

# Flow Simulation of Plastic Life Cycle Considering Carbon Renewability and Environmental Impact

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## ABSTRACT

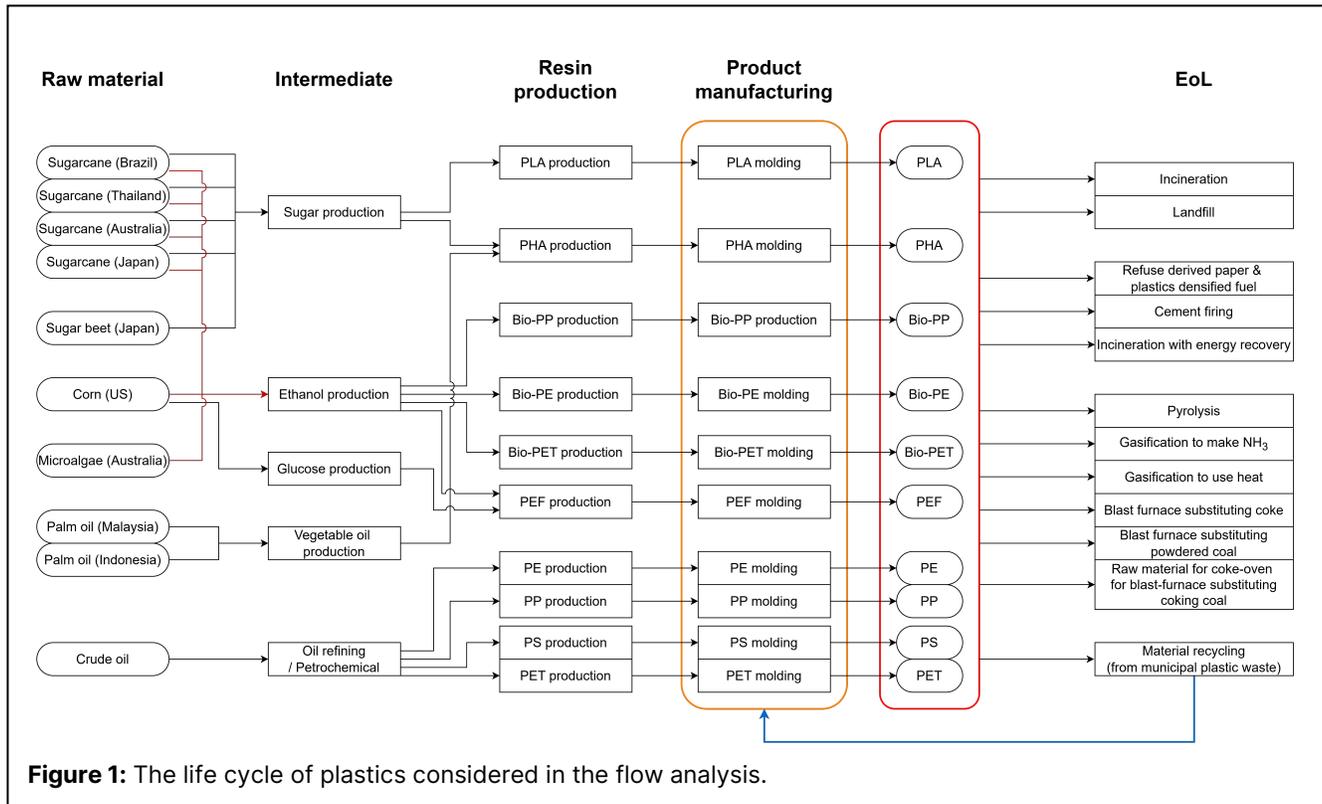
Renewable carbon sources, such as biomass and waste, are being explored as alternatives for sustainable plastic production. However, the significant uncertainties surrounding the environmental impact of biomass supply processes raise questions about whether these plastics positively contribute to society. Furthermore, the lack of systematic knowledge about plastics and incomplete understanding among stakeholders pose challenges to conducting comprehensive assessments and designing effective plastic life cycle systems. This study aims to clarify the carbon flow within the life cycle of biomass- and recycled-derived plastics and to design a plastic life cycle that enables the introduction of renewable carbon sources. To this end, the study analyzed the structure of plastics containing renewable carbon and conducted a flow analysis of packaging plastics in Japan. The flow analysis was conducted in the form of an optimization problem. Greenhouse gas (GHG) emissions and the proportion of renewable carbon were selected as assessment indicators and objective functions. Constraints for optimization included the availability of biomass supply, the demand for product resins, and the processing capacity of various End-of-Life (EoL) methods. As a result, it was revealed that the priority of resin types to be produced and recycled shifts in response to changes in constraints such as biomass input and recycling capacity. Furthermore, a trade-off between reducing environmental impact and increasing the renewability of carbon was identified, highlighting the necessity of designing systems that balance these factors. This research provides valuable insights for designing sustainable plastic life cycles in the future.

