Plastics recycling and redesign in the BOTTLE Consortium

DOE BETO/AMMTO Plastics Circularity Workshop
June 8, 2023
Gregg T. Beckham, NREL

Introduction to the BOTTLE Consortium

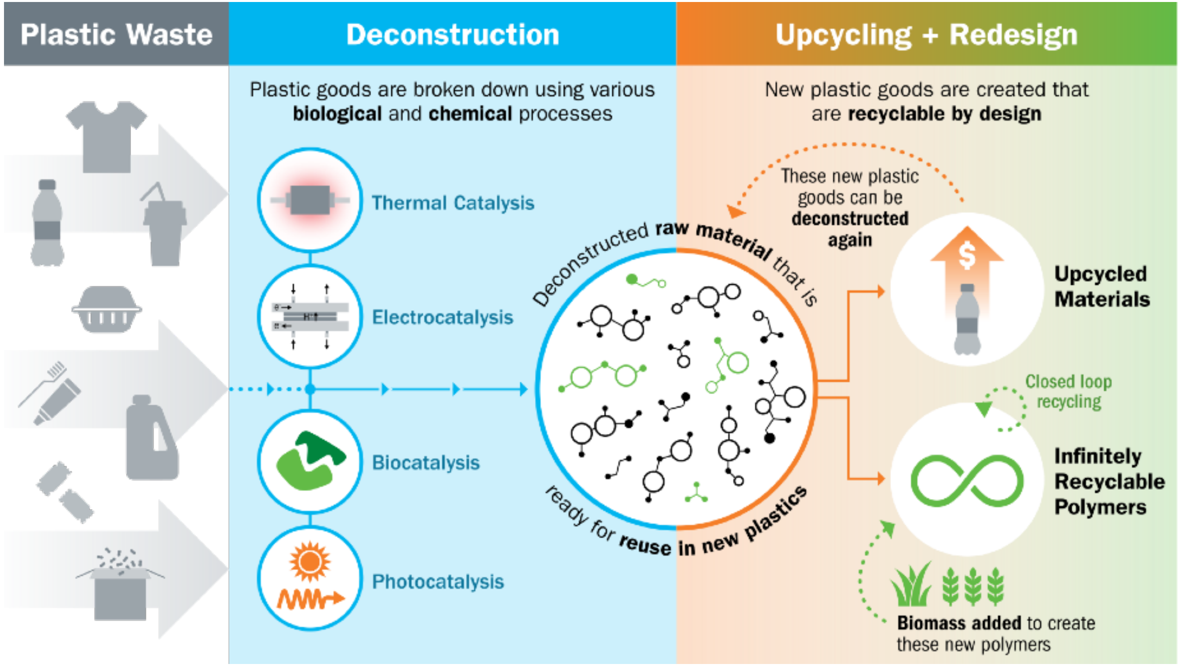
BOTTLE: Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment

Vision

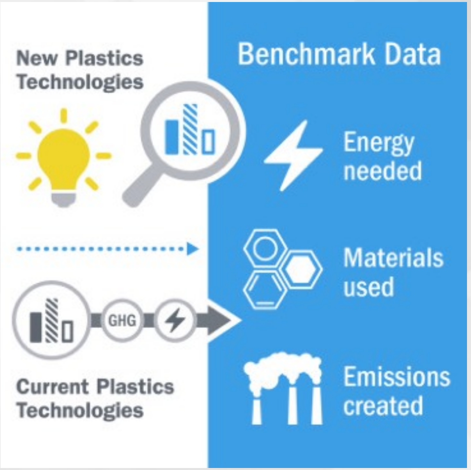
- **Scalable recycling technologies** that enable cost-effective recycling, upcycling, and energy efficiency for plastics

Mission

- Develop processes to **recycle and upcycle** existing waste plastics, and
- Develop new plastics that are **recyclable-by-design**
- Work with industry partners on your challenging problems



Introduction to analysis efforts in BOTTLE



Updated estimates on plastics entering US landfills

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Quantification and evaluation of plastic waste in the United States

