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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.

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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**

* 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.

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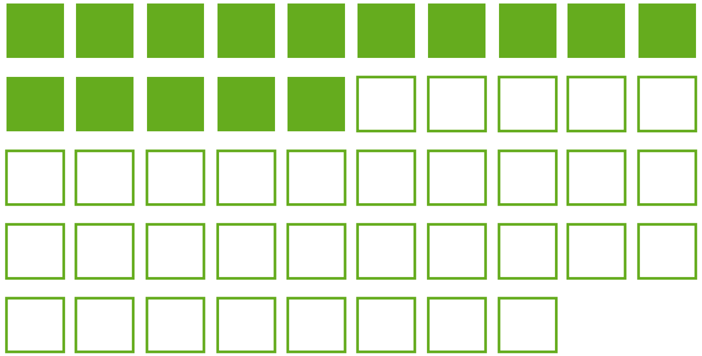
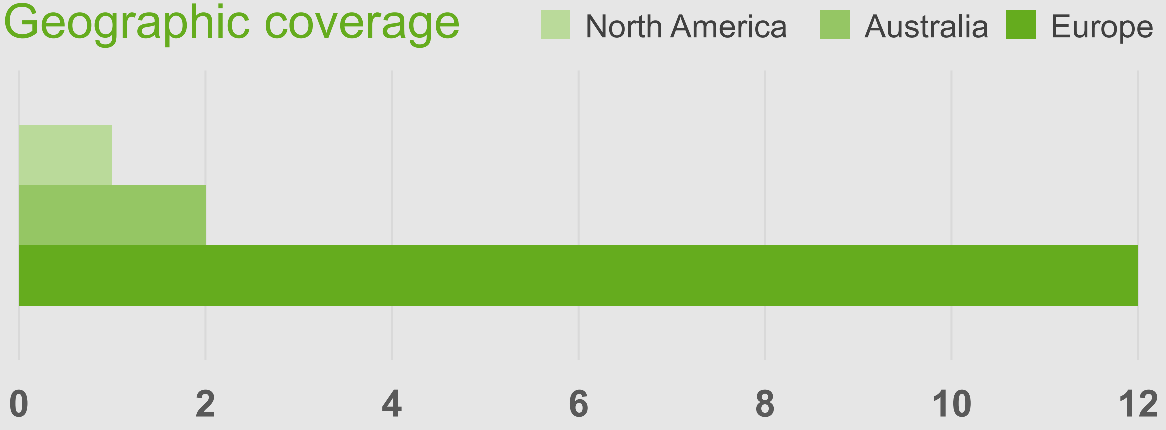
Literature sources covered