**Keywords:** Life Cycle Analysis, Flow analysis, Biomass-derived plastic, Recycling, Carbon renewability

## INTRODUCTION

Fossil-based plastics, owing to their convenience, are materials that contribute significantly to modern societal benefits. However, their production and disposal are accompanied by substantial environmental challenges, including GHG emissions [1] and the issue of marine plastic pollution [2], making it clear that urgent countermeasures are required. Plastics derived from biomass or recycled materials utilize sustainable carbon sources and are considered to emit lower GHG levels across their life cycles. As such, their broader adoption is being explored as an alternative to conventional fossil-based plastics. Research on the environmental impacts of these plastics has been vigorous. For instance, case studies employing life cycle assessment (LCA) have assessed

the environmental and economic impacts of specific plastics, such as PHBH (Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)) and Bio-PE, comparing them to traditional fossil-derived plastics [3, 4]. Nevertheless, it remains unclear whether the adoption of these materials will genuinely yield positive environmental and societal outcomes. Variations in environmental assessments arise due to differences in factors such as the type of biomass used as feedstock, resin production processes, and geographic boundaries. Moreover, comprehensive and quantitative assessments of the environmental impacts that arise from introducing multiple resins into existing societal systems remain scarce. A further complication is the incomplete understanding of the carbon flow pathways within the plastic life cycle. This lack of clarity weakens the connections between stakeholders involved



in various stages of the plastic life cycle, creating challenges in designing flexible, sustainable life cycles aligned with a sustainable society.

This study first aims to elucidate the potential changes in the overall carbon life cycle brought about by the introduction of plastics derived from biomass and recycled carbon sources. Building on this understanding, it aims to conduct a flow analysis from the perspectives of environmental impact and carbon renewability. Ultimately, the study aspires to design more sustainable life cycles that facilitate the adoption of biomass- and recycled-derived plastics.

## METHOD

### Assessment targets / indicators

In this study, a case analysis was conducted, focusing exclusively on plastics used for packaging applications in Japan. The resins selected for assessment included conventional fossil-derived plastics commonly used in packaging (PE, PP, PS, PET) as well as biomass-derived plastics such as Bio-PE, Bio-PP, Bio-PET, PEF (Polyethylene Furanoate), PHA (Polyhydroxyalkanoates), and PLA (Poly-Lactic Acid). PHA, PLA, and PEF were chosen as examples of biomass-derived plastics with either significant current production volumes or well-established manufacturing technologies [5]. Meanwhile, Bio-PE, Bio-PP, and Bio-PET were selected to explore the feasibility of substituting existing fossil-based plastics

with biomass-derived counterparts that possess identical physical properties. Additionally, recycled resins produced through material recycling of these plastics were also included in the assessment.

The assessment criteria were established based on challenges identified in the current plastic life cycle. Climate change, measured through GHG emissions, was selected as the key indicator for assessing environmental impacts. To quantify the renewability of carbon within the life cycle, the amount of renewable carbon (sourced from biomass or recycling) within the system was adopted as a supplementary indicator.