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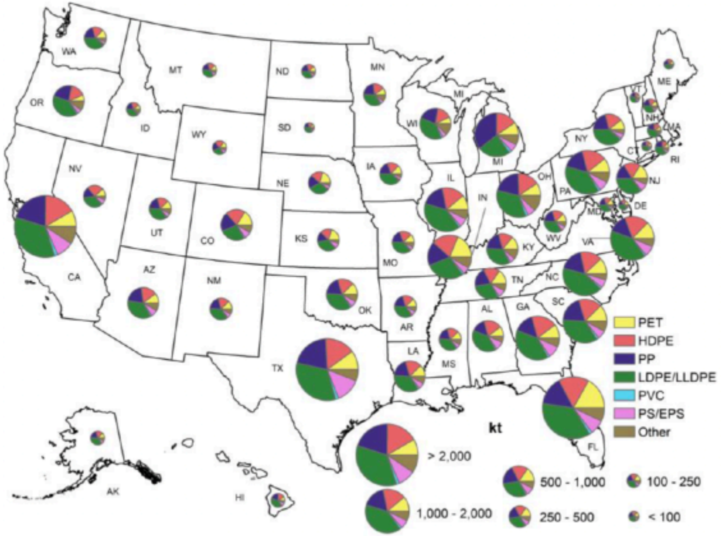
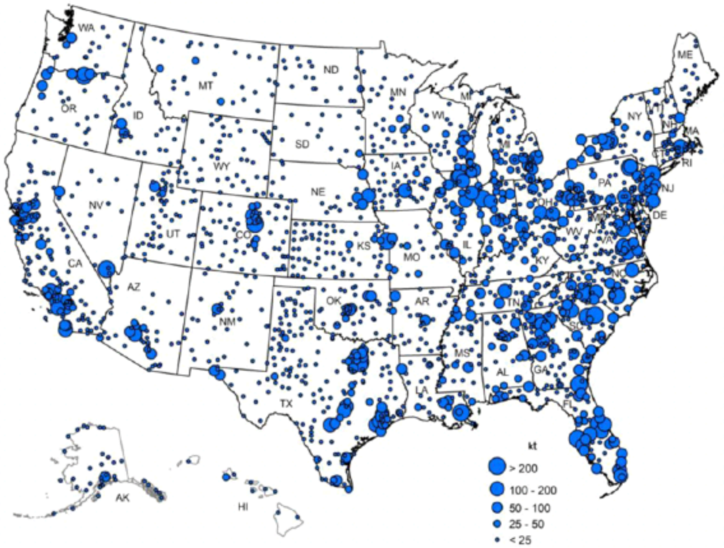
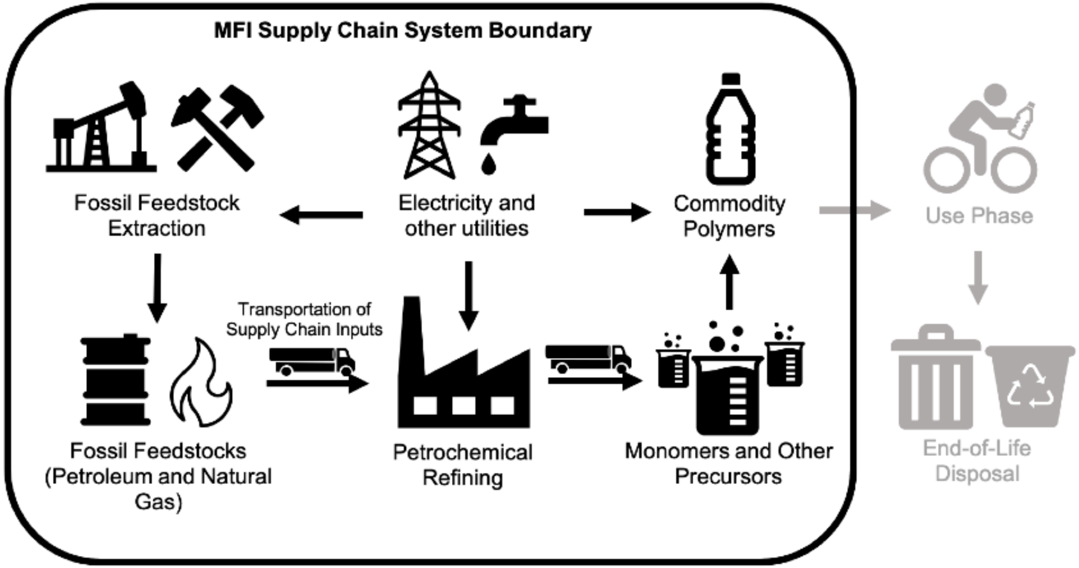
- 2019 US recycling rate was 5%
- 2019 US landfilling rate was 86%
- $7.2 B lost market value





