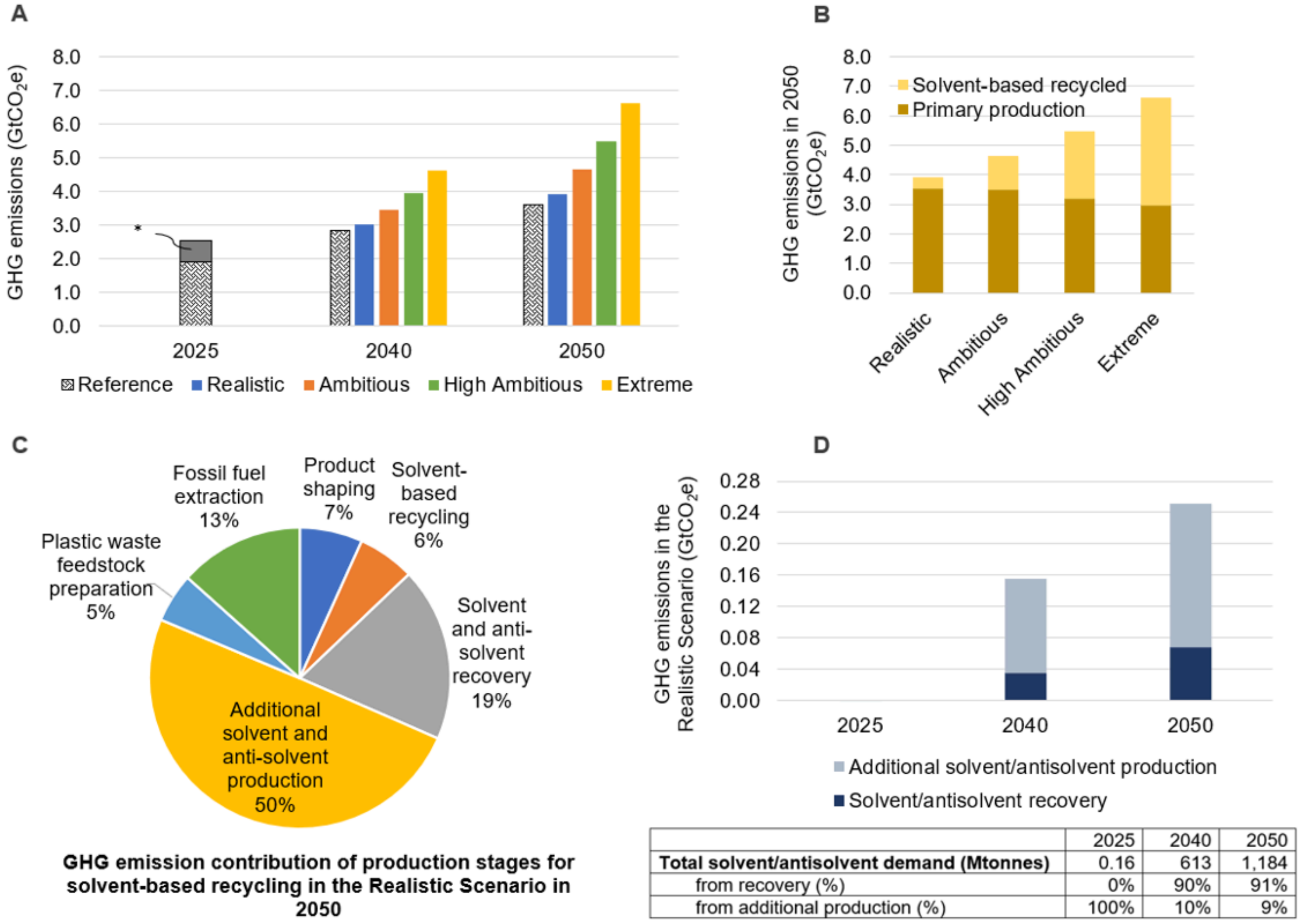


Figure 1

System boundaries for modeling chemical recycling technologies in the plastic production value chain

Note: See Supplementary Methods section of Supplementary Information for detailed material flow charts of each chemical recycling technology and polymer.