### System boundaries

To establish the system boundary, a bibliometric analysis was first conducted to cluster relevant literature, extracting key terms associated with the resins and technologies under assessment. Subsequently, based on these keywords, an extensive review of existing literature on plastics was carried out. Information on raw materials, manufacturing methods, applications, and EoL strategies—including those not yet commercialized—was collected for various plastics. This data facilitated the creation of a superstructure for the plastic lifecycle [6]. The superstructure revealed that the introduction of renewable carbon into the plastic system creates numerous combinations of technologies at both the raw material and EoL stages [7, 8]. The choice of raw material, the resulting resin, and the selection and combination of EoL

strategies significantly influence the environmental impact and carbon renewability across the entire lifecycle. The system boundary for analyzing the flow of plastic packaging materials was constructed based on this superstructure, as illustrated in **Figure 1**. In this study, sugarcane, sugar beet, corn, microalgae, and palm oil were considered as biomass feedstock options. The geographic boundaries for each raw material were also taken into account. The raw materials are processed into plastics via intermediate products such as sugar, bioethanol, starch, and vegetable oils. For waste plastics, the EoL options examined included no-recovery methods like incineration and landfilling, as well as energy recovery, non-closed-loop chemical recycling, and closed-loop material recycling.

### Model construction

A linear programming approach was employed to optimize the flow. The objective functions for environmental impact and carbon renewability were defined as shown in equations (1) and (2), respectively, and calculations were performed for each.

$$\text{Min. } G_{total} = \sum_{mat}^{all} \sum_{tech}^{all} \sum_{resin}^{all} M_{mat,tech,resin} E_{mat,tech,resin} + \sum_{resin}^{all} \sum_{EoL}^{all} M_{resin,EoL} E_{resin,EoL} \quad (1)$$

$$\text{Min. } W_{total} = \sum_{mat}^{fossil} \sum_{tech}^{all} \sum_{resin}^{all} M_{mat,tech,resin} + w \cdot G_{total} \quad (w \cdot G_{total} \ll M_{mat,tech,resin}) \quad (2)$$

Here,  $M$  [t] represents the mass of product resin in the equation,  $E$  [t-CO<sub>2</sub> eq/t-product] denotes the GHG emission factor, and  $w$  [-] signifies the weighting coefficient in the weighted sum method. The second term in equation (2) is provided to manage the flows at the product's EoL stage, excluding material recycling processes that do not affect carbon renewability. GHG emission factors and inventory data for each process in the equations were primarily sourced from the literature. The details of the

data sources are provided in the supplementary information. The constraints considered include technological feasibility, the supply availability of various biomass feedstocks, the demand for product resins, and the processing capacities of each EoL method. Technological feasibility was defined such that  $M = 0$  t for flows deemed infeasible or excluded under specific cases. The upper limits for biomass supply were set based on the current production ratios for each raw material and were assumed to vary proportionally while maintaining these ratios. The demand for product resins was estimated from the current consumption volumes (assumed equal to production volumes) of PE, PP, PS, and PET in packaging applications [9], representing the functional requirements plastics must fulfill in society. It was assumed that these functional requirements would remain unchanged even if replaced with renewable carbon-derived plastics. For substitution with other resin types, calculations were based on prior studies comparing the environmental impacts of bio-based and fossil-based plastics [10-12], assuming resins of the same volume have equivalent functionality. The upper limits for the processing capacities of EoL methods were determined using data on the current processing volumes for each method in Japan.

