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Integrating Decarbonization in the Plastic Value Chain for U.S. Plastic Waste Pollution Mitigation

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Plastics have shown economic and environmental benefits to human activities and cause intensive pollution due to the consumption surge over decades. Utilizing recycling coupled with alternative materials to substitute plastic use could reduce waste generation and its derived pollution by macro- and microplastic debris. This study uses an optimization-based approach to identify low-carbon and plastic pollution mitigation strategies aided by life cycle assessment and techno-economic analysis methodologies. A multi-objective plastic value chain optimization model is formulated to maximize the unit net present value (NPV) and minimize unit global warming potential. Results show that utilizing biomass for 60 % of plastic and alternative material production in 2024 could more than halve carbon emissions, compared to traditional fossil-based methods, which peaks the economic performance. Enhancing carbon capture and utilization's carbon conversion rates by 20 % can mitigate waste generation and pollution, reduce 25 % of climate impacts, and extend plastic material's recyclability and reusability after 2040.

1. Introduction

Since its invention in 1950, plastic has penetrated residential, industrial, and transportation sectors and has benefited human lives from its good physical and chemical properties for decades (Fan et al., 2022). By 2060, plastic consumption will double compared to the 2020 level, accounting for 3.4 % of global carbon emissions due to heavy energy and fossil resource use in material production (Chin et al., 2022). Although material alternatives, such as biodegradable packaging materials, have attracted wide research attention to show their potential in substituting plastic use and reducing carbon emissions, their high production costs and technological immaturity hindered scale-up manufacturing and wide application. The resulting incremental plastic consumption can lead to material debris generation by tons over the entire life cycle, especially in the runoffs of cost-effective land-based waste disposals, including open dumping and landfills. These foreign particles can burden air, water, and soil compartments by yielding macro- (>5 mm) and micro-sized debris (<5 mm), depicted by macro- and microplastics (MPs) (Zhao and You, 2023). With age, these minute particulates generate volatile organic chemical emissions, such as methane (Bang et al., 2023), and tax the climate (Zhao et al., 2022). As these environmental burdens accumulate from the material source to sink, mitigation efforts demand systematic technology solutions to curb waste generation and climate impacts exacerbated by global production and use surges to pursue carbon neutrality by 2050 (Gontard et al., 2022). Minimizing plastic pollution demands associated practices incorporated within the entire value chain, encompassing material production, use and reuse, and waste End-of-Life (EoL) treatment. High energy and input chemical consumption of waste chemical recycling and alternative materials production within the plastic value chain can further increase the climate burdens and disadvantage the low-carbon future (Costa et al., 2021). Carbon capture and utilization (CCU) processes, which repurpose captured carbon emissions for basic chemical manufacturing (Rudin et al., 2017), are technologically feasible in producing plastic monomers via hydrogenation, reverse water gas shifting (Bora et al., 2020), and electrocatalysis processes while reducing plastics' life cycle climate impacts. Producing alternative materials, including ephemeral or edible packaging (Hutchings et al., 2021), sourced from CCU processes can help reduce plastic consumption and pollution simultaneously with minimum carbon emissions. Nevertheless, coupling all these sustainable pollution mitigation strategies to maximize both the climate and

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economic benefits of the plastic value chain, as per the United Nation's (UN's) Global Plastic Treaty, remains a knowledge gap. Under both the United Nation's (UN's) Global Plastic Treaty and low carbon future contexts, our study provides by far the first investigation on the most economically and environmentally sustainable technology pathways aided by the holistic life cycle analysis and optimization accounting for the entire U.S. plastic value chain from 2024 to 2060, when the plastic pollution level is expected to triple without effective pollution control. Based on the optimal technology pathways, this study then identified the key technology and policy drivers that further maximize these sustainability benefits to pinpoint systematic innovation strategy for the entire material life cycle with the integration of carbon capture and utilization processes and energy decarbonization. Specifically, a bottom-up systems optimization approach is deployed to investigate the U.S. technology roadmaps with minimum plastic waste generation and pollution, considering the adoption of advanced technology in repurpose, reuse, and recycling (3R) practices with maximum economic and climate benefits to envision the improvement of existing interventions. The economic and environmental effectiveness of decarbonization for plastic pollution mitigation through advanced 3R practices is also examined.

