Life Cycle Assessment of Plastic Waste Conversion Technologies: Pyrolysis vs. Incineration

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ABSTRACT

Plastic waste management is a critical environmental challenge worldwide. Among the available technologies for plastic waste treatment, pyrolysis and incineration are commonly used for converting plastic waste into energy or useful byproducts. This manuscript presents a comprehensive life cycle assessment (LCA) comparing pyrolysis and incineration technologies for plastic waste conversion, focusing on environmental impacts, energy recovery efficiency, and emission profiles. The study employs a cradle-to-grave analysis including raw plastic waste collection, processing, conversion, and disposal stages, with emphasis on carbon footprint, energy consumption, and pollutant emissions. Results indicate pyrolysis offers advantages in resource recovery and lower emissions of dioxins and furans, while incineration is characterized by higher thermal energy output but increased pollutant release. The conclusions provide insights for policymakers and engineers to optimize plastic waste management systems using sustainable and environment-friendly approaches.

KEYWORDS

Plastic waste management, pyrolysis, incineration, life cycle assessment, environmental impact, energy recovery, emission analysis

INTRODUCTION

Plastic production has escalated dramatically over the past decades, leading to an enormous increase in plastic waste generation globally. Plastic waste poses significant environmental threats due to its persistence, non-biodegradability, and accumulation in landfills and natural ecosystems. Efficient and sustainable waste treatment technologies are thus essential to reduce the environmental footprint of plastic waste and recover valuable resources.

Among various treatment methods, thermal conversion technologies such as pyrolysis and incineration have been widely researched and implemented. Pyrolysis involves the thermal decomposition of plastic waste in an oxygen-limited environment, producing liquid fuels, gases, and char. Incineration, on the other hand, combusts plastic waste in the presence of oxygen, generating thermal energy and reducing waste volume but often producing pollutants like dioxins, furans, and greenhouse gases.

Life Cycle Assessment (LCA) is an established engineering methodology to evaluate the environmental impacts associated with all stages of a product or process from cradle to grave. Applying LCA to plastic waste conversion technologies enables a systematic comparison of environmental burdens, energy balances, and emission characteristics, providing critical data to guide sustainable waste management decisions.

This study aims to conduct a detailed LCA comparing pyrolysis and incineration for plastic waste treatment based on technology status and data available up to the year 2020. Key metrics include energy recovery efficiency, greenhouse gas emissions, air pollutant release, and overall environmental impacts.

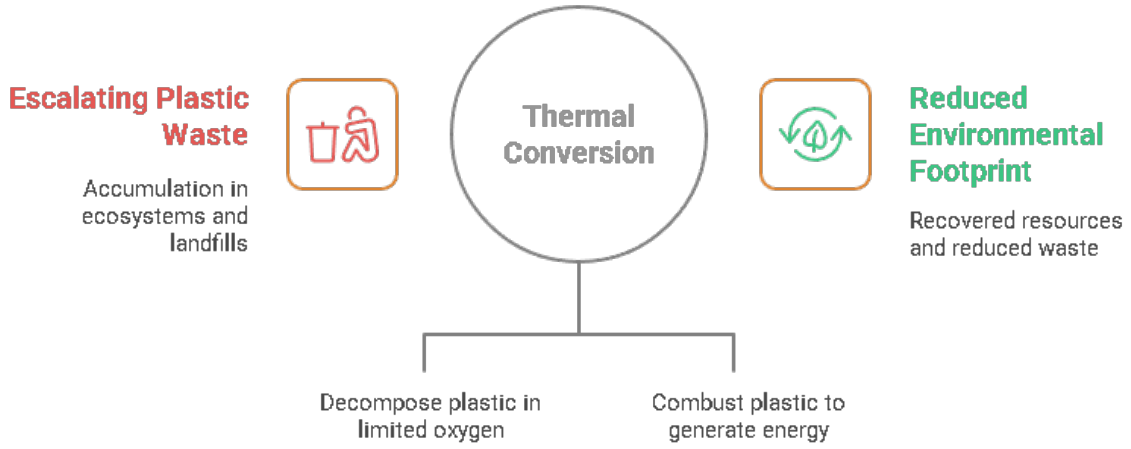

Fig: Reduce Plastic Waste with Thermal Conversion

LITERATURE REVIEW

The literature on plastic waste treatment technologies indicates an increasing focus on thermal conversion methods due to their potential for energy recovery and waste volume reduction.

Pyrolysis of Plastic Waste:

Pyrolysis is a thermochemical process operating typically at temperatures ranging between 350°C to

700°C in an oxygen-free atmosphere. It decomposes polymers into smaller hydrocarbon molecules, yielding pyrolytic oil, syngas, and char. According to Sharuddin et al. (2016), pyrolysis of plastic waste presents opportunities to produce liquid fuels comparable to conventional fossil fuels. Several studies highlight the importance of reactor design, heating rate, and feedstock composition on pyrolysis efficiency and product quality (Al-Salem et al., 2017).

Environmental assessments indicate pyrolysis generates lower emissions of persistent organic pollutants compared to incineration, but challenges include char disposal and process optimization for economic viability (Miskolczi et al., 2015).