Number of reviewed publications

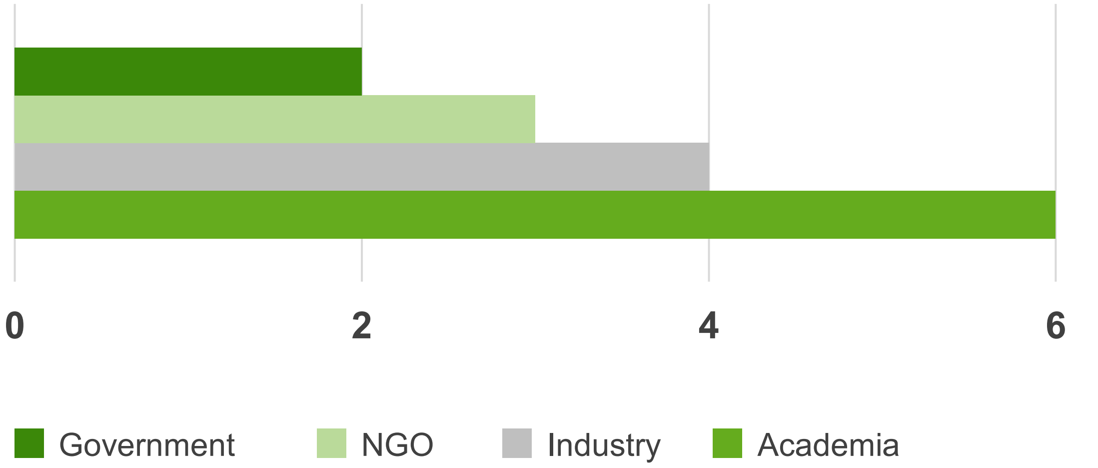


Included / initial screening = 15 / 47

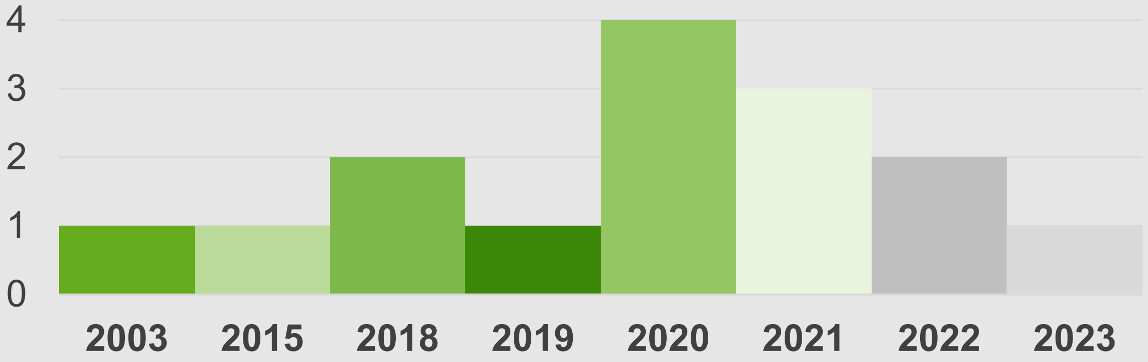
Geographic coverage



Publication contribution by source



Publication year



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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)	vs.	Chemical recycling
Treated waste		Valuable product
Credits for recovered energy	AND	Credits for recovered product

Product perspective		
The production of X tons of valuable product		
X ton of product		
Conventional process	vs.	Chemical recycling
Virgin feedstock		Plastic waste
Plus waste management	OR	**Minus** waste management

Legend:
- Functional 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	BASF 2021, BMBF 2019, Quantis 2020, CE-Delft 2020, Anadolu U 2015, KIT 2021, KIDV 2018, RMIT U 2019, RMIT 2018, TNO 2021, ZWE 2022*, JRC 2023
Product Perspective: **CR vs. products from virgin material**	
– **System expansion by subtraction** (avoided waste treatment) per kg of product, e.g. syngas, plastic, etc.	BASF 2021, Quantis 2020
– **System expansion by addition** (waste treatment of conventional product) per kg of product + kg waste managed	The Consumer Goods Forum 2022
– **No system expansion** per kg of product + kg waste managed	Eastman 2020
Basket method Processing and recovery of 1 t mixed cable waste	Vinyl 2010 2003

* 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

Waste perspective, product perspective and basket method

Waste Perspective	**System expansion by subtraction** (material and energy substitution)	Includes waste collection, chemical recycling (pyrolysis) and material and/or energy substitution (**waste-to-grave**) KIT 2021, ZWE 2022, and JRC 2023 assess the combination of MR and CR	BASF 2021, BMBF 2019, Quantis 2020, CE-Delft 2020, Anadolu U 2015, KIT 2021, KIDV 2018, RMIT U 2019, RMIT 2018, TNO 2021, ZWE 2022*, JRC 2023
Product Perspective	**System expansion by subtraction** (avoided waste treatment)	Includes waste collection, chemical recycling (pyrolysis), and avoided waste treatment (incineration/landfill) (**waste-to-gate**).	BASF 2021, Quantis 2020
	System expansion by addition	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 (**waste-to-gate**)	The Consumer Goods Forum 2022
	No system expansion	Includes waste collection, chemical recycling (pyrolysis) (no credits for produced products or avoided waste management [landfill]) (**cradle-to-grave**)	Eastman 2020
	Basket method	Compares alternative technologies by expanding the system to include output from each system and make them comparable (**waste-to-gate**)	Vinyl 2010 2003

* 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.

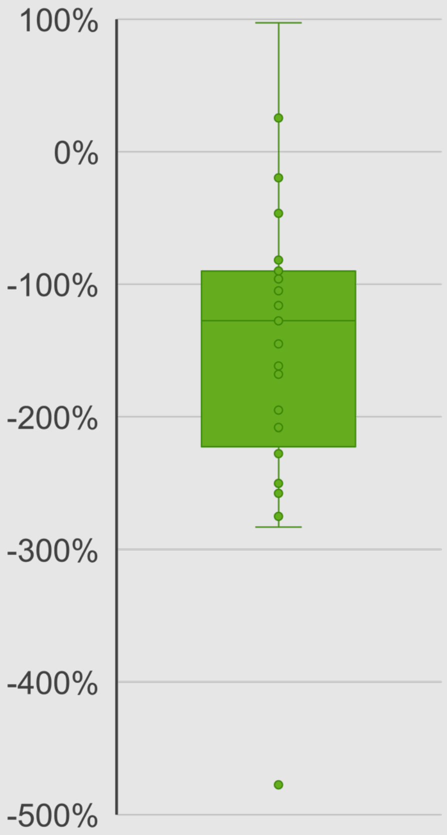
Results

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.

