Energy Recovery Evaluation of Thermochemical Conversion Technologies for Non-Recyclable Plastic Waste

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Annual global production of plastics has increased more than 200-fold since 1950.

In 2015 the world produced more than 380 million tonnes of plastic.

For context, this is roughly equivalent to the mass of two-thirds of the world population.
By 2015 cumulative plastic production was more than 7.8 billion tonnes.

This is equivalent to more than one tonne of plastic for every person alive today.
Of the **global plastic produced** over the period from 1950 to 2015:

- **55%** straight to landfill,
- **30%** was still in use,
- **8%** was incinerated,
- **6-7%** was recycled.

Of **5.8 billion tonnes** of plastic no longer in use, **9%** was recycled.
Longer-term innovations should aim to shift away from a linear make-use-dispose model.

To be effective, innovation needs to take account of:

- How essential plastic is in many aspects.
- Plastic alternatives often have other environmental impacts. There are usually trade-offs.  
- To be globally effective, must be scalable and cheap.
This chart presents the **total plastic waste generation by country**, measured in tonnes per year.

With the largest population, China produced the largest quantity of plastic, at nearly 60 million tonnes.

This was followed by the United States at 38 million, Germany at 14.5 million, and Brazil at 12 million tonnes.
Packaging is the largest contributor to plastic waste; accounting for around 42% of the total.

Packaging is the dominant form of waste because it:

- is the sector which uses the most plastic,
- has a very low product lifetime, so typically becomes waste within 6 months.
It is estimated that in 2015, around:

- 55% of global plastic waste was **discarded**,
- 25% was **incinerated**,
- 20% was **recycled**.

Source: Gayer et al. (2017)
This table summarizes:

- **the key categories of plastics,**
- **their common uses,** and
- **whether they can be recycled or not.**

Most plastic items have a marked symbol numbered from 1 to 7 on them — this provides guidance on recyclability.

### Which plastics are recyclable?

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Polymer</th>
<th>Common Uses</th>
<th>Properties</th>
<th>Recyclable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PETE</td>
<td>Polyethylene terephthalate</td>
<td>Plastic bottles (water, soft drinks, cooking oil)</td>
<td>Clear, strong and lightweight</td>
<td>Yes; widely recycled</td>
</tr>
<tr>
<td>2 HDPE</td>
<td>High-density polyethylene</td>
<td>Milk containers, cleaning agents, shampoo bottles, bleach bottles</td>
<td>Stiff and hardwearing; hard to breakdown in sunlight</td>
<td>Yes; widely recycled</td>
</tr>
<tr>
<td>3 PVC</td>
<td>Polyvinyl chloride</td>
<td>Plastic piping, vinyl flooring, cabling insulation, roof sheeting</td>
<td>Can be rigid or soft via plasticizers; used in construction, healthcare, electronics</td>
<td>Often not recyclable due to chemical properties; check local recycling</td>
</tr>
<tr>
<td>4 LDPE</td>
<td>Low-density polyethylene</td>
<td>Plastic bags, food wrapping (e.g. bread, fruit, vegetables)</td>
<td>Lightweight, low-cost, versatile; fails under mechanical and thermal stress</td>
<td>No; failure under stress makes it hard to recycle</td>
</tr>
<tr>
<td>5 PP</td>
<td>Polypropylene</td>
<td>Bottle lids, food tubs, furniture, houseware, medical, rope, automobile parts</td>
<td>Tough and resistant; effective barrier against water and chemicals</td>
<td>Often not recyclable; available in some locations; check local recycling</td>
</tr>
<tr>
<td>6 PS</td>
<td>Polystyrene</td>
<td>Food takeaway containers, plastic cutlery, egg tray</td>
<td>Lightweight; structurally weak; easily dispersed</td>
<td>No; rarely recycled but check local recycling</td>
</tr>
<tr>
<td>7 OTHER</td>
<td>Other plastics (e.g. acrylic, polycarbonate, polyactic fibres)</td>
<td>Water cooler bottles, baby cups, fiberglass</td>
<td>Diverse in nature with various properties</td>
<td>No; diversity of materials risks contamination of recycling</td>
</tr>
</tbody>
</table>

Source: Based on general US & UK guidelines and chemical polymer properties. Icon graphics from Noun Project.

