Comparative Life Cycle Assessment of Incineration, Gasification, and Pyrolysis for Plastic Waste Treatment

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ABSTRACT

The increasing use of plastics has led to a continuous rise in the generation of plastic waste. Due to their high calorific value, plastic waste has traditionally been treated primarily through incineration with energy recovery. However, environmental concerns have been raised regarding greenhouse gas emissions, air pollutants, and resource losses associated with the incineration process. Accordingly, chemical recycling technologies, which convert post-consumer plastic waste into feedstocks or chemical products for subsequent reuse, have recently attracted attention as a potential alternative to conventional waste treatment methods. Nevertheless, a quantitative assessment is required to evaluate the relative environmental performance of chemical recycling and conventional incineration, particularly when the treatment processes and resource recovery are taken into consideration. Therefore, this study compares the environmental impacts of plastic waste treatment through incineration, gasification and pyrolysis using a Life Cycle Assessment(LCA) approach. The environmental impacts of each treatment process were assessed using a consistent functional unit and system boundary, with particular consideration given to greenhouse gas emissions and the environmental benefits associated with energy and material recovery. The results showed that the gasification scenario (S4) achieved the largest net GHG reduction of −531.59 kg CO_2-eq per ton of waste plastic, followed by incineration with heat recovery (S2) at −28.75 kg CO_2-eq. In contrast, incineration with electricity generation (S1) and pyrolysis with oil recovery (S3) resulted in net GHG emissions of 1,545.97 and 1,499.77 kg CO_2-eq, respectively. These results indicate that gasification with chemical product recovery and high-efficiency heat recovery can provide greater GHG reduction potential than conventional incineration with electricity generation.

Keywords: Life Cycle Assessment/ Plastic Waste/ Chemical Recycling/ Gasification/ Pyrolysis

1. INTRODUCTION

Plastic consumption has continued to increase globally, resulting in a rapid rise in plastic waste generation. Although plastics offer excellent physicochemical properties and economic advantages, their widespread use has intensified environmental concerns associated with waste management [1]. In recent years, chemical recycling, including pyrolysis and gasification, has attracted attention as a potential alternative for treating plastic waste that is difficult to process through mechanical recycling. By converting waste plastics into feedstocks or chemical products, these technologies can contribute to resource recovery and circularity. However, chemical recycling also involves environmental burdens from energy and raw material consumption, as well as process emissions and by-products. Therefore, a life cycle-based assessment is needed to comprehensively evaluate its environmental performance. This study applies Life Cycle Assessment (LCA) to compare the environmental impacts of plastic waste treatment through incineration, gasification, and pyrolysis, considering both process-related emissions and environmental benefits from material and energy recovery. In particular, actual operational data from an actively operating gasification facility were used to improve the representativeness of the assessment. Figure 1 illustrates the system boundary defined for the LCA of plastic waste treatment.

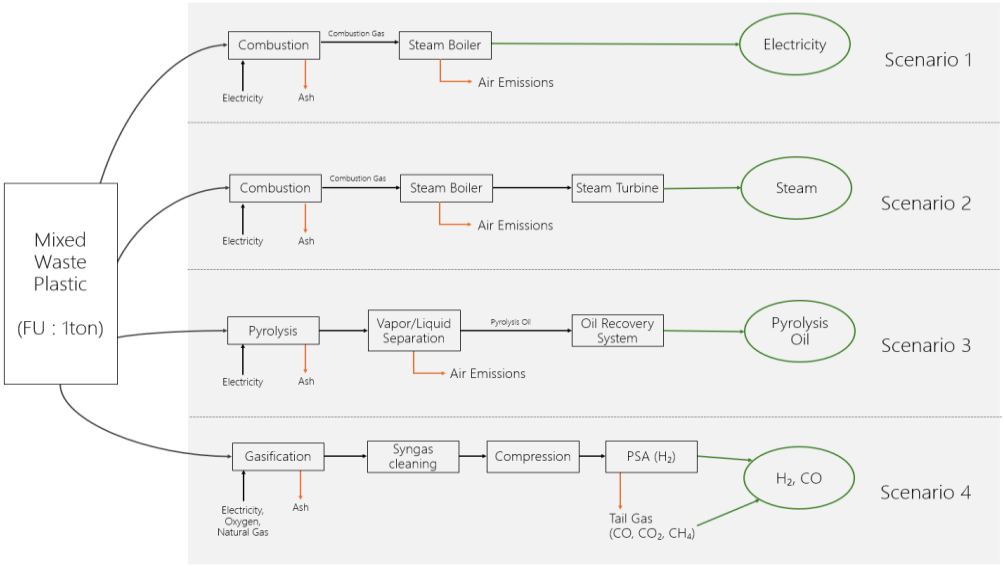

Figure 1. System Boundary of the LCA for Plastic Waste Treatment

2. METHODOLOGY

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology used to quantitatively evaluate the environmental impacts generated throughout the entire life cycle of a product or service, from raw material production to manufacturing, use, disposal, or recycling. LCA is conducted based on the principles and requirements specified in ISO 14040 and ISO 14044 [3,4] and generally consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. LCA has been widely applied not only to assess the environmental performance of products and processes but also in various fields, including process design and policy development. In recent years, chemical recycling, including pyrolysis and gasification, has attracted attention as a potential alternative for treating plastic waste that is difficult to process through mechanical recycling [2].

