Life-Cycle Assessments of Chemical Recycling: An overview
Focus on Carbon Footprint
Ludwigshafen am Rhein, June 2023
Motivation

Industry, R&D and stakeholders need more information about environmental impacts of chemical recycling. Several life-cycle assessments have been conducted since 2003.

BASF would like to understand the potential impacts of different approaches of environmental assessment on the performance of chemical recycling.
Scope and Methodology
**Scope and methodology of LCA meta study**

Target: Review of different LCA studies on chemical recycling

- Literature review* with focus on pyrolysis
- The review focuses on carbon footprint
- Functional units: Waste and recycled product perspective
- Feedstock: Mixed plastic waste

- Time frame: 2003 until April 2023
- Global scope
- The reviewed studies were conducted by academia, industry or NGOs
- Meta study was generated by Sphera

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* Sources: The International Journal of LCA, Google Scholar, ScienceDirect
** Other chemical recycling technologies mentioned in the studies but not covered in the review are: Depolymerization, Dissolution, Gasification, Hydrolysis, and Solvolysis.
Literature sources covered

Number of reviewed publications

- Included / initial screening = 15 / 47

Publication contribution by source:

- Government
- NGO
- Industry
- Academia

Geographic coverage

- North America
- Australia
- Europe

Publication year

- 2003
- 2015
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
Waste perspective vs. Product perspective

Waste perspective
The treatment of X tons of plastic waste

X ton of plastic waste

Waste management (incineration or landfill)

Treated waste

Credits for recovered energy

VS.

Chemical recycling

Valuable product

AND

Credits for recovered product

Product perspective
The production of X tons of valuable product

X ton of product

Conventional process

Virgin feedstock

Plus waste management

VS.

Chemical recycling

Plastic waste

OR

Minus waste management

Credits for recovered product

Credits for recovered energy

Function unit

Activity under study

Feedstock / product

System expansion
End-of-life allocation approaches
Waste perspective, product perspective and basket method

**Waste Perspective:**
CR vs. reference waste treatment technologies
- **System expansion by subtraction** (material and energy substitution; credits for recovered energy and product) per kg of waste managed

**Product Perspective:**
CR vs. products from virgin material
- **System expansion by subtraction** (avoided waste treatment) per kg of product, e.g. syngas, plastic, etc.
- **System expansion by addition** (waste treatment of conventional product) per kg of product + kg waste managed
- **No system expansion** per kg of product + kg waste managed

**Basket method**
Processing and recovery of 1 t mixed cable waste

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* ZWE 2022 is not an original LCA study, it is a scenario analysis based on pyrolysis data from The Consumer Goods Forum 2022 LCA study.

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BASF 2021, Quantis 2020

The Consumer Goods Forum 2022

Eastman 2020

Vinyl 2010 2003
## System boundaries

### Waste perspective, product perspective and basket method

<table>
<thead>
<tr>
<th>Waste Perspective</th>
<th>System expansion by subtraction (material and energy substitution)</th>
<th>System expansion by subtraction (avoided waste treatment)</th>
<th>System expansion by addition</th>
<th>No system expansion</th>
<th>Basket method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Includes waste collection, chemical recycling (pyrolysis) and material and/or energy substitution <strong>(waste-to-grave)</strong></td>
<td>Includes waste collection, chemical recycling (pyrolysis), and avoided waste treatment (incineration/landfill) <strong>(waste-to-gate)</strong>.</td>
<td>Compares CR with conventional process by adding the environmental burden of a conventional waste treatment process to the conventional material production to make the systems comparable <strong>(waste-to-gate)</strong>.</td>
<td>Includes waste collection, chemical recycling (pyrolysis) (no credits for produced products or avoided waste management [landfill]) <strong>(cradle-to-grave)</strong></td>
<td>Compares alternative technologies by expanding the system to include output from each system and make them comparable <strong>(waste-to-gate)</strong></td>
</tr>
</tbody>
</table>

### System Expansion

- **BASF 2021, Quantis 2020**
- **The Consumer Goods Forum 2022**
- **Eastman 2020**
- **Vinyl 2010 2003**

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* ZWE 2022 is not an original LCA study, it is a scenario analysis based on pyrolysis data from The Consumer Goods Forum 2022 LCA study.
System boundaries and End-of-Life Allocation Approaches

- **Waste Perspective – System expansion by subtraction** is the most widely used approach
  - Compares chemical recycling processes with conventional waste treatment process (incineration with energy recovery)
  - Credit for the recycled product or recovered energy – the avoided burden depends on the product being substituted (pyrolysis oil for naphtha or chart for lignite, etc.)

- However, only the **product perspective** calculates the **environmental footprint of the chemically recycled material**.
Methodological observations

- The studies published in the selected period were mostly from academia and industry

- The *Waste perspective* is the most widely used approach (CR vs. reference waste treatment technologies; 12 out of 15 studies)

- The *Product perspective* is being used more recently (CR vs. products from virgin material)

- A wide range of carbon footprint for CR has been observed – attributed to different methodological approaches

- The *system boundary & End-of-Life allocation* approach used have significant influence on the overall results. The approaches fall into five categories which are described in the subsequent slides.
Results

1. Waste perspective
Waste perspective: Comparing pyrolysis with incineration

- Pyrolysis shows **better carbon footprint performance than incineration**.