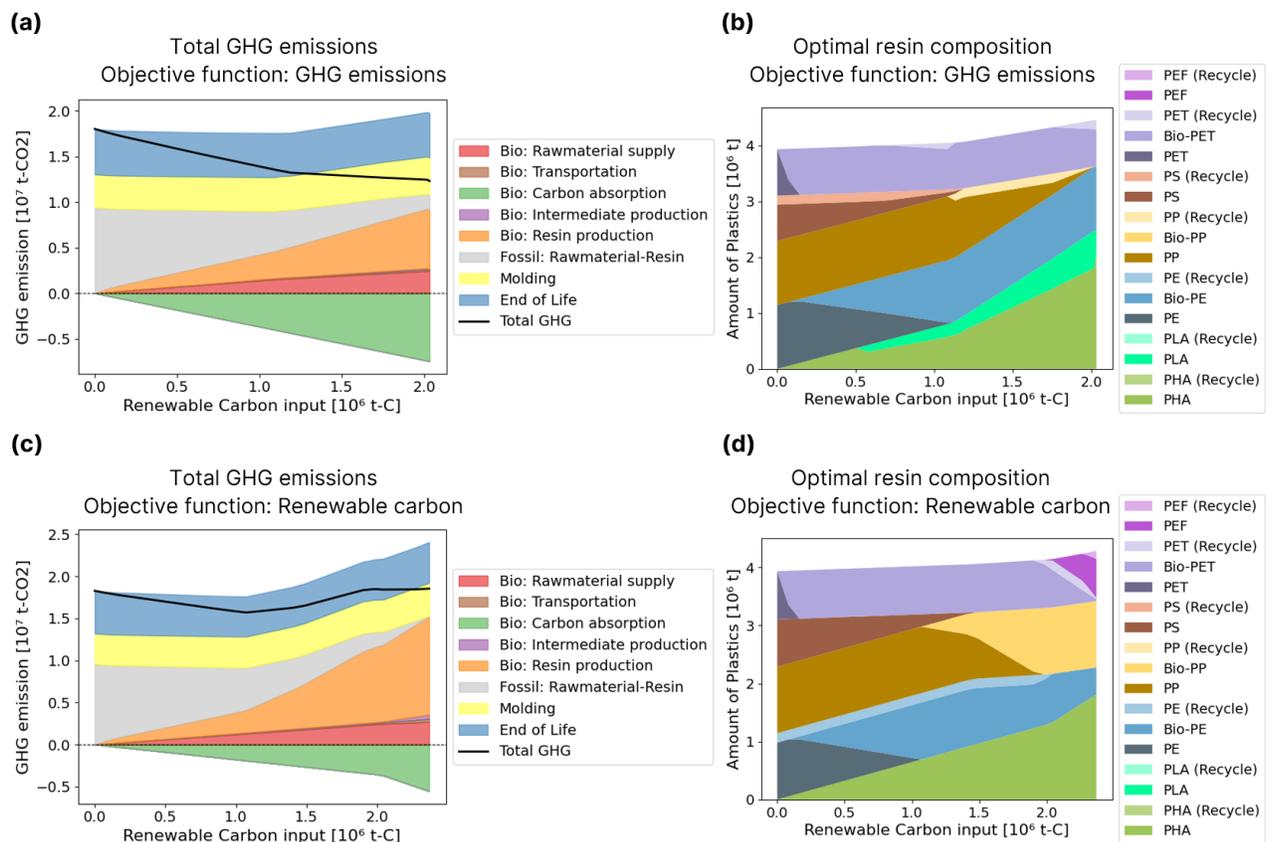
In this study, three cases, as shown in **Table 1**, were examined to visualize changes in the life cycle due to variations in constraint conditions. Case I and Case II represent cases in which the availability of biomass supply improves, while Case III alters the values of constraint conditions related to both the biomass supply and the capacity for material recycling processing. In Case I, the production of all resins shown in **Figure 1** is considered. In contrast, Case II excludes PHA from the target resins, reflecting the fact that the life cycle of PHA is not yet well established. All other constraint conditions and parameters are set identically.