2.2 LCA Modeling and Assessment Settings

In this study, a life cycle assessment (LCA) model was developed using openLCA to quantitatively evaluate the environmental impacts of waste plastic treatment processes. The functional unit was defined as the treatment of 1 ton of waste plastic, and life cycle inventory (LCI) databases including ELCD v3.2 and ecoinvent were utilized. Process data were compiled from actual operational data, theoretical calculations based on preliminary laboratory experiments, and literature reviews. The IPCC 2021 GWP 100 method was applied for the impact assessment. Furthermore, the substitution effect of recovered heat, electricity, and recycled raw materials from incineration, pyrolysis, and gasification processes on conventional fossil fuel-based energy and products was incorporated, thereby comprehensively evaluating both direct environmental burdens and avoided burdens resulting from resource and energy recovery.

3. RESULTS AND DISCUSSION

3.1 LCA Results and Discussion

The life cycle assessment (LCA) results are presented in Figure 2. The gasification scenario (S4) showed the largest net GHG reduction, with a net impact of –531.59 kg CO_2-eq, followed by the incineration with heat recovery scenario (S2), which also achieved a net reduction of –28.75 kg CO_2-eq.In contrast, the incineration with electricity generation scenario (S1) and the pyrolysis with oil recovery scenario (S3) resulted in positive net GHG emissions of 1,545.97kg CO_2-eq and 1,499.77 kg CO_2-eq, respectively. Despite using the same incineration process, S2 showed a substantially lower net GHG emissions than S1, which can be attributed to the higher efficiency of heat recovery and the greater avoided emissions associated with the displacement of fossil-fuel-based steam production. The gasification scenario (S4) exhibited the lowest net GHG emissions among the evaluated waste plastic treatment options because the produced hydrogen and carbon monoxide could displace conventionally produced hydrogen and carbon monoxide, such as steam methane reforming (SMR)-based hydrogen production, resulting in substantial avoided emissions. In contrast, the relatively high emissions associated with auxiliary fuel consumption in the pyrolysis process contributed to its higher environmental burden. Therefore, optimizing the reaction temperature and improving the reuse of by-product gases as an internal energy source could further improve the environmental performance of the pyrolysis process. Overall, the results suggest that high-efficiency heat recovery and chemical recycling through gasification may provide greater potential for GHG reduction than conventional incineration with electricity generation.

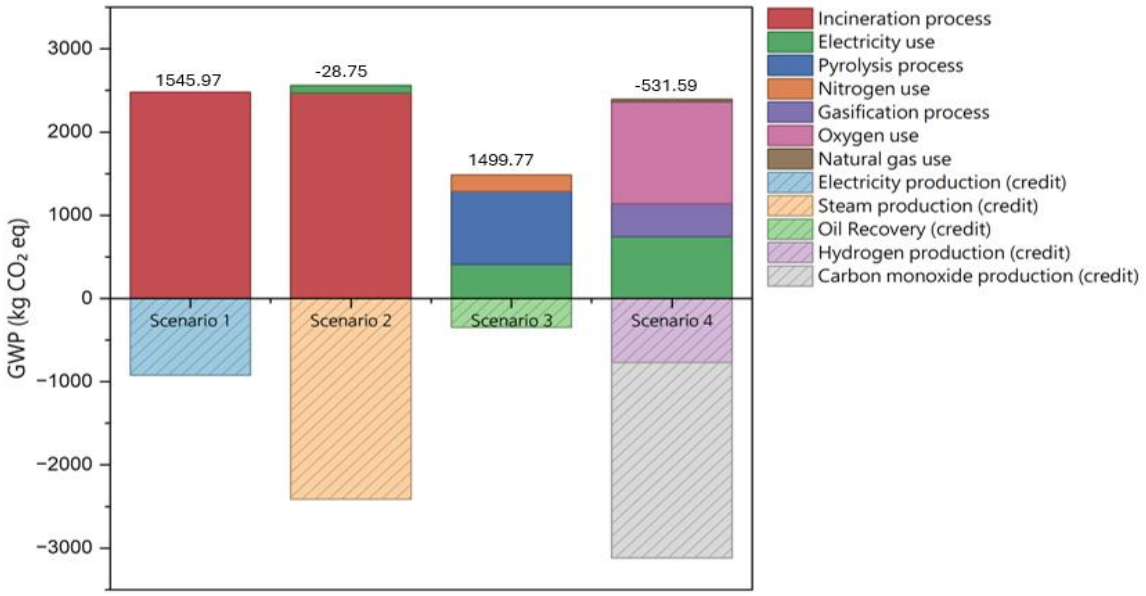

Figure 2. Life Cycle Global Warming Potential of Different Scenarios

4. CONCLUSIONS

Based on the life cycle assessment and scenario analysis in this study, several key conclusions are drawn as follows:

1. The gasification process (S4) achieved the lowest net GHG impact of -531.59 kg CO_2-eq, demonstrating the highest greenhouse gas mitigation potential by replacing conventional fossil fuel-based SMR hydrogen and carbon monoxide production.
2. For incineration pathways, heat recovery (S2) exhibited substantially lower net emissions than electricity generation (S1), as higher thermal recovery efficiency (70% vs. 20%) generated larger avoided emission credits from fossil steam displacement.
3. The pyrolysis process (S3) was modeled using literature data to supplement the low oil yield from preliminary laboratory experiments, confirming that GHG mitigation benefits remain limited under single oil recovery conditions. Accordingly, future research intends to incorporate the recovery and energetic utilization of byproduct syngas to comprehensively evaluate and improve its environmental performance.

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