Licensed under CC-BY-SA by the authors.
This chart shows the global primary plastic waste generation by polymer type, measured in tonnes per year.

**Polymers** have been coloured based on recyclability, where:

- **blue** is widely recycled,
- **yellow** is sometimes recycled depending on local context, and
- **red** is usually non-recyclable.
Plastics & Plastic Pollution

Global mismanaged plastic by region, 2010

Share of global mismanaged plastic waste by region in 2010. This is measured as the total mismanaged waste by populations within 50km of the coastline, and therefore defined as high risk of entering the oceans. Mismanaged plastic waste is defined as "plastic that is either littered or inadequately disposed. Inadequately disposed waste is not formally managed and includes disposal in dumps or open, uncontrolled landfills, where it is not fully contained. Mismanaged waste could eventually enter the ocean via inland waterways, wastewater outflows, and transport by wind or tides."

<table>
<thead>
<tr>
<th>Region</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Asia and Pacific</td>
<td>60%</td>
</tr>
<tr>
<td>South Asia</td>
<td>11%</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>8.9%</td>
</tr>
<tr>
<td>Middle East and North Africa</td>
<td>8.3%</td>
</tr>
<tr>
<td>Latin America and Caribbean</td>
<td>7.2%</td>
</tr>
<tr>
<td>Europe and Central Asia</td>
<td>3.6%</td>
</tr>
<tr>
<td>North America</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

If all countries had effective waste management, **mismanaged plastic waste** could be reduced by 80%.

For comparison: total mismanaged waste from North America & Europe was less than 5%.

Even a complete plastic ban across the richest countries would have a relatively small impact at the global scale.
Plastics & Plastic Pollution

European Plastics Life Cycle

- EU-27 Plastics Production: 57 Mtonne
- Converter demand: 45.9 Mtonne
- Consumer demand
- Export
- Import

- Recycling: 6.6 Mtonne
- Recovery: 8.9 Mtonne
- Post-consumer plastics: 25.2 Mtonne
- Disposal: 9.6 Mtonne

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Non-Recyclable Plastic Waste as Energy Source

✓ An **effective system** for managing **non-recyclable plastic waste** must be **techno-economically**, **environmentally**, and **socially** sound.

✓ A range of **waste-to-energy** technologies are now well-known for exploiting the potential of **non-recyclable plastic waste** as an **energy** source, varying from **basic** systems to more **advanced** conversion processes.

✓ The conversion of **non-recyclable plastic waste to energy** is based on three main routes: **thermochemical**, **biochemical**, and **physicochemical**.

✓ **Non-recyclable plastic waste** is an excellent **feedstock** for **thermochemical** conversion technologies, due to their significant **heating value**.

✓ A **study** by the Columbia University Earth Engineering Center showed the **LHV** (Lower Heating Value) of **non-**
Non-Recyclable Plastic Waste as Energy Source

Currently, there is a few published research pertaining to work done on the techno-economic, environmental, and social outcomes of non-recyclable plastic waste processed via thermochemical conversion technologies based on their associated characteristics.

This research attempts to provide a new perspective on the Energy Recovery Evaluation of Thermochemical Conversion Technologies for Non-Recyclable Plastic Waste by applying the multicriteria method PROMETHEE II, based on three different weighting strategies.
Thermochemical Conversion

The method of thermochemical conversion includes thermal decomposition of non-recyclable plastic waste to generate either heat or petroleum or gas.

Thermochemical conversion is best aligned to feedstock with reduced humidity and is usually less selective for materials.

Gasification, pyrolysis, and incineration are the primary technological choices in this category.