## RESULTS AND DISCUSSIONS

**Figure 2** presents the results of GHG emission optimization in Case I based on Equation (1). The horizontal

**Table 1:** Cases of Future Changes in Plastic Life Cycles Considered in the Flow Analysis

	Case I	Case II	Case III
<b>Assessment targets</b>	All plastics shown in Figure 1	Excluding PHA from Case I	All plastics shown in Figure 1
<b>Biomass Supply Potential</b>	Variable	Variable	Constant (1% of the production volume of each biomass material is available for use)
<b>Recycling capacity</b>	Constant (equivalent to current capacity)	Constant (equivalent to current capacity)	Variable

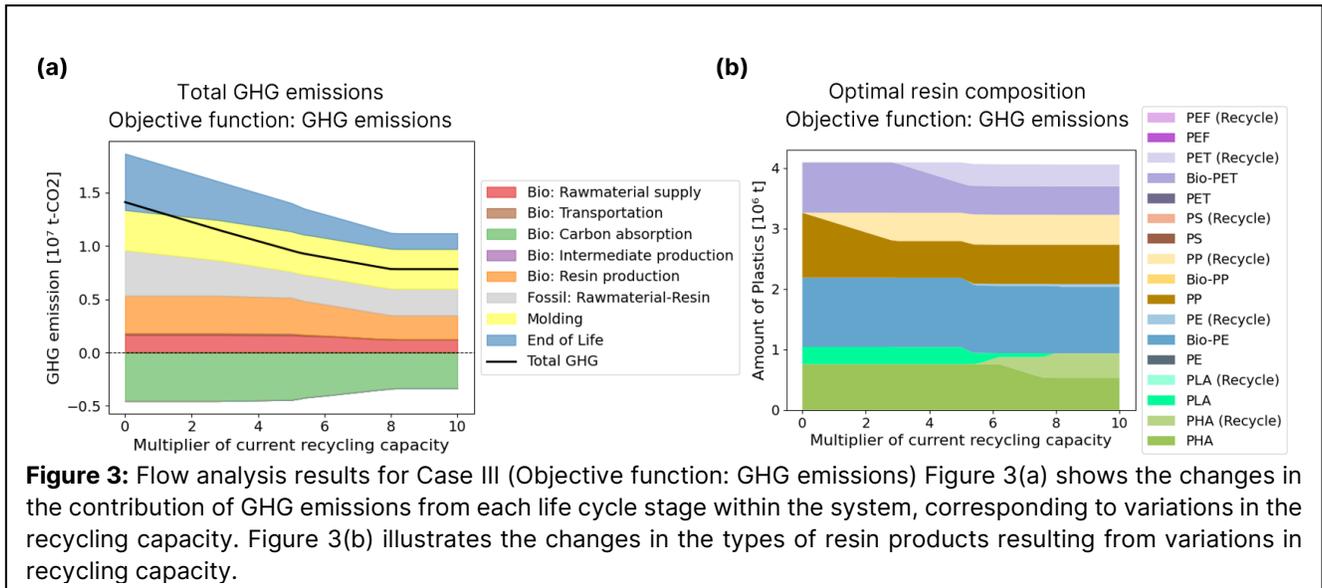


**Figure 2:** Flow analysis results for Case I. (a, c) Objective function: GHG emissions (b, d) Objective function: Renewable carbon within the system. The left-hand diagram shows the changes in the contribution of GHG emissions from each life cycle stage within the system, corresponding to variations in the amount of renewable carbon introduced. The right-hand diagram illustrates the changes in the types of resin products as the amount of renewable carbon introduced varies.

axis represents the amount of renewable carbon introduced into the system. The points at which the slope of total GHG emissions changes in **Figures 2(a) and 2(c)** correspond to shifts in the types of resins prioritized for production or recycling, as well as transitions in the raw materials used for production, as shown in **Figures 2(b) and 2(d)**. As shown in **Figure 2(a)**, GHG emissions decrease with increasing biomass input, demonstrating the superiority of biomass from the perspective of GHG emission reduction. This reduction is primarily attributed to carbon sequestration during biomass cultivation. Additionally, regardless of the level of biomass input, various life cycle stages—such as raw material supply, carbon absorption by biomass, resin production, and EoL processes—significantly contribute to the total GHG emissions of container and packaging plastics. This highlights the necessity of designing the system across the entire life cycle. **Figure 2(b)** reveals that PET should be replaced with Bio-PET and PS should be substituted with PHA or recycled alternatives as a priority. This indicates that considering the environmental burdens of biomass feedstock and the avoided impacts of recycling, these