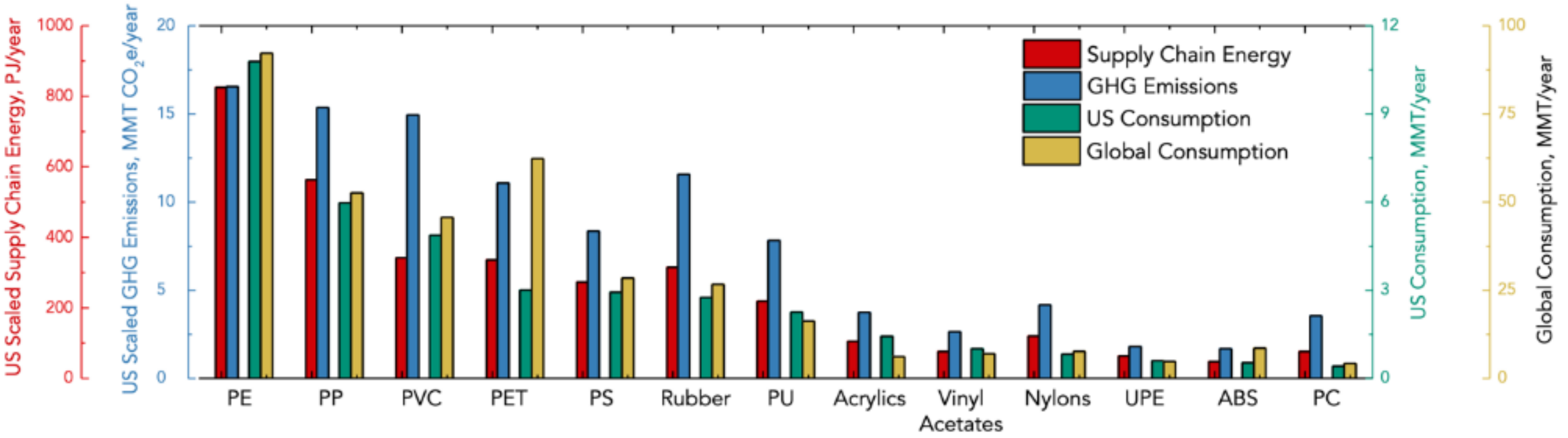
Plastics recycling technologies require accurate baselines

- Goal: Estimate supply chain energy and greenhouse gas (GHG) emissions from US-based plastics consumption
- Scope: Polymers with global consumption of ≥1 MMT per year



SR Nicholson, NA Rorrer *et al.* *Joule* 2021

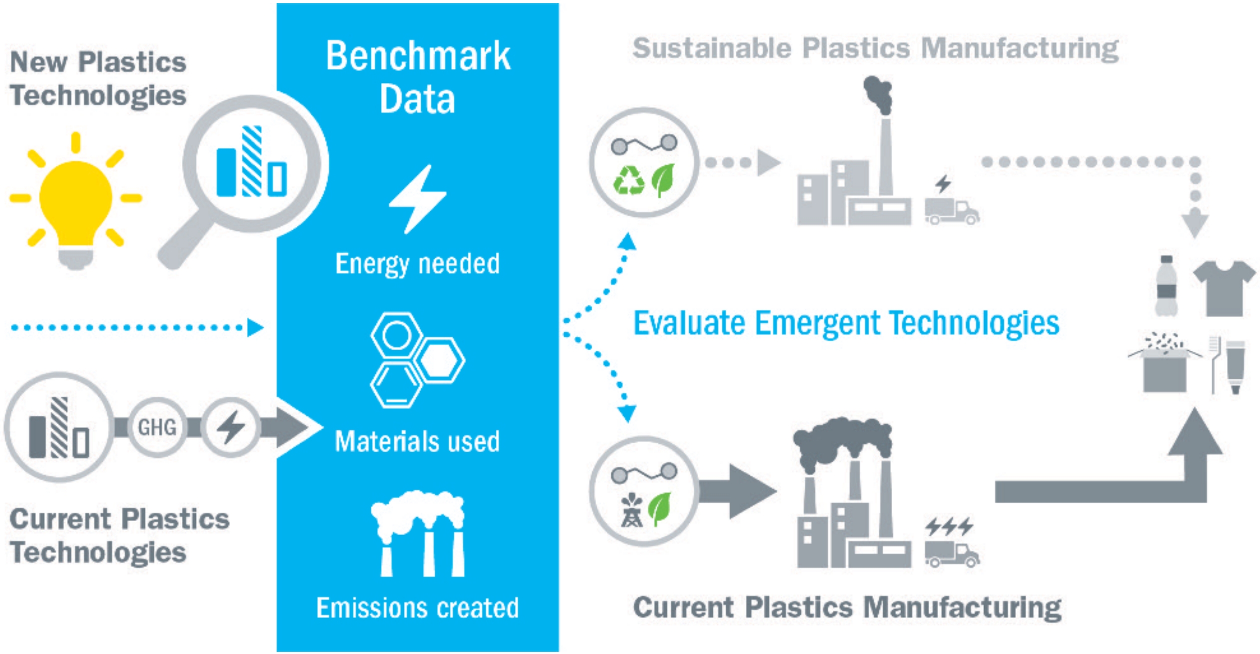
Baseline analyses for commodity plastics



- Baseline data for comparing new technologies in chemical recycling and for replacing these polymers
- 3.2 quadrillion BTUs (Quads) in the US
- 104 MMT CO_{2e} in the US

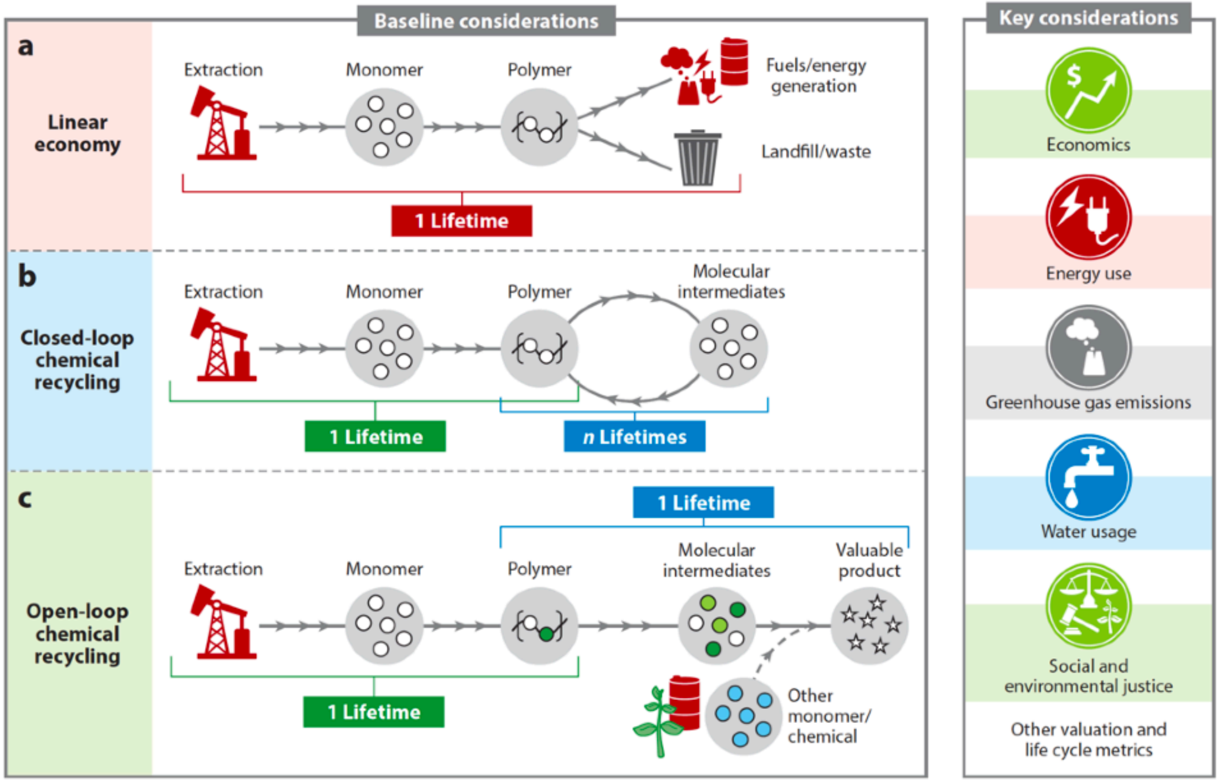
SR Nicholson, NA Rorrer *et al.Joule* 2021

Benchmarking compared to incumbent practices



SR Nicholson, NA Rorrer *et al.* *Joule* 2021

Analysis frameworks for analysis of new recycling processes



SR Nicholson, JE Rorrer, A Singh *et al.*, *Annual Rev. Chem. Biomolec. Eng.*, 2023

Illustrative analysis case studies for PET closed-loop recycling

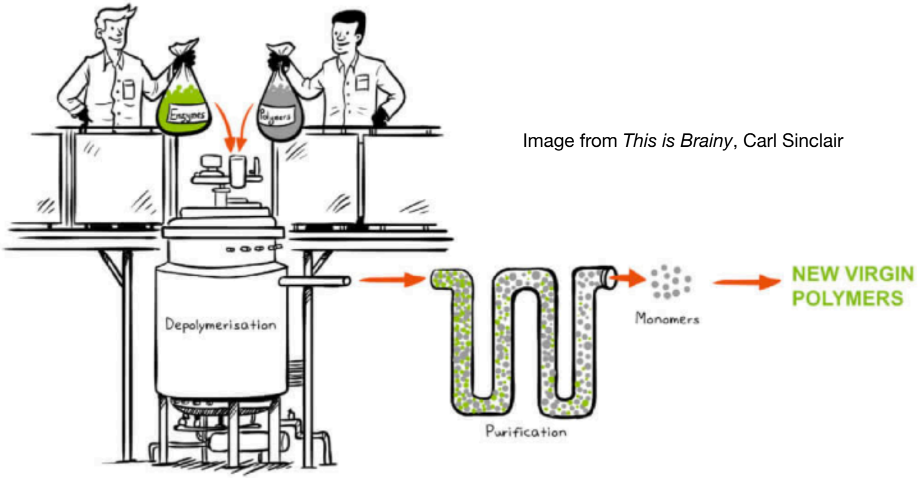
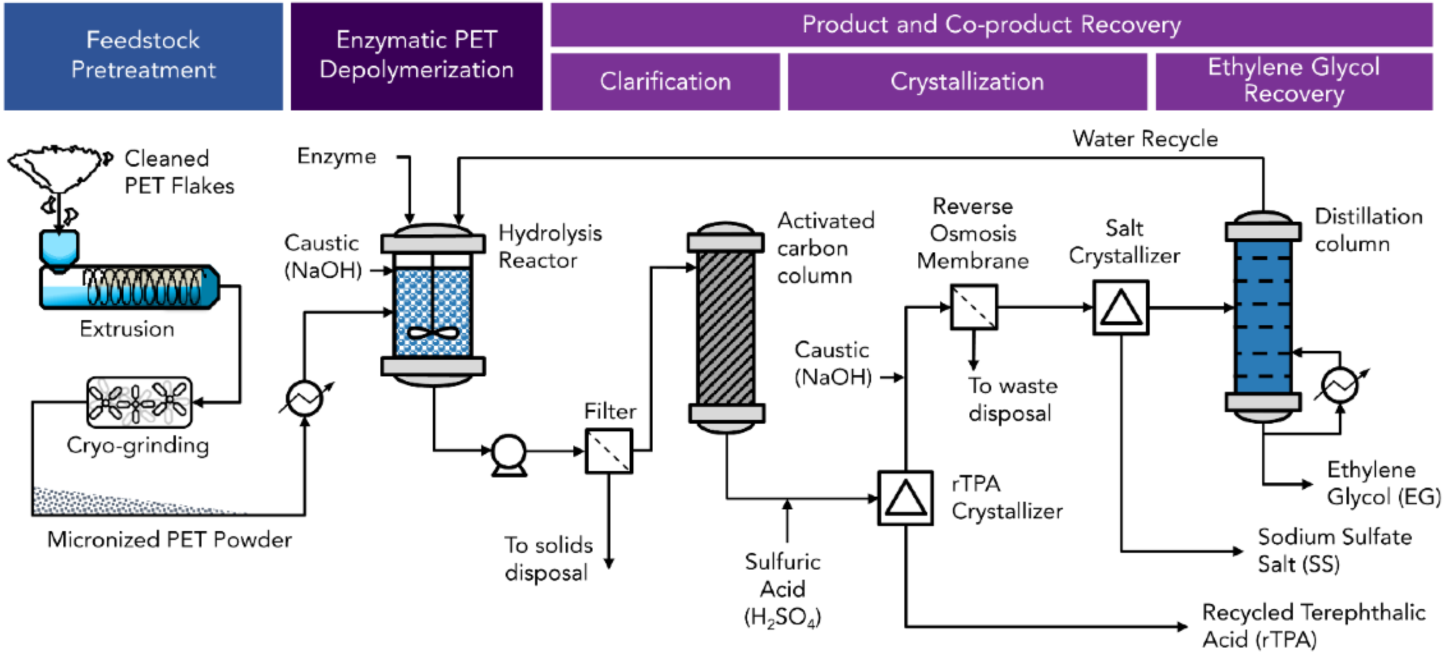


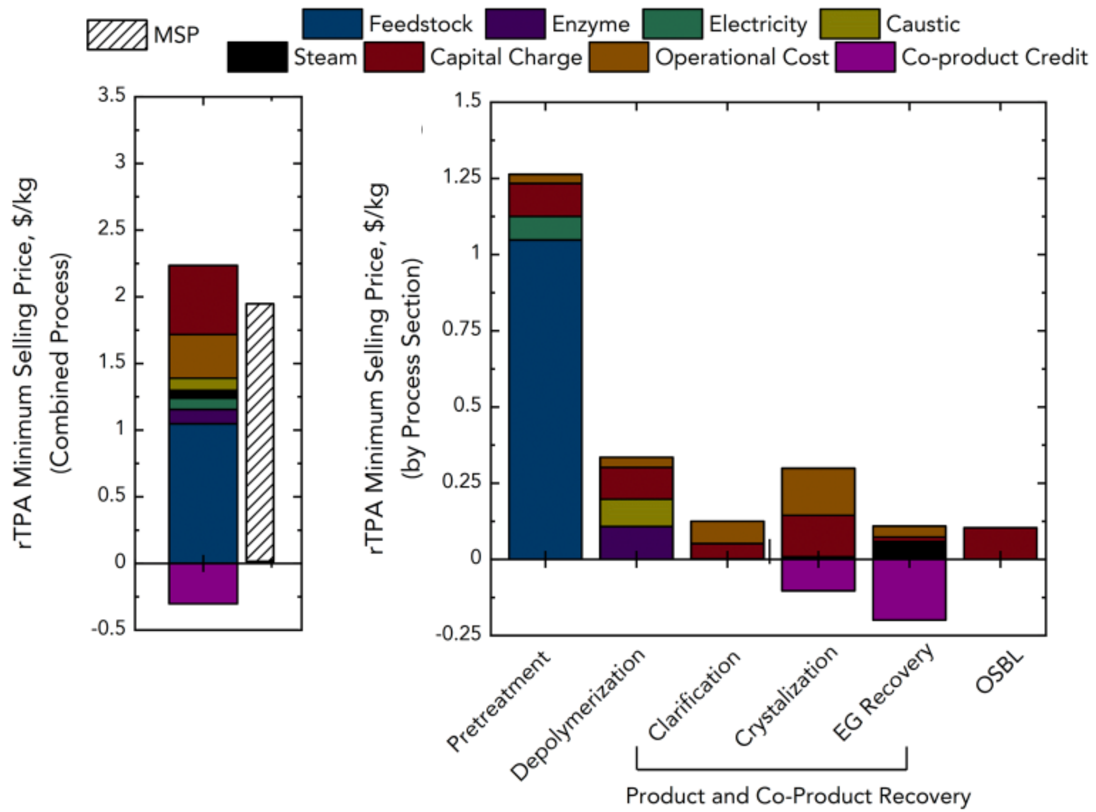
Image from *This is Brainy*, Carl Sinclair

PET enzymatic hydrolysis



A Singh *et al.* *Joule* 2021

Economics results for PET enzymatic hydrolysis

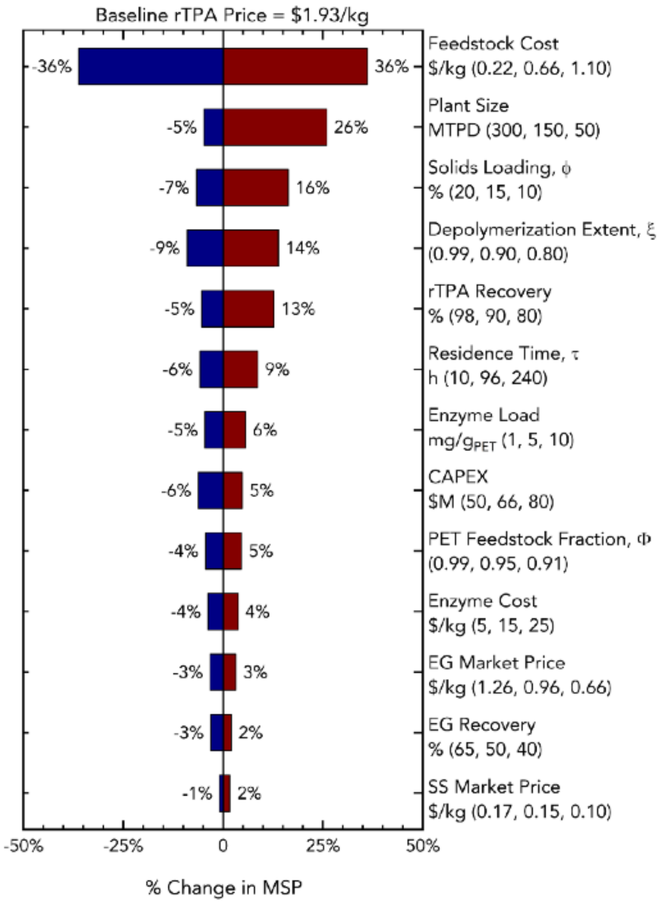


Enzymatic PET recycling shows promise relative to virgin polyester manufacturing:

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

A Singh *et al. Joule* 2021

Sensitivity analysis highlights major cost drivers

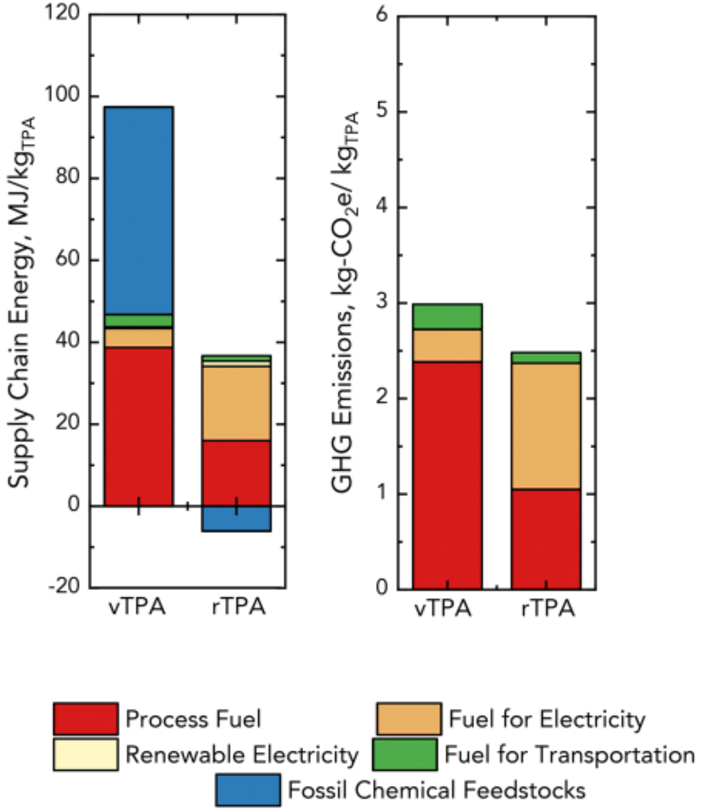


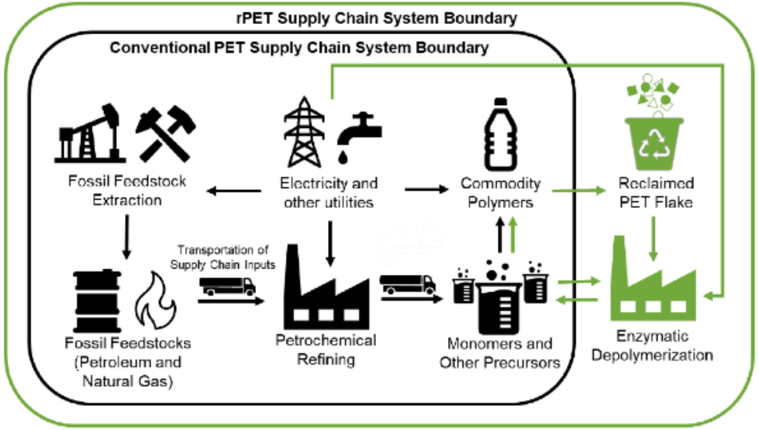
Feedstock cost, plant size, solids loading, and TPA yield are main cost drivers

- Residence time for enzymatic depolymerization, enzyme cost not major drivers

A Singh *et al. Joule* 2021

Enzymatic PET recycling can reduce energy use, and opportunities remain



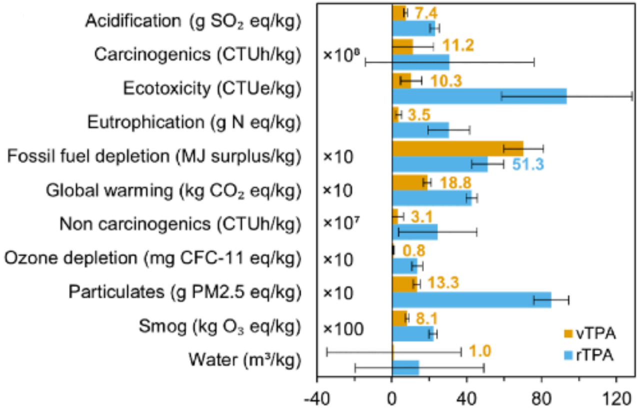


