Data, analysis, and decision tools for evaluating the circular economy of plastics

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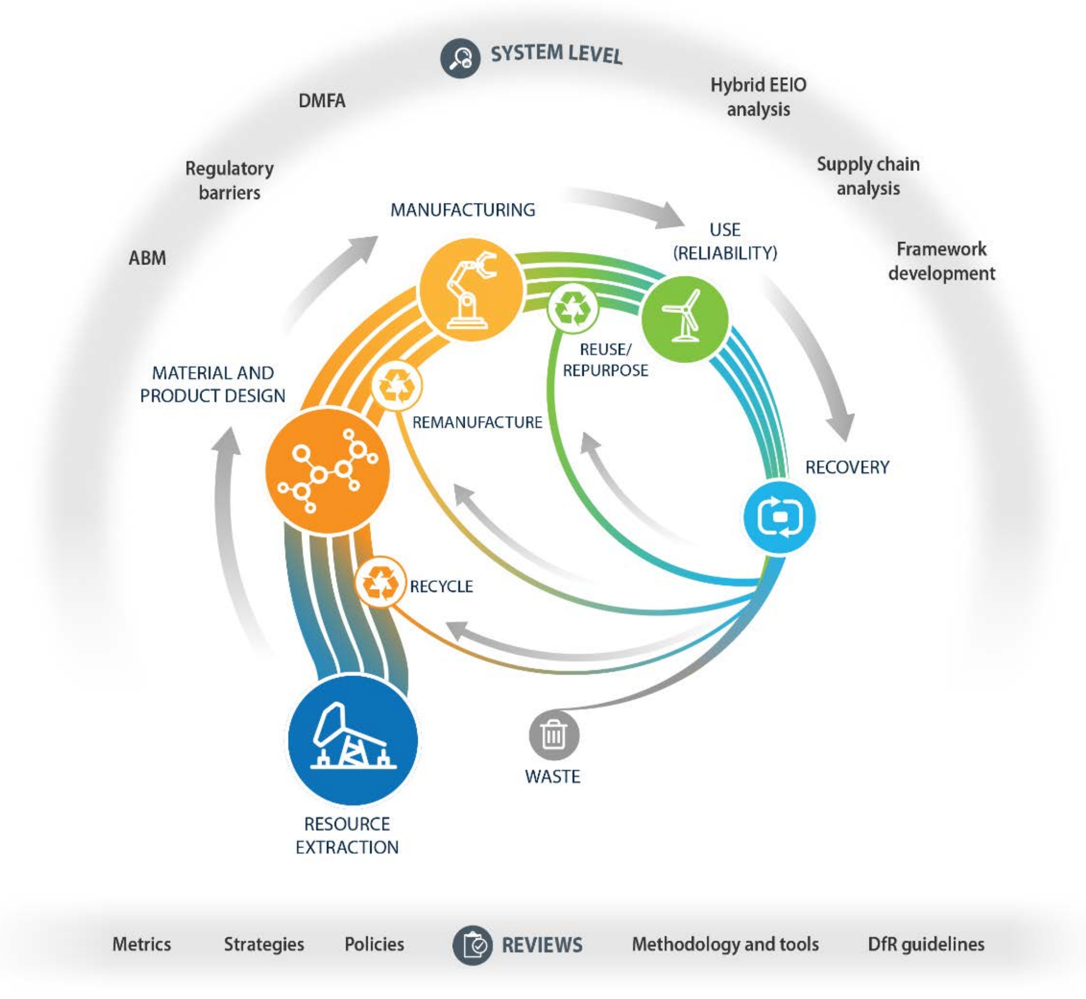

Approach

- BOTTLE (Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment) Consortium approach – Techno-Economic Analysis (TEA), Life Cycle Assessment (LCA) (Materials Flows through Industry) MFI tool, process, environmentally extended input output (EEIO))
  - Carbon, energy and economic targets
  - Informing the research
- Technology performance
- Systems thinking tools for broader perspective

Metrics for BOTTLE projects

The mission of BOTTLE is to:

- Develop robust processes to upcycle existing waste plastics, and
- Develop new plastics and processes that are recyclable-by-design

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BOTTLE projects will aim to meet 3 key metrics:

Energy:

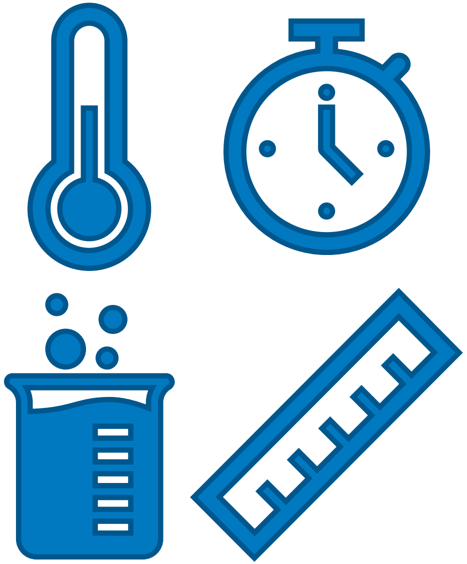
- ≥50% energy savings relative to virgin material production
- Closed-loop recycling estimated to save 40-90% energy[1]

Carbon:

- ≥75% carbon utilization from waste plastics
- Estimated based on recycling of commodity thermoplastics

Economics:

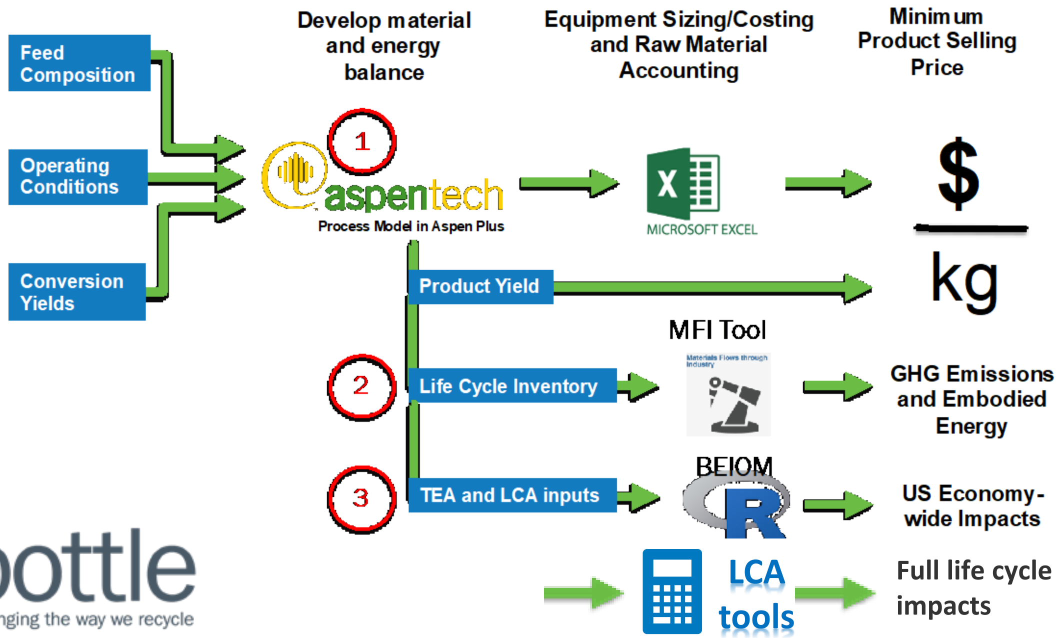
- ≥ 2x economic incentive over reclaimed materials

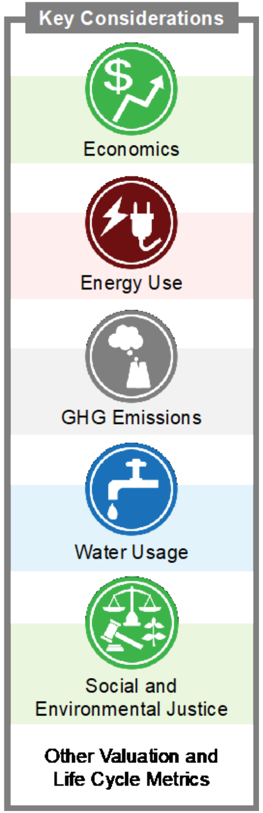


1. Rahimi and Garcia, *Nature Reviews Chemistry*, 2017

Analysis Approach

- Analysis helps guides polymer and process R&D
- Techno-economic analysis (TEA) using Aspen Plus
- Energy/GHG assessment via Materials Flows through Industry (MFI)
- Socio-economic and environmental assessment with the EEIO framework





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Case study: PET enzymatic hydrolysis

Goals:

- Determine key drivers for community to enable enzymatic PET depolymerization
- Provide base model to compare enzyme-based approaches for PET recycling to chemo-catalytic and thermal methods
- Highlight areas for further impactful development of biocatalysis-enabled plastics recycling

Methods:

- TEA, MFI, LCA, EEIO
- Process data from patent and peer-reviewed literature
- Experimental validation

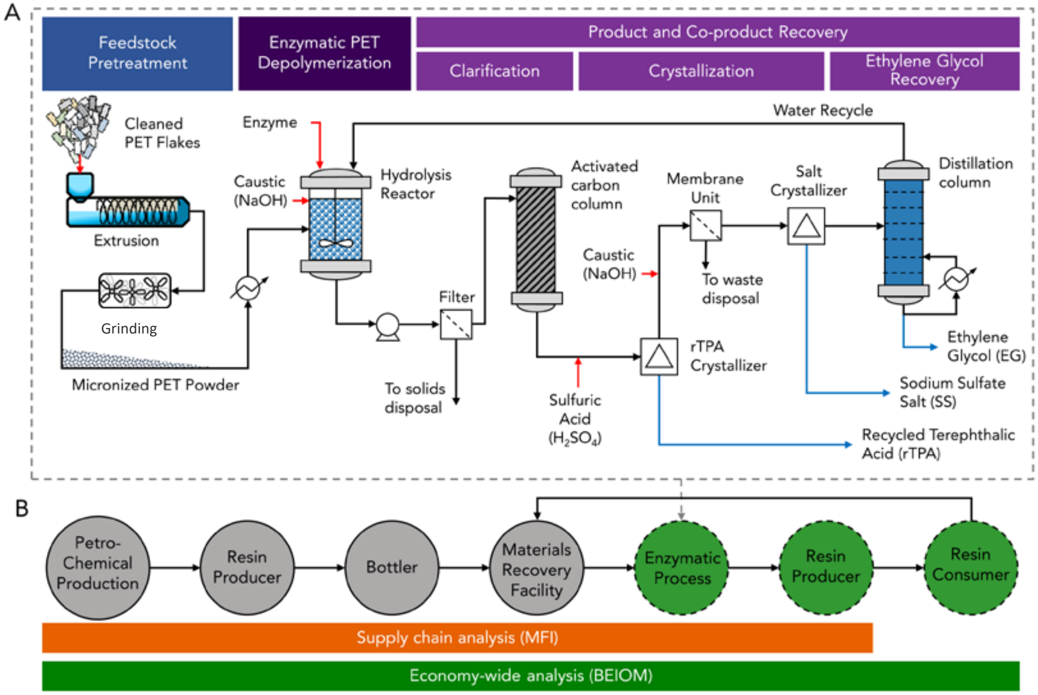
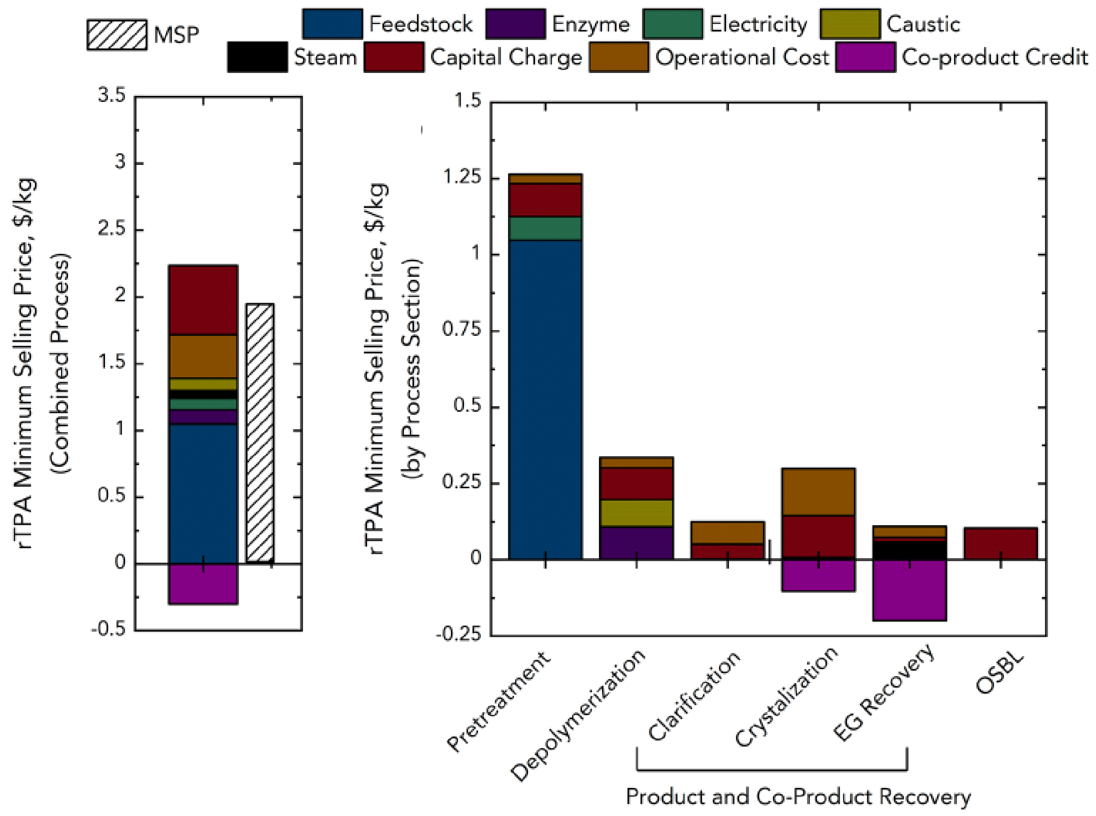