Gasification can be defined as the thermochemical conversion—by the supply of a gasifying agent—of a solid carbon-based material into a fuel gas.

Pyrolysis is a thermochemical reaction which involves the molecular breakdown of larger molecules into smaller molecules in the presence of heat and in the absence of oxygen.
Thermochemical Conversion Processes & Products
Evaluation Process

The multicriteria method, **PROMETHEE II** (Preference Ranking Organization Method for Enrichment Evaluation), has been selected.

It is well adapted to problems where a finite number of alternatives are to be ranked considering several conflicting criteria.

**Criteria:** According to the literature review, the most frequently used criteria are the following:

- **Capital Cost** (Economic criterion)
- **Technological Complexity** (Technological criterion)
- **Public Acceptability** (Social criterion)
- **Diversion from landfill** (Environmental criterion)
- **Energy produced (kWh/ton)** (Technological criterion)
The values obtained for each criterion are shown in the following Table.

The values are selected through literature review.

For simplification, in the present study, the indifference threshold has been ignored, and the V-type preference equation has been used for the quantitative criteria. The "usual" type of preference equation has been used for the qualitative criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Pyrolysis</th>
<th>Gasification</th>
<th>Incineration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>C 1</td>
<td>Very high</td>
<td>High</td>
</tr>
<tr>
<td>Technological Complexity</td>
<td>C 2</td>
<td>Very high</td>
<td>Very high</td>
</tr>
<tr>
<td>Public acceptability</td>
<td>C 3</td>
<td>Medium</td>
<td>Very high</td>
</tr>
<tr>
<td>Diversion from landfill</td>
<td>C 4</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Energy produced</td>
<td>C 5</td>
<td>660</td>
<td>660</td>
</tr>
</tbody>
</table>
Weighting of Criteria

• Weighting of criteria is carried out according to the hierarchical ranking of criteria, Simos approach.
• The weights of the criteria have been elicited from interviews with stakeholders.
• The following policy scenarios have been developed:

  ✓ **Scenario 1**: A preference is given in the environmental aspect, and in a second level in technological aspect.
  ✓ **Scenario 2**: A preference towards the technological criteria.
  ✓ **Scenario 3**: A preference is given in the environmental and social impact at the same time.
It is obvious that the environmental criterion, “Diversion from landfill” and the criterion “Energy produced” are in the preferences of stakeholders as the most important in all the examined Scenarios.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>C1</td>
<td>13%</td>
<td>21%</td>
</tr>
<tr>
<td>Technological Complexity</td>
<td>C2</td>
<td>24%</td>
<td>31%</td>
</tr>
<tr>
<td>Public acceptability</td>
<td>C3</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Diversion from landfill</td>
<td>C4</td>
<td>35%</td>
<td>13%</td>
</tr>
<tr>
<td>Energy produced</td>
<td>C5</td>
<td>24%</td>
<td>31%</td>
</tr>
</tbody>
</table>
Results

[Graph showing comparisons between Scenario 1, Scenario 2, and Scenario 3 with processes such as Gasification, Pyrolysis, and Incineration labeled.]

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**Conclusions**

- Based on the currently available information and data; the outcome of this *Multiple Criteria Decision Analysis* of decision options demonstrates that *Gasification* provides the most significant improvement in net energy recovery rates, mitigates greenhouse gas emissions, and is widely accepted by the public.

- *Gasification* is consistent with the principles of Sustainable Materials Management and a more Circular Economy.

- With high contents of carbon and hydrogen in non-recyclable plastic waste, thermal degradation processes at an elevated temperature can lead to the production of value-added electricity, hydrocarbon fuels, and chemical products.

- The selected criteria fall into the most crucial axes for the evaluation of Thermochemical Conversion Technologies for Non-Recyclable Plastic Waste.

- Further research will focus on the multicriteria assessment of the other technologies, biochemical and physicochemical conversion of non-recyclable plastic waste to energy in order to compare the results with the current study.
Thank you for your attention!