GHG emission contribution of production stages for solvent-based recycling in the Realistic Scenario in 2050

	2025	2040	2050
Total solvent/antisolvent demand (Mtonnes)	0.16	613	1,184
from recovery (%)	0%	90%	91%
from additional production (%)	100%	10%	9%

Figure 2

GHG emissions analysis for solvent-based recycling scenarios

(A) Total GHG emissions from solvent-based recycling scenarios versus the Reference scenario; (B) Total GHG emissions from recycled and primary plastic production in solvent-based recycling scenarios in 2050; (C) GHG emission contribution by production stage in the Realistic scenario of solvent-based recycling in 2050; (D) Demand for and GHG emissions from solvent/antisolvent recovery and additional production in the Realistic scenario of solvent-based recycling.

*Note: * The grey box indicates the GHG emissions from other polymers in the Reference scenario that are not included in the solvent-based scenarios.*

See Supplementary Information for plastic polymer-specific results.

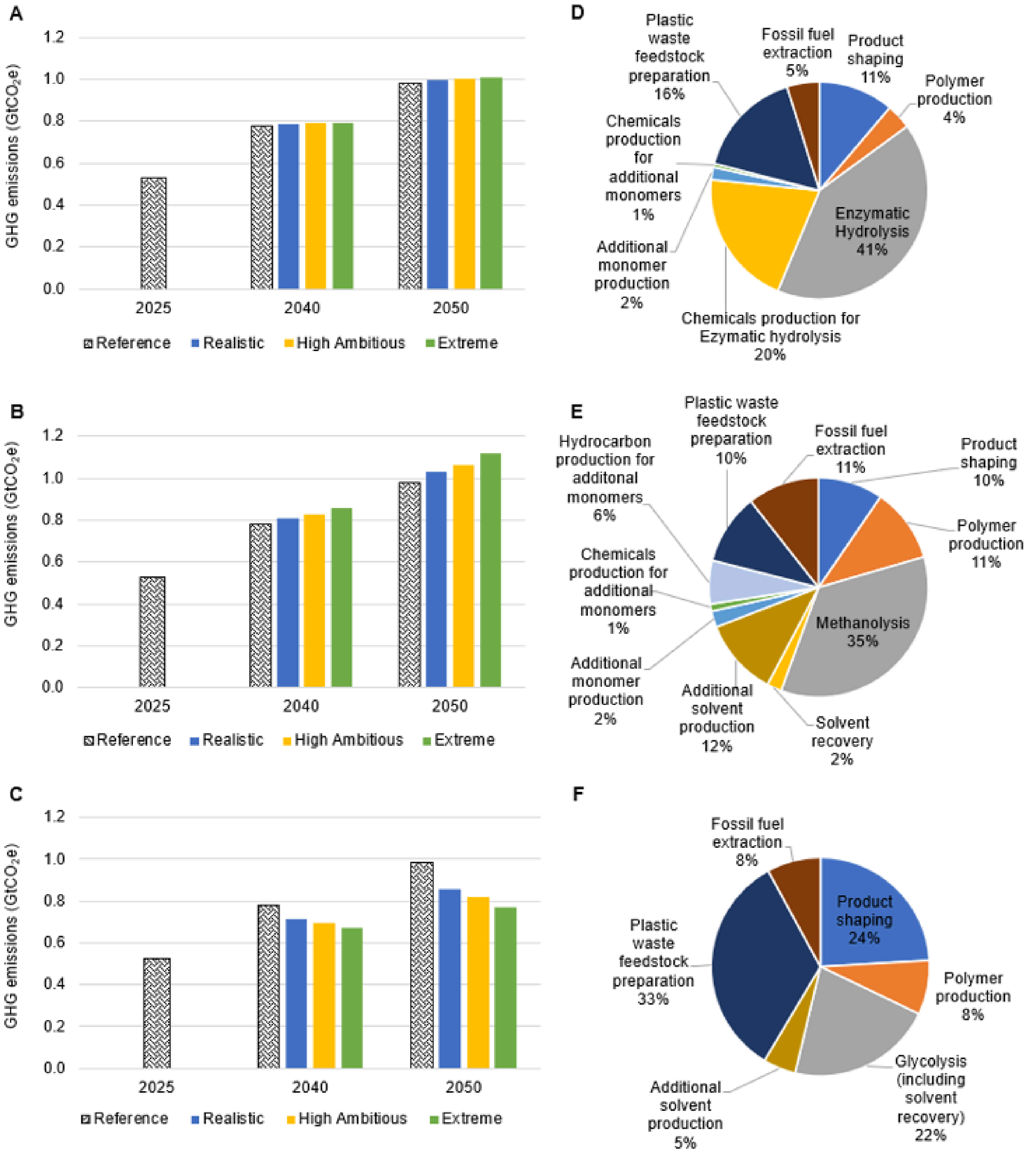


Figure 3

GHG emissions analysis for PET depolymerization recycling scenarios

(A) Enzymatic hydrolysis, (B) Methanolysis, (C) Glycolysis: GHG emissions from depolymerization recycling scenarios versus the Reference scenario; (D) Enzymatic hydrolysis, (E) Methanolysis, (F) Glycolysis: GHG emissions shares by production stage in the Realistic scenario in 2050.

Note: Chemicals used in enzymatic hydrolysis are sodium hydroxide and sulfuric acid. Solvents in methanolysis and glycolysis are methanol and EG, respectively. See Supplementary Methods section of Supplementary Information for more details.

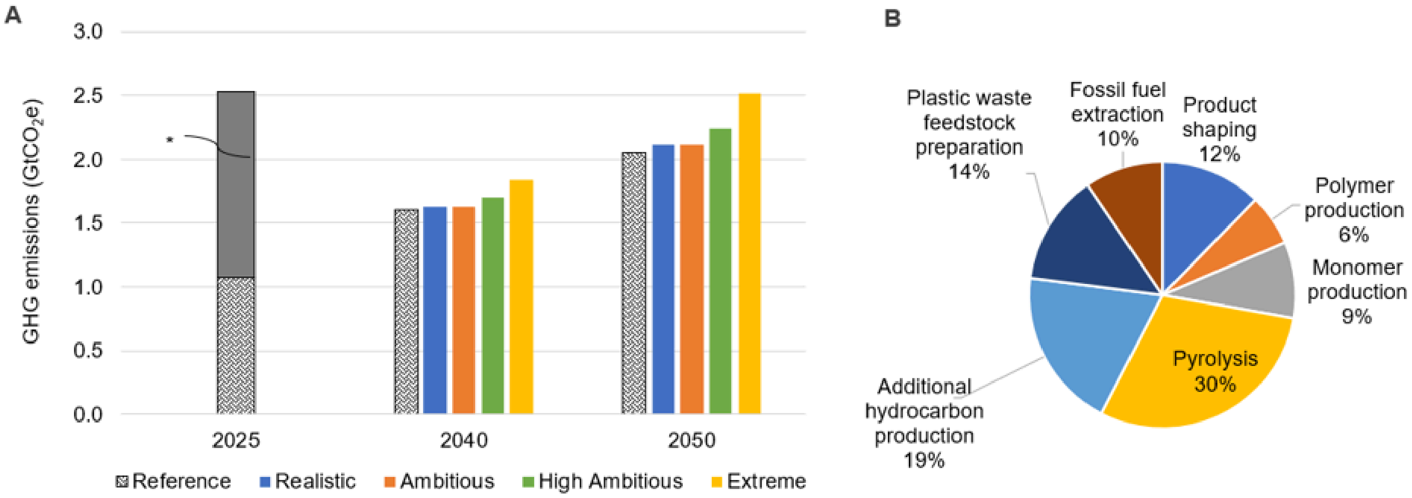


Figure 4

GHG emissions analysis for closed-loop pyrolysis recycling scenarios

(A) GHG emissions from closed-loop pyrolysis recycling scenarios compared to the Reference scenario; (B) GHG emissions shares by production stage in the Realistic scenario in 2050.

*Note: * The grey box indicates the GHG emissions from other polymers in the Reference scenario that are not included in the pyrolysis scenarios.*

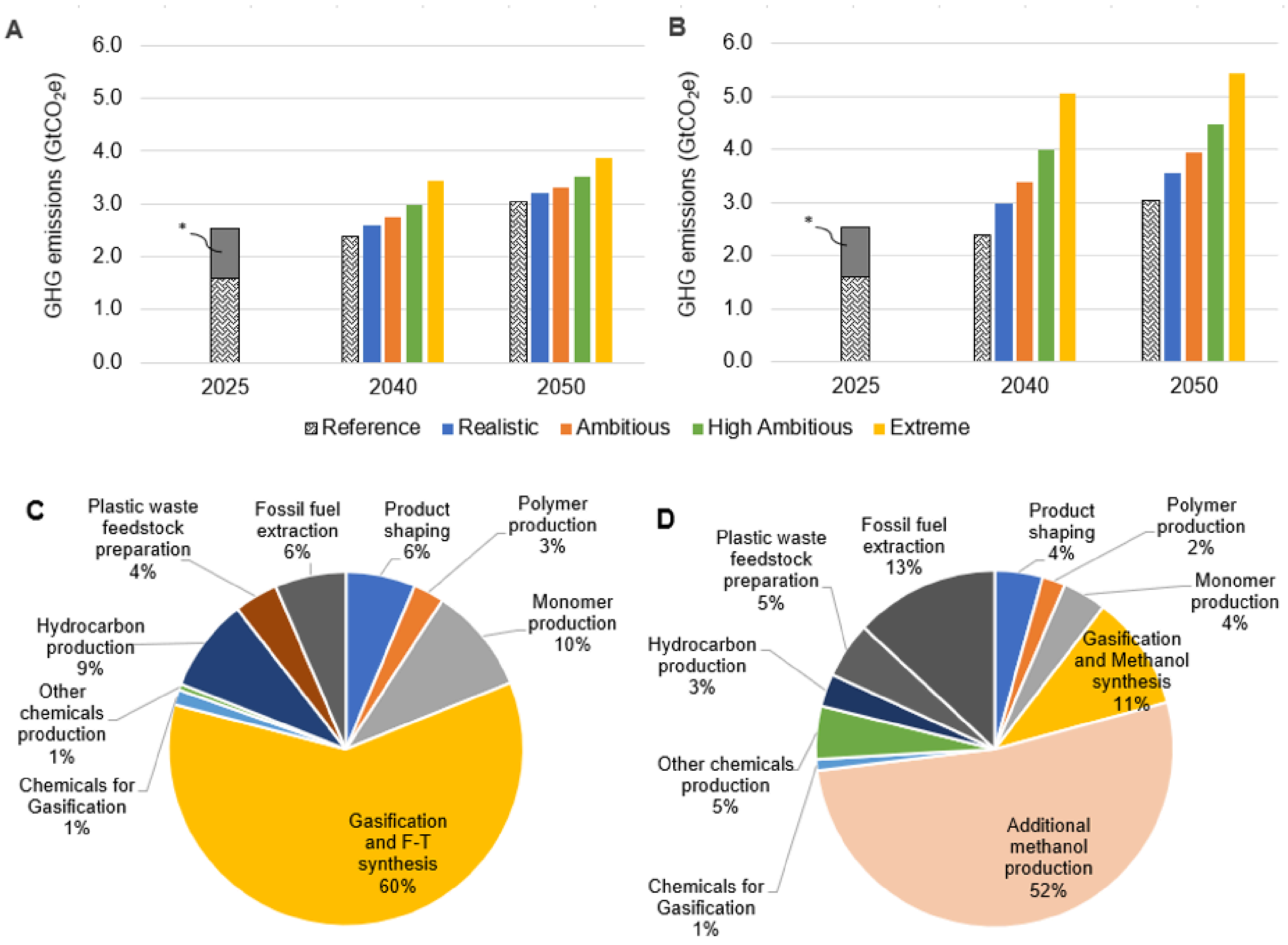


Figure 5

GHG emissions analysis for closed-loop gasification recycling scenarios

(A) GHG emissions from closed-loop gasification with F-T synthesis recycling scenarios compared to the Reference scenario; (B) GHG emissions from closed-loop gasification with methanol synthesis recycling scenarios compared to the Reference scenario; (C) GHG emissions shares by production stage for gasification with F-T synthesis in the Realistic scenario in 2050; (D) GHG emissions shares by production stage for gasification with methanol synthesis in the Realistic scenario in 2050.

*Note: * The grey box indicates the GHG emissions from other polymers in the Reference scenario that are not included in the gasification scenarios.*

Supplementary Files

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- Karalietal.6.9.25SupplementaryInformationNComm.pdf