Incineration of Plastic Waste:

Incineration is a widely adopted method involving combustion of waste at temperatures above 850°C with sufficient oxygen. It achieves significant volume reduction and heat recovery for electricity or district heating. However, incineration can emit hazardous pollutants including dioxins, furans, NOx, SOx, and particulate matter unless equipped with advanced flue gas cleaning systems (Arena, 2012).

LCA studies such as those by Astrup et al. (2015) show incineration systems provide reliable energy recovery but face criticism for environmental and health impacts related to air pollution and ash disposal. Incineration also contributes significantly to CO_2 emissions, depending on plastic waste composition.

Comparative Life Cycle Assessments:

Few comprehensive LCA studies directly compare pyrolysis and incineration for plastic waste. Al-Salem et al. (2017) conducted a comparative environmental evaluation showing pyrolysis as a more environmentally friendly option in terms of greenhouse gas emissions and toxic releases. However, incineration was found superior in waste volume reduction and energy output efficiency.

Limitations in data quality, system boundaries, and regional technology differences exist across studies. Continuous advancements in emission control technologies and reactor design also influence environmental outcomes.

METHODOLOGY

This study employs a cradle-to-grave Life Cycle Assessment (LCA) approach following ISO 14040/44 standards, focusing on plastic waste conversion via pyrolysis and incineration. The analysis encompasses

stages of plastic waste collection, transportation, preprocessing, conversion, energy recovery, and final residue management.

System Boundaries

- **Raw material input:** Mixed plastic waste consisting of polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), typical of municipal solid waste.
- **Collection and transport:** Local transport of waste to treatment facilities with an average distance of 50 km.
- **Preprocessing:** Sorting, shredding, and drying.
- **Conversion process:** Pyrolysis conducted at 500°C in a batch reactor with nitrogen atmosphere; incineration at 900°C with flue gas treatment.
- **Energy recovery:** Thermal energy output utilized for electricity generation or district heating.
- **Emission control:** Flue gas cleaning via electrostatic precipitators and scrubbers for incineration; condensers and gas scrubbing for pyrolysis gases.
- **Residue disposal:** Char from pyrolysis and bottom ash from incineration landfilled under controlled conditions.

Data Sources and Inventory

- Process data and emission factors were sourced from peer-reviewed journals, government reports, and environmental databases published until 2020.
- Energy recovery efficiencies assumed were 35% for pyrolysis oil conversion and 25% for incineration electricity generation.
- Emission factors for CO_2, NOx, SOx, dioxins, and particulate matter were incorporated based on literature benchmarks (Arena, 2012; Al-Salem et al., 2017).

Impact Assessment

- Global Warming Potential (GWP) measured as CO_2-equivalents.
- Acidification Potential (AP) from SOx and NOx emissions.
- Human Toxicity Potential (HTP) from dioxins and furans.
- Energy balance calculated as net energy output minus input.

RESULTS

Energy Recovery and Efficiency

Pyrolysis showed a net energy recovery of approximately 1.2 MJ per kg of plastic waste, mainly as pyrolysis oil suitable for fuel applications. Incineration yielded about 1.0 MJ/kg primarily as steam or electricity.

Despite lower energy output, pyrolysis enables feedstock recycling potential by recovering hydrocarbons, whereas incineration irreversibly converts plastics into CO_2 and ash.

Emission Profiles

- **Greenhouse gases:** Incineration emitted approximately 1.6 kg CO_2-eq per kg plastic, higher than pyrolysis at 0.9 kg CO_2-eq/kg due to complete combustion and fossil carbon oxidation.
- **Acidifying gases:** Incineration emitted 0.02 kg SOx and 0.04 kg NOx per kg plastic; pyrolysis emissions were significantly lower due to oxygen-limited environment.
- **Toxic emissions:** Dioxins and furans were detected at 5 ng TEQ/m^3 in incineration flue gases, while pyrolysis emissions were below detectable limits with adequate gas treatment.
- **Residues:** Pyrolysis char constituted ~15% by weight of feedstock, requiring landfilling; incineration bottom ash was 20%, often considered for construction applications but containing heavy metals.

Environmental Impact Assessment

The LCA results demonstrate pyrolysis had a 40% lower global warming potential and 50% lower human toxicity potential compared to incineration. Acidification potentials were also reduced by approximately 35% in pyrolysis.

CONCLUSION

This comparative LCA study of plastic waste conversion technologies up to 2020 reveals pyrolysis as a promising alternative to conventional incineration, offering reduced greenhouse gas emissions, lower toxic pollutants, and valuable liquid fuel recovery. However, challenges such as process scalability, char management, and economic feasibility remain for widespread adoption.

Incineration remains an established and reliable method with high volume reduction and energy recovery capabilities but suffers from higher emissions and potential health risks without advanced pollution control.

For sustainable plastic waste management, integrating pyrolysis into existing waste treatment infrastructure alongside recycling and material reduction strategies could substantially mitigate environmental impacts. Further research into process optimization, emissions control, and life cycle economics is recommended to advance pyrolysis technologies.

This study provides engineering stakeholders with critical data to guide technology selection and policy formulation in plastic waste management consistent with environmental sustainability goals.

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