Figure: (A) Simplified process flow diagram of the PET enzymatic depolymerization process (B) A representation of the bottom-up supply chain model (MFI tool) scope and top-down environmentally-extended input-output (BEIOM model) scope

EEIO = environmentally-extended, input-output, rTPA = recycled terephthalic acid, PET=Polyethylene terephthalate

Economics results for PET enzymatic hydrolysis



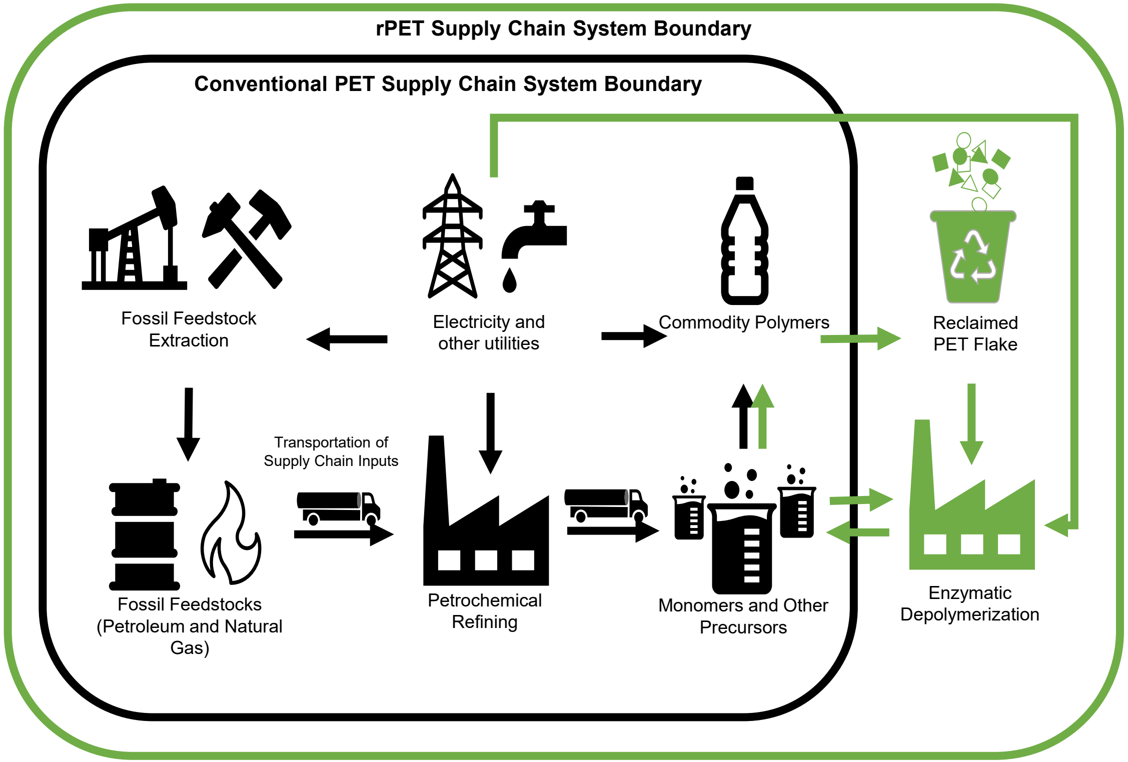
Enzymatic PET recycling shows substantial promise relative to virgin polyester manufacturing:

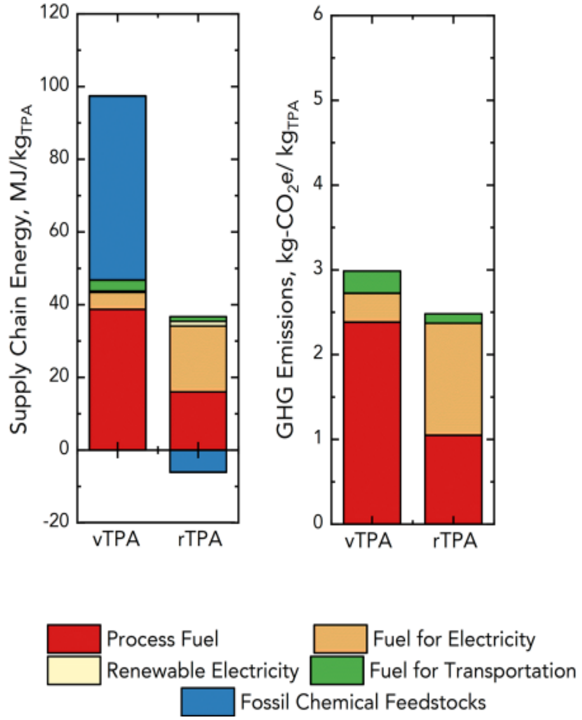
- Virgin TPA price $0.50 – $1.50/kg
- Recycled TPA from enzymatic recycling predicted to be $1.93/kg from processed, clean flake ($0.66/kg)
- Cheaper feedstock enables cost parity

A Singh *et al. Joule* 2021

TPA = terephthalic acid

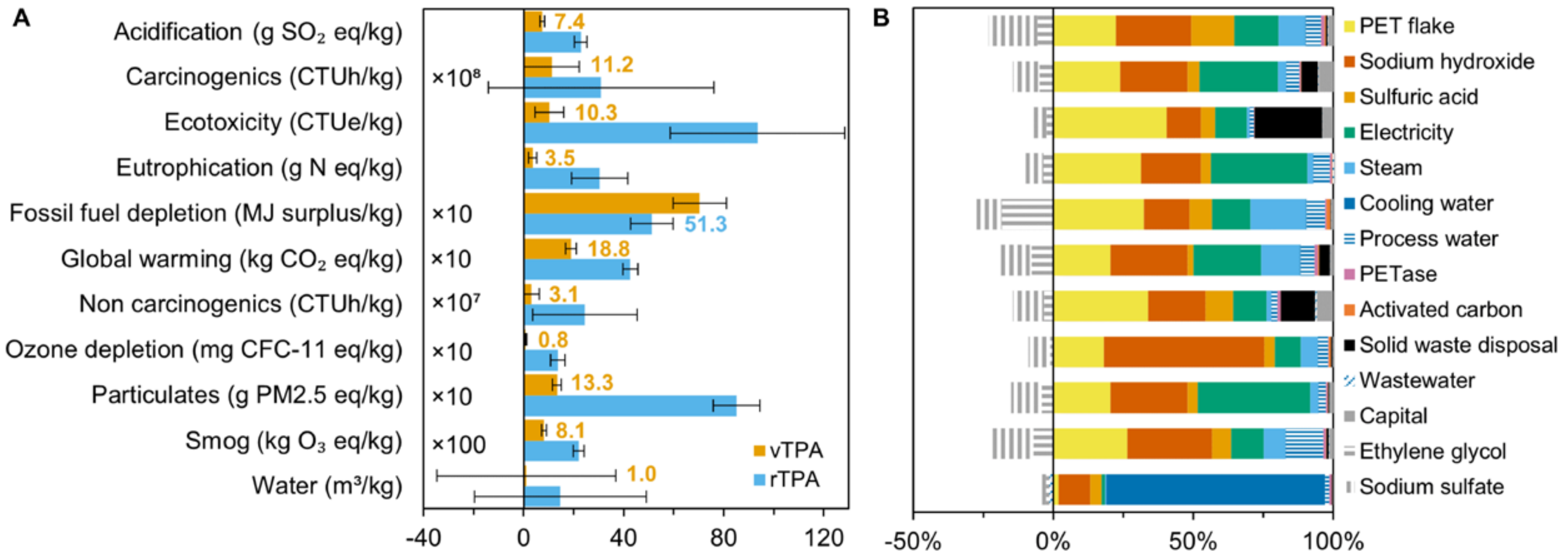
Enzymatic PET recycling can reduce energy and GHG emissions