2. LCA and Plastic Value Chain Optimization Methodology

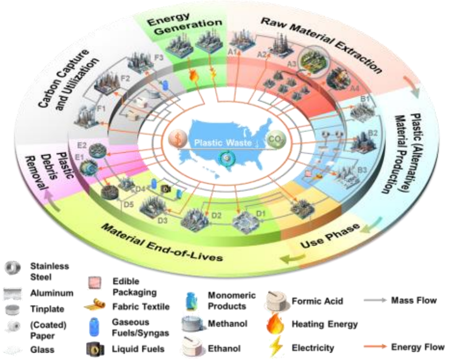

Figure 1: The system boundary of the plastic value chain for the plastics and alternative materials

2.1 Goal and Scope Definition

Our study mainly focused on pollution mitigation from the major use of plastic and its waste reuse, recycling, and EoL management by incineration and landfills. The practices for reorganizing plastic material production, including retrofitting the existing non-degradable polyolefin production into degradable alternatives sourced from biomass and carbon dioxide, effectively reduce waste generation. Our study also pinpointed relevant technological innovation spaces in this context by identifying the key technology and policy drivers toward minimizing plastic waste generation and climate impacts. This study evaluates the climate impacts of the proposed plastic value chain encompassing the "cradle-to-grave" life cycles of plastic and alternative materials (Chowdhury et al., 2023). Figure 1 depicts the plastic value chain encompassing all relevant processes to manufacture (processes A1−A4), use, and EoL waste management of plastic and alternative materials to replace plastic use (processes D1−D5). The major types of plastic materials aligned with the U.S. Environmental Protection Agency (USEPA) include polyethylene terephthalate (PET) (high density, low density, and linear low density) polyethylene (HDPE, LDPE, and LLDPE), polypropylene (PP), polystyrene (PS), and polylactic acid (PLA). The plastic materials are classified by durability into rigid and flexible counterparts (de Mello Soares et al., 2022), both of which are composed of single and multiple plastic components. Polyesters with high biodegradability, including PET and PLA, are widely used in mono-material plastic bottles, plates, bags, and cups. Polyolefins are the main components of rigid and flexible mono-material plastic packaging and household goods, such as Styrofoam made with PS. All these polyolefins are also blended into the multi-material widely used for business-to-business films, sachets, and other household goods, including plastic diaper components. According to the United Nations Conference on Trade and Development (UNCTAD), the alternative materials to substitute plastic use include glass, paper materials (paper board cartons and coated papers), natural fabrics, metals, and edible and ephemeral packaging embracing similar usability as plastics but with much higher degradability. Natural gas (Process A1) and crude oil (Process A2) are typical fossil-based raw materials to produce monomeric chemicals for plastic manufacturing (Process B1), while biomass-based conversion pathways (Process A3) yield these chemicals from wood chips and pellets, bark chips, miscanthus, sugar crops, oil crops, and algae through thermal-processing and fermentation processes. After use, the plastic and alternative materials undergo incineration, landfills, and recycling, including primary, secondary, and tertiary processes, to extend reusability and reduce virgin material production. Primary recycling (Process D1) onsite reuses the post-use materials after manual cleaning, while secondary recycling (Process D2) utilizes mechanical reclamation to effectively sort the unprocessed wastes from primary recycling to extend their material lifespan. Both primary and secondary recycling processes enable multiple uses of mono-material plastic materials for packaging and household goods (Dahlbo et al., 2018). Complex chemical components of the multi-materials without fractionation, such as the chemical additives or multiple plastic components within the durable goods (Vogt et al., 2021), can hamper the selectivity and yield of targeted monomeric products from traditional solvent-based depolymerization processes. Thermal-based chemical recycling effectively converts material waste with complex chemical compositions and yields plastic raw materials onsite with economic and environmental benefits. Given the large proportion of multi-material durable goods (38 %) within the U.S. domestic plastic wastes, the thermal-based processes (Process D3) accounted for the effective chemical recycling of these waste mixtures (Alqahtani et al., 2023). Conventionally used plastic and alternative material landfills (Process D5) generate material debris and derived MPs removed by ocean clean-ups (Cordier and Uehara, 2019) (Process E2) and water management processes utilized in wastewater or drinking water treatment plants (Process E1) coupled with incineration (Process D4) as typical EoLs for the captured particles. Existing studies have proven that CCU technologies can be integrated into the plastic life cycle to manufacture raw materials in the low-carbon future. These processes capture the free carbon dioxide (Process F1) and produce alkyl alcohols, acids, and syngas via hydrogenation, reverse water gas shifting (Bachmann et al., 2023), and electrocatalysis processes (Processes F1−F2) to supplement the subsequent plastic and alternative material production. The functional unit is chosen as one t of the plastic and alternative materials used within the value chain to align the mass and energy balances between each life cycle stage and help identify the environmental pros and cons of using these materials.