- Differences depend on the sorting yield, energy grid mix, credit for recovered energy, incineration paths of sorting residues.

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1 Incineration (due to high credit for carbon intensive grid mix) (RMIT U 2018, 2019) shows lower carbon footprint than chemical recycling.

2 Polymers that are able to form a large amount of their monomer under the right pyrolysis circumstances. It includes PMMA, PS, EPS, HIPS, Nylon 6 (TNO 2021).
**Waste perspective: Comparison of Global Warming Potential**

- **Chemical recycling** has the second-best carbon footprint performance after mechanical recycling in most cases.

- **Incineration / energy recovery** appears to be the worst compared to chemical recycling and mechanical recycling in most cases.

- **Landfilling** shows better carbon footprint performance than chemical recycling due to low degradability of mixed plastic waste.

<table>
<thead>
<tr>
<th>Source</th>
<th>Chemical Recycling (CR)</th>
<th>Mechanical Recycling (MR)</th>
<th>Incineration (energy recovery)</th>
<th>Landfilling</th>
<th>Combination of CR &amp; MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASF 2021</td>
<td>1</td>
<td>NA</td>
<td>2</td>
<td>NA</td>
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<tr>
<td>Quantis 2020</td>
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<tr>
<td>BMBF 2020</td>
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<td>1</td>
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<tr>
<td>TNO 2021</td>
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<tr>
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<tr>
<td>RMIT University 2018, 2019</td>
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<td>Vinyl 2010 2003</td>
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</tbody>
</table>

**Key points:**

- Chemical recycling has the second-best carbon footprint performance after mechanical recycling in most cases.
- Incineration / energy recovery appears to be the worst compared to chemical recycling and mechanical recycling in most cases.
- Landfilling shows better carbon footprint performance than chemical recycling due to low degradability of mixed plastic waste.
Results

2. Product perspective
Product perspective: Comparing pyrolysis output with virgin production

- 8 out of 10 scenarios across 4 studies show a reduction in carbon footprint for the chemically recycled product.

- The performance of pyrolysis depends on:
  - greenness of the energy grid mix used,
  - the avoided waste management (incineration/landfill),
  - pyrolysis yield,
  - and end-of-life scenarios.

Relative performance of CR over reference technology, (kg CO₂e, delta)

- Avoided incineration with energy recovery based on electricity from lignite and heat from heavy fuel oil
- Pyrolysis oil (2030 grid mix) vs. virgin fossil naphtha with 100% landfill EoL scenario
- Food grade film from MPW vs. from virgin fossil naphtha: variation due to grid mix, yield, and EoL scenarios
- LDPE via pyrolysis vs. virgin plastic from naphtha (based case: avoided incineration of mixed waste plastics & combustion of refuse-derived fuel)
- Energy for pyrolysis is based on electricity from hydro power and heat from biomass and biogas

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1 BASF 2021
2 The Consumer Goods Forum 2022
Product perspective: Comparison of Global Warming Potential

- Chemical recycling shows better carbon footprint performance than virgin production, if waste for incineration was used.

- The waste plastic quality requirement is a key driver between chemical recycling and mechanical recycling.

- No material degradation factored into mechanical recycling.

<table>
<thead>
<tr>
<th>Source</th>
<th>Chemical Recycling (CR)</th>
<th>Virgin production</th>
<th>Mechanical Recycling (MR)</th>
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<tr>
<td>BASF 2021</td>
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Summary and Conclusion
Global Warming Potential (GWP)

- In the majority of the studies (7 out of 9) that address the waste perspective, pyrolysis shows better GWP performance than incineration with energy recovery.

- Pyrolysis shows better GWP performance than virgin production in all studies that address the product perspective.

- Only in one study pyrolysis appears to have higher GWP impact than incineration. This is mainly due to the high carbon intensity of the grid mix and large credit for energy recovery.
Chemical recycling leads to a reduction in carbon footprint in most cases

- **Waste perspective**: In 7 out of 9 studies, pyrolysis shows better GWP performance than incineration.

- **Product perspective**: Pyrolysis shows better GWP performance than virgin production in all studies.

- The performance of pyrolysis depends on the greenness of the grid mix used, the reduced emissions from waste management (e.g., incineration), pyrolysis yield, and end-of-life scenarios. The shift towards a cleaner energy grid mix in the future and improvement in yield would further support the environmental performance of chemical recycling.

- Inconsistency in system boundary setting and end-of-life allocation leads to different results. Nevertheless, the results show a consistent picture.
We create chemistry
<table>
<thead>
<tr>
<th>Region</th>
<th>Origin</th>
<th>Year</th>
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<tbody>
<tr>
<td>Vinyl 2010</td>
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