LCA results

- TPA → **3-17x** higher impacts for enzymatic hydrolysis than virgin
- Major drivers include PET collection and flaking, NaOH for pH control, electricity
- Expanded system boundary includes emissions, waste, PET collection

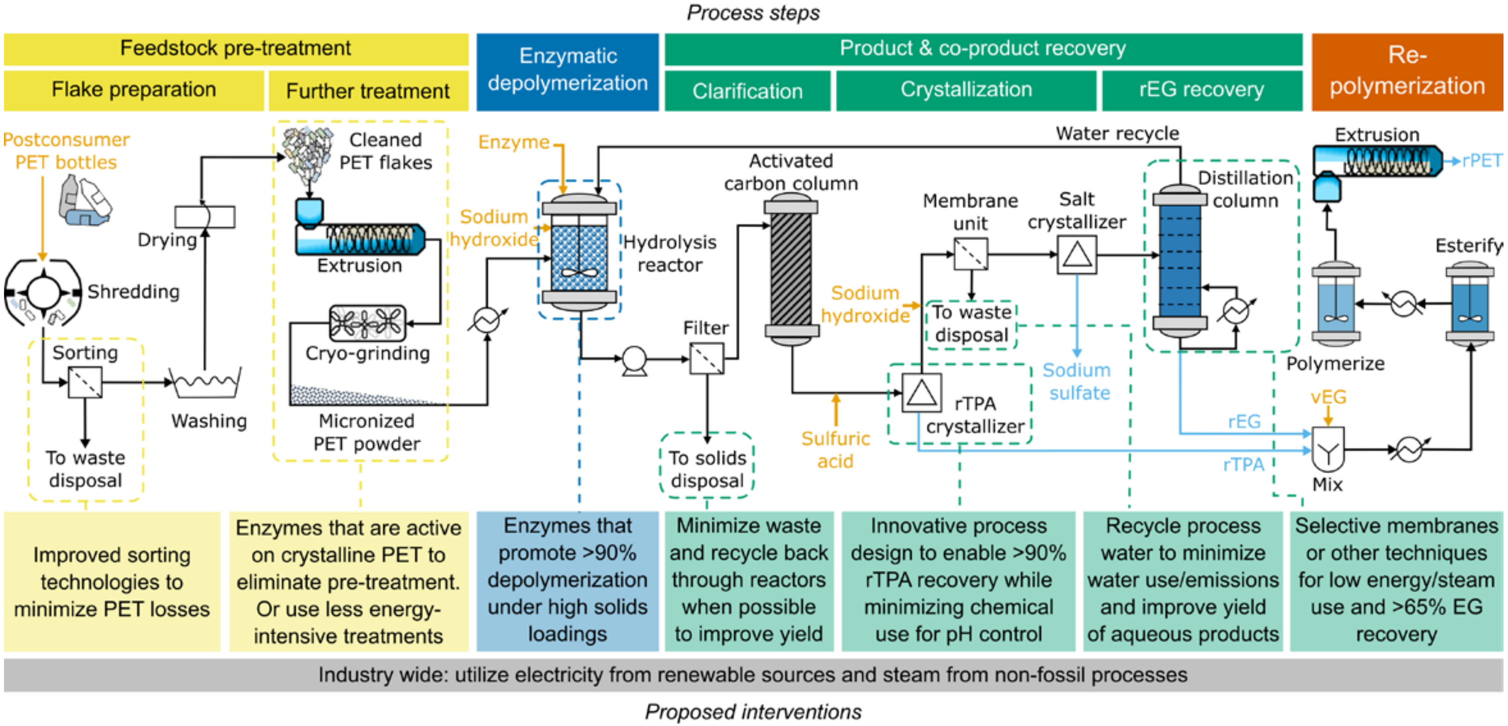


Comparison between enzymatic recycling & virgin production

Contribution of recycling process components

Uekert, et al., 2022, accepted

Research insights