substitutions achieve significant reductions in GHG emissions. **Figures 2(c) and 2(d)** illustrates the results when minimizing the amount of fossil-derived carbon within the system in Case I. By introducing approximately 2.3 Mt of renewable carbon, defossilization within the system was achieved. Compared to the GHG-optimized result, as seen in **Figure 2(d)**, the types and order of resins prioritized for introduction or recycling differ, with Bio-PP introduction and PE recycling taking precedence. However, as shown in **Figure 2(c)**, a trade-off was observed in which the total net GHG emissions increased with biomass introduction. This suggests that balancing environmental impacts and renewability must be carefully considered when designing a sustainable system reliant on biomass.

In the GHG optimization results for Case II, PLA and PEF were selected as biomass applications instead of PHA, which was prioritized for introduction in Case I but was absent in Case II. However, as PLA and PEF are less advantageous than PHA in terms of environmental impact, the system's total GHG emissions increased by up to 4% during the renewable carbon introduction process.



**Figure 3** presents the results of GHG emission optimization in Case III, based on Equation (1). The horizontal axis represents the multiplier relative to the current material recycling capacity. From the results in **Figure 3(b)**, it is evident that material recycling is prioritized in the order of PP, PET, and PHA. This prioritization reflects the combined environmental impact of recycling itself and the avoided environmental burden of raw material supply, favoring resins with the greatest reduction potential. As shown in **Figure 3(a)**, an increase in the upper limit of recycling capacity leads to a monotonic decrease in the system's overall GHG emissions, supporting the effectiveness of recycling. However, when the input of biomass feedstock is low, increasing recycling capacity beyond a certain point no longer impacts the objective function value, and complete defossilization remains unachieved. At this stage, the proportion of carbon derived from recycling is approximately 30-40%. This limitation arises from incorporating the substitution rate into the model to account for the degradation in quality of recycled materials. These findings suggest that, while recycling is effective, achieving greater system renewability requires the continued expansion of biomass feedstock introduction. Furthermore, closed-loop chemical recycling methods, such as repolymerization, which were not considered in this study, have the potential to reintegrate plastics into their life cycle while maintaining high quality. Such methods may offer advantages over the currently considered EoL processes in terms of both environmental impact and resource renewability [13, 14]. Therefore, incorporating these advanced recycling methods into flow analysis is essential for designing a more sustainable life cycle.

## CONCLUSIONS

In this study, a flow analysis methodology was developed to assess the plastic life cycle in Japan's packaging sector, focusing on the introduction of biomass-derived and recycled carbon. The assessment was conducted from the perspectives of environmental impact and carbon renewability. The findings revealed the types of resins that should be prioritized for production and recycling under constrained conditions, such as limited biomass supply and recycling capacity, as well as the effects of such prioritization. Furthermore, it was demonstrated that a trade-off may exist between reducing GHG emissions and improving carbon renewability. Achieving a low-GHG, decarbonized system requires the dual advancement of biomass utilization and recycling expansion.

The developed flow analysis framework is adaptable to changes in assessment targets, technologies, and variables. Future expansions of the model should incorporate additional applications, resin types, and processes, including chemical recycling, to enable more comprehensive flow analyses. Moreover, sustainability discussions should assess additional environmental indicators, such as eutrophication—which may be significantly affected by the introduction of biomass—and the potential for introducing biodegradable plastics, taking into account plastic leakage into the environment. Taking these considerations into account, a sustainable life cycle should be carefully designed through scenario analysis that takes into account future system changes.

## DIGITAL SUPPLEMENTARY MATERIAL

For a detailed explanation of the methodology for system boundary construction and the data sources

used for flow analysis model construction, including GHG emission intensities, please refer to the supplementary material available at <https://psecommunity.org/LAPSE:2025.0040>.

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