2.2 Life Cycle Inventories and Impact Assessment

The mass- and energy balance between the life cycle stages builds the entire plastic value chain's life cycle inventory (LCI) data (Lal and You, 2023). Specifically, the monomeric chemical product yields and energy consumption of fossil and biomass-based conversion pathways, which are extracted from relevant literature, are collated with the process-based LCI embedded in the Ecoinvent V3.10 Database as the LCI data of the upstream raw material extraction and material production (Zhao and You, 2024). The LCIs of material EoLs, including incineration, recycling, and landfills, are extracted from the Ecoinvent V3.10 Database and relevant studies on municipal solid waste management (FitzGerald et al., 2023), while the energy and chemical input data for chemical recycling are leveraged from the current plastic waste fast pyrolysis studies (Zhao et al., 2021). The avoided burden approach, minus the market processes of raw chemicals produced onsite via chemical recycling and CCU processes, is adopted to account for the environmental benefits of avoiding offsite production in the plastic value chain. The yield of monomeric products to manufacture plastic and alternative materials can be found in the relevant CCU studies. The electricity LCIs from 2024 to 2050 are built based on the energy mix percentages given by the U.S. e-Grid and USEPA data for the energy transition to 2050. These LCI data are then compiled with their associated characterization factors based on Intergovernmental Panel on Climate Change (IPCC) 2021, widely used for plastic waste processing LCA studies, to systematically analyze the overall environmental impacts and specific values of each life cycle stage interpreted as environmental breakdowns. These investigations can help identify the pros and cons of adopting 3R practices in the plastic value chain from 2030 to 2060. Specifically, the climate impacts are further collated into the environmental objectives in the following Plastic Value Chain Optimization Modelling Framework subsection to examine the most sustainable plastic value chain with minimum pollution and waste generation for a low carbon future.

2.3 Plastic Value Chain Optimization Modelling Framework

Based on the proposed plastic value chain, multiple material flow-based multi-objective optimization models are formulated and solved to identify the process adoption roadmaps with minimum unit global warming potential (GWP) and maximum economic feasibility measured by the unit NPV (*npv*), both of which values equal to their overall values over the project life span divided by the total plastics and alternative material consumption. The environmental objective function (*envv*) is the summation of those from basic chemical production, plastic manufacturing, recycling, other EoL waste management processes, and environmental impacts avoided by onsite chemical production. The economic objective is the unit NPV (*npv*) calculated by the total capital costs, operating expenditures, and total income from the entire plastic value chain. The optimization model includes five constraints to identify the most economically and environmentally sustainable technology pathway.

- **Pre-consumption Constraints:** Identify the technologies adopted for the upstream processes, including raw material conversion and plastic (alternative) material production, and indicate the mass flows of basic chemicals, intermediate and final products, and wastes among these life cycle stages.

- **Post-consumption Constraints:** Assess the plastic and alternative material consumption and waste generation each use cycle and the waste and plastic debris, in the forms of macro- and MPs, released to the natural environment from the entire material life cycle.
- **Energy Analysis Constraints:** Calculate the electricity and heat consumption and generation within the plastic value chain subjected to the optimization objectives and U.S. energy transitions.
- **Techno-economic Assessment Constraints:** Estimate the unit NPV of operating the processes adopted in the plastic value chain subjected to the optimization objectives.
- **Life Cycle Climate Impact Assessment Constraints:** Assess the climate change impacts posed by material and energy consumption, generation, and waste emissions within the entire plastic life cycle.