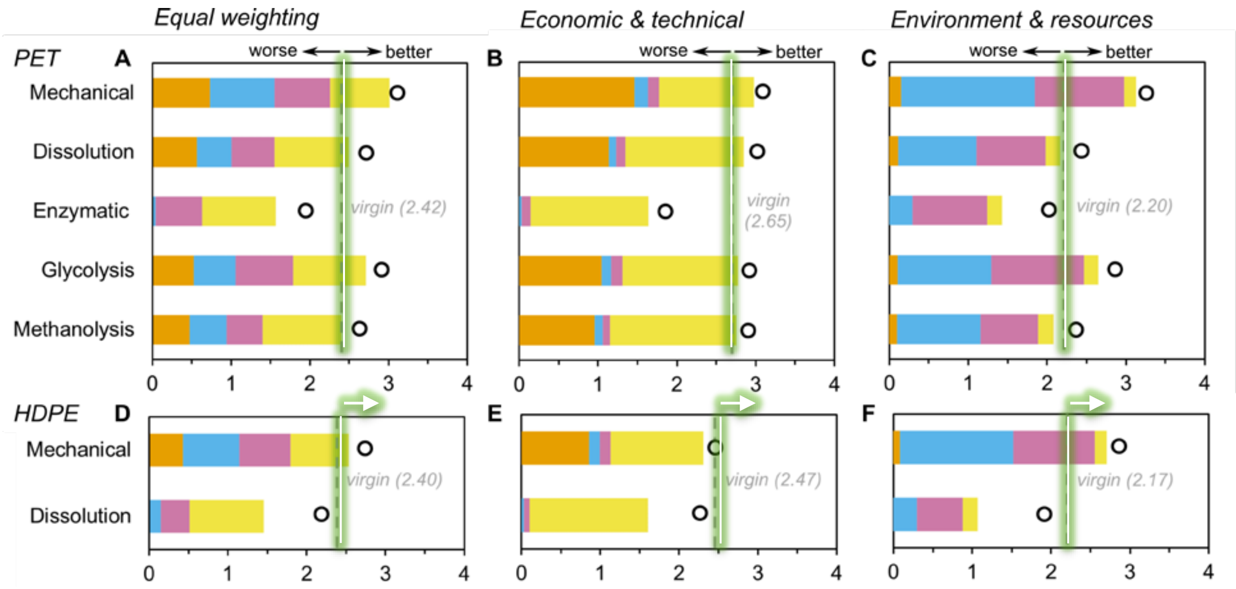
Improvements across **many** of these process areas will likely be necessary for scale-up of enzymatic recycling

Tradeoffs: many inexpensive components (water, steam, waste, etc.) are costly from an environmental perspective

Uekert, et al., **2022**, accepted

Multi-criteria decision analysis

- Multi-criteria decision analysis (MCDA) – allows for the evaluation of conflicting criteria