Relative performance of CR over reference technology, (kg CO_2e, delta)



2 out of 8 studies show higher carbon footprint for chemical recycling.[1]

6 out of 8 studies show that **chemical recycling is performing better than incineration** as a reference technology.

Pyrolysis to monomers vs. waste incineration.[2]

[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).

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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.

Source	Chemical Recycling (CR)	Mechanical Recycling (MR)	Incineration (energy recovery)	Landfilling	Combination of CR & MR
BASF 2021	1	NA	2	NA	
Quantis 2020	2	NA	3	1	
BMBF 2020	2	1	3	NA	
TNO 2021	1	1	2	NA	
CE-Delft 2020	2	1	3	NA	
KIT 2021	3	2	NA	NA	1
KIDV 2018	2	1	3		
RMIT University 2018, 2019	3	NA	2	1	
JRC 2023	2	1	3	NA	
Vinyl 2010 2003	2	1	3	2	

Results

2. Product perspective

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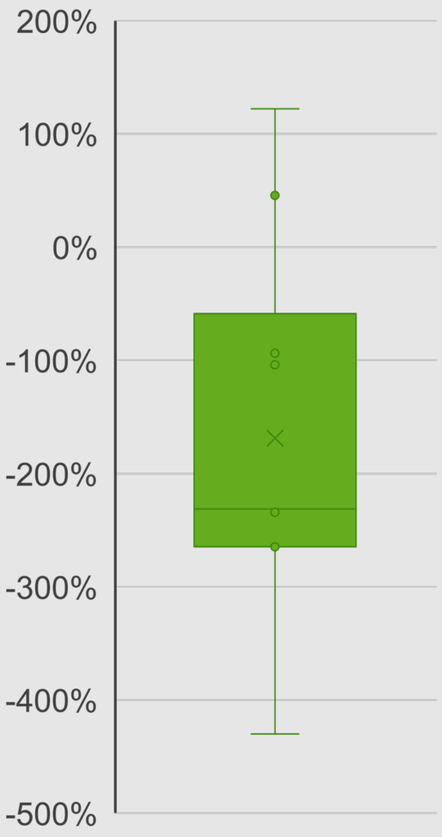
Product perspective: **Comparing pyrolysis output with virgin production**

- **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 CO_2e, delta)



- Avoided incineration with energy recovery based on electricity from lignite and heat from heavy fuel oil[1]
- Pyrolysis oil (2030 grid mix) vs. virgin fossil naphtha with 100% landfill EOL scenario.[2]
- Food grade film from MPW vs. from virgin fossil naphtha: variation due to grid mix, yield, and EoL scenarios.[2]
- LDPE via pyrolysis vs. virgin plastic from naphtha (based case: avoided incineration of mixed waste plastics & combustion of refuse-derived fuel)[1]
- Energy for pyrolysis is based on electricity from hydro power and heat from heat from biomass and biogas.[1]

[1] BASF 2021
[2] The Consumer Goods Forum 2022

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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

Source	Chemical Recycling (CR)	Virgin production	Mechanical Recycling (MR)	Combination of CR & MR
BASF 2021	1	2	NA	
Quantis 2020	2	3	1	
The Consumer Goods Forum 2022	1	2	NA	
Eastman 2020	1	2	NA	
ZWE 2022	3	NA	2	1

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Summary and Conclusion

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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.

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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.

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Literature categorization

	Region	Origin	Year
Vinyl 2010	Europe	Industry	2003
Anadolu University	Europe	Academia	2015
KIDV	Europe	NGO	2018
RMIT University	Australia	Academia	2018/2019
BMBF	Europe	Government	2020
Eastman	North America	Industry	2020
CE-Delft	Europe	Academia	2020
Quantis	Europe	Industry	2020
BASF	Europe	Industry	2021
KIT	Europe	Academia	2021
TNO	Europe	Academia	2021
ZWE	Europe	NGO	2022
The Consumer Goods Forum	Europe	NGO	2022
JRC	Europe	Government	2023