Optimizing these two unit-based objectives helps industrial sectors identify key technology strategies under a fair comparison between each technology pathway regardless of their treatment capacities. Adoption of these strategies by industries or large corporations can foster economic and climate co-benefits in ongoing plastic pollution mitigation practices. The optimal economic performance of the entire value chain with minimum environmental pollution (*envv*) can also pinpoint necessary economic incentives from governmental agencies and NGOs and financial support for industries and large corporations in technology scale-ups and adoption. The model formulation can be found below:

max *npv*
min *envv*
s.t. Pre-consumption constraints
Post-consumption constraints
Energy consumption analysis constraints
Techno-economic assessment constraints
Life cycle climate impact assessment constraints

This plastic value chain technology roadmap optimization problem is formulated as a multi-objective mixed-integer linear programming (MILP) problem. The *ε*-constraints method is used to linearize the environmental objective function *envv* based on the auxiliary parameter (*EPSS*), and the entire multi-objective optimization model is reformulated into single-objective, which guarantees finite iterations for effective solutions (Zhong and You, 2014). The reformulated MILP model was solved by the CPLEX 22.1.1.0.

$$envv \leq EPSS \quad (1)$$

3. Results and Discussion

3.1 Low-carbon and Pollution Plastic Value Chain

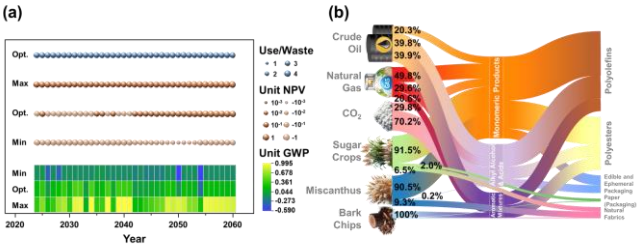

Figure 2: Sustainability performances and material consumption in 2024 of the plastic value chain

One primary goal in improving U.S. plastic pollution mitigation strategies from the value chain is maximizing their economic and environmental benefits with minimum waste generation and pollution. Figure 2a represents the economic and environmental performances, plastic pollution, and waste generation of the most economically and environmentally sustainable plastic value chain technology pathway. By 2024, producing plastics from more than 60% biomass, including wood chips, sugar crops, miscanthus, and bark chips, embraces the maximum climate benefits (-0.11 t CO_2eq/t) with 126 % lower carbon emissions compared to the most economically feasible alternatives utilizing fossil resources for plastic production (0.53 t CO_2eq/t), as shown in Figure 2. Biomass cultivation absorbs carbon dioxide and reduces the life cycle carbon emissions to negative while utilizing the fossil resources, including crude oil and natural gas, to produce plastic monomers from refineries, avoid biomass cultivation and processing costs, and maximize economic profitability. Onsite carbon conversion via CCU processes to basic chemicals, including monomeric and alkyl alcohol and acids shown in Figure 2b, can benefit the climate but also come with high capital costs (over 500 \$/t CO_2 treated), turning the economic feasibility negative. Figure 2a shows that replacing over 30 % plastic for packaging and household use with alternative materials, including paper and natural fabrics, can enhance material reusability and further help reduce 75 % of plastic waste generation and derived pollution posed by macro debris and MPs. As the UNFCCC suggests, biomass-based plastic production and waste chemical recycling will become more technically mature in the long term to 2060, which reduces their capital costs for technology implementation in plastic pollution mitigation. After 2043, the enhanced adoption of these processes will contribute to the positive unit NPV (Figure 2a) within the plastic value chain and improve carbon benefits, as indicated by over 80 % carbon reduction compared to 2023. Given these long-term co-benefits of decarbonization efforts, bio-based production, and effective recycling on the plastic value chain, a detailed investigation of their effects on plastic circularity and pollution mitigation is crucial to pinpoint specific measures and their time points to deploy with improved economic and climate co-benefits.