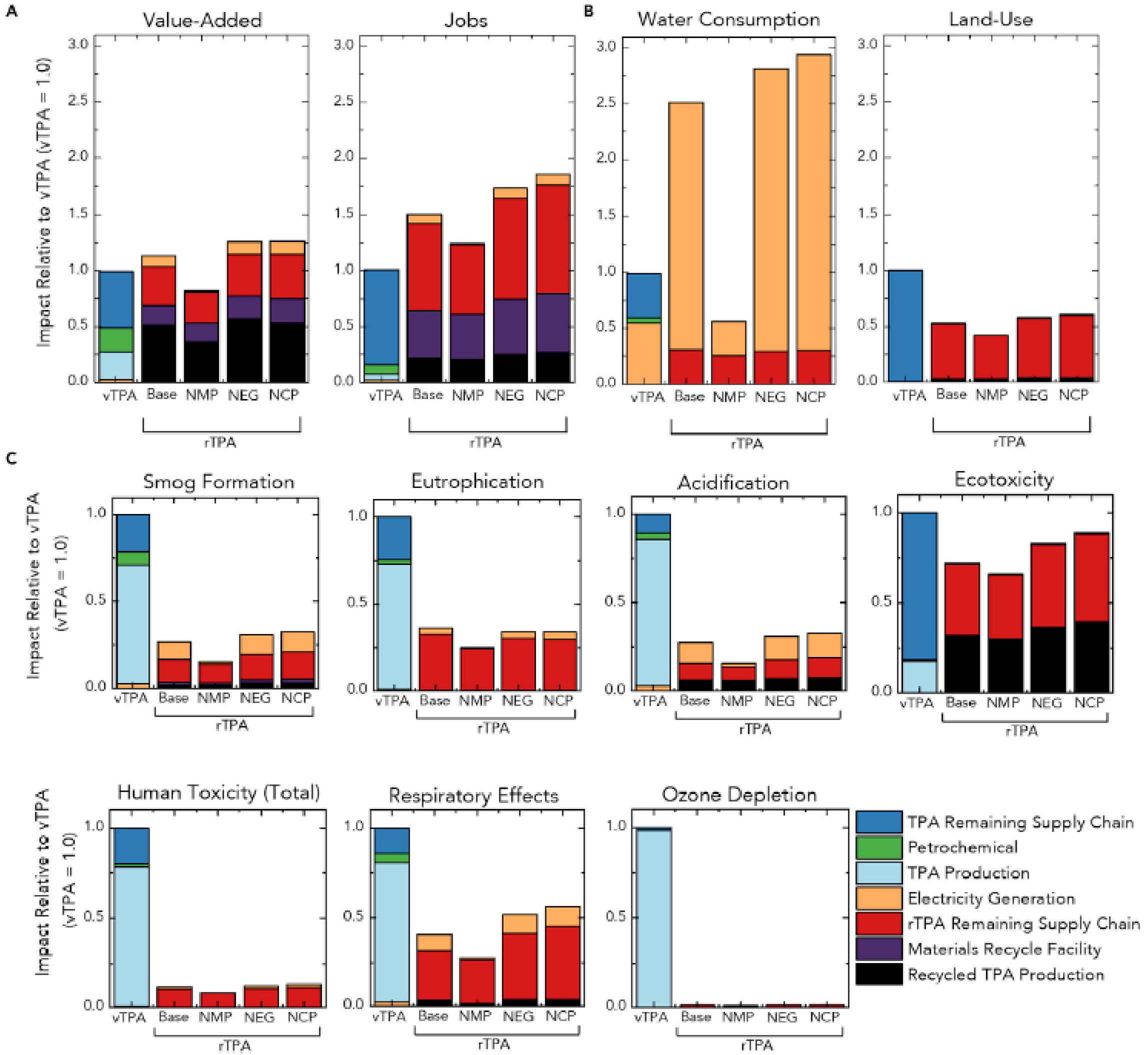


- Some recycling technologies already offer better alternative than virgin
- Many emerging technologies perform worse under environmental weighting → need streamlining
- Does not necessarily mean technologies with low scores are “bad”

Uekert et al., 2022, in preparation

Bio-based circular carbon economy **E**nvironmentally extended **I**nput-**O**utput **M**odel Analysis Results

BEIOM is a top-down, macro-level model that assesses the economy-wide social and environmental impacts of emerging technologies

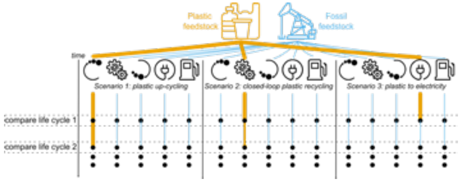


A Singh *et al. Joule* 2021

Other relevant tools

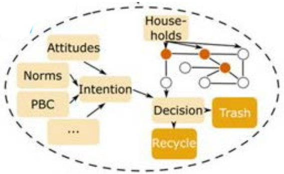
Plastics Parallel Pathways Platform (4P)

- Compare plastic end-of-life pathways that generate different products
- Assess environmental and economic impacts over multiple lifetimes
- Include circularity indicators



Plastics Recycling Agent-based model (ABM)

- Map plastic recycling, landfilling, and “wishcycling” behavior in households
- Determine social interventions that increase recycling rates



LiAISON

- Python-based, prospective LCA to preempt trade-offs and unintended and inform R&D prioritization of new technologies

Risk & impact assessment for technology adoption

- De-risk technology adoption by identifying routes from technology readiness to market and from market readiness to market share

Thank you!

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Techno-economic, life cycle, and socio-economic impact analysis of enzymatic recycling of poly(ethylene terephthalate). A. Singh, et al. Joule 5, 2479–2503, September 15, 2021. https://doi.org/10.1016/j.joule.2021.06.015

Life cycle assessment of enzymatic poly(ethylene terephthalate) recycling. T. Uekert, et al. Accepted to Green Chemistry.

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