3.2 Decarbonization Efforts Facilitate Plastic Pollution Mitigation

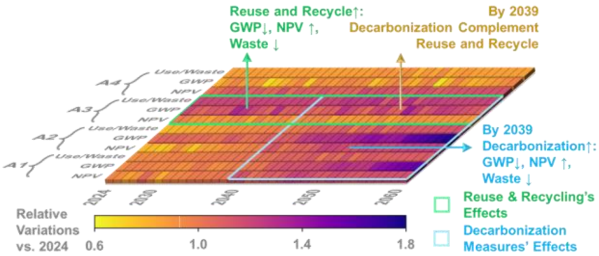

Figure 3: Effects of decarbonization efforts and plastic recyclability on the plastic value chain performances

The effects of two decarbonization drivers, including promoting carbon credits and carbon dioxide conversion efficiency aligning with the Inflation Reduction Act (IRA), were systematically investigated on the economic and environmental performances of the proposed optimal plastic value chain in plastic pollution mitigation. A1−A4 represents the scenarios associated with promoting carbon credits, enhancing and reducing plastic reusability and recyclability, and improving carbon dioxide conversion efficiency. Figure 3 indicates that after 2040, enhancing the carbon capture and utilization conversion rates by 20 % associated with case A4 can reduce the waste generation pollution and climate impacts by 10 % and 25 % while extending the plastic material's recyclability and reusability aided by more degradable plastics manufactured from CCU processes. A 20 % increment on the carbon credits can incentivize CCU technology adoption to facilitate carbon conversion via reverse water shifting and hydrogenation processes, expanding the production of basic chemicals for manufacturing plastic and alternative materials and mitigating the GWP by 15 % from 2024 to 2039, as shown by Figure 3. Another venue for obtaining dual benefits on climate and plastic pollution mitigation is coupling decarbonization with advanced waste recycling processes, such as chemical recycling, to improve material reusability and recyclability. For instance, extending 20 % more plastic reusability and recyclability enables a reduction of 10 % in climate impacts and 33 % in waste yield in 2039, as shown in Figure 3. By 2039, the lower capital costs can promote the adoption of CCU technologies when coupled with advanced chemical recycling processes, both of which will improve the climate and economic co-benefits by over 10 % of the plastic value chain while reducing waste generation. Issuing higher carbon credits and enhancing carbon conversion can further improve these co-benefits by over 9 %, which continues to grow by 47 % until 2060, shown in Figure 3. Our study drew on the country-average data to offer local technological solutions but did not capture the U.S. state-level variances in plastic production, consumption, and technology adoption and feasibility influenced by the regional economies, which did not capture the various uncertainties in plastic purities, and technology adoptions and operations.

4. Conclusions

To address the global plastic pollution and climate concerns growing with age, this study identified the most economically and environmentally sustainable technological strategies across the entire U.S. plastic value chain, encompassing sustainable production, use, and EoL waste management. Through delineating these comprehensive strategic technology roadmaps over decades and evaluating their sustainability performances in processing domestic or imported plastic wastes, this study offered crucial preliminary insights into future technology improvement spaces. These implications help associated stakeholders pinpoint and substantiate specific plastic pollution mitigation policy measures necessitating both local and global efforts. Technological innovations such as repurposing carbon emissions to plastic materials via biomass conversion should be incentivized to decarbonize the plastic value chain with a 55 % GWP reduction. Coupling such practices with advanced waste chemical recycling and CCU technologies enables onsite monomeric material production for plastic and alternative material manufacturing with improved climate and economic benefits of over 35%. This integrated approach also promotes material circularity and subsequently cuts waste generation and pollution from the plastic value chain by replacing plastic use with yielded alternative materials. Economic support for these plastic value chain decarbonization efforts includes issuing higher carbon credits or incentivizing CCU technology adoption and innovation. These policy tools boost carbon conversion to raw materials by 20 %, including monomers and alkyl alcohols, utilized in plastic and alternative material production that helps reduce plastic waste generation. Such practices can also avoid carbon emissions from exterior production and facilitate decarbonizing the plastic value chain, encompassing material production, use, and EoL waste management under the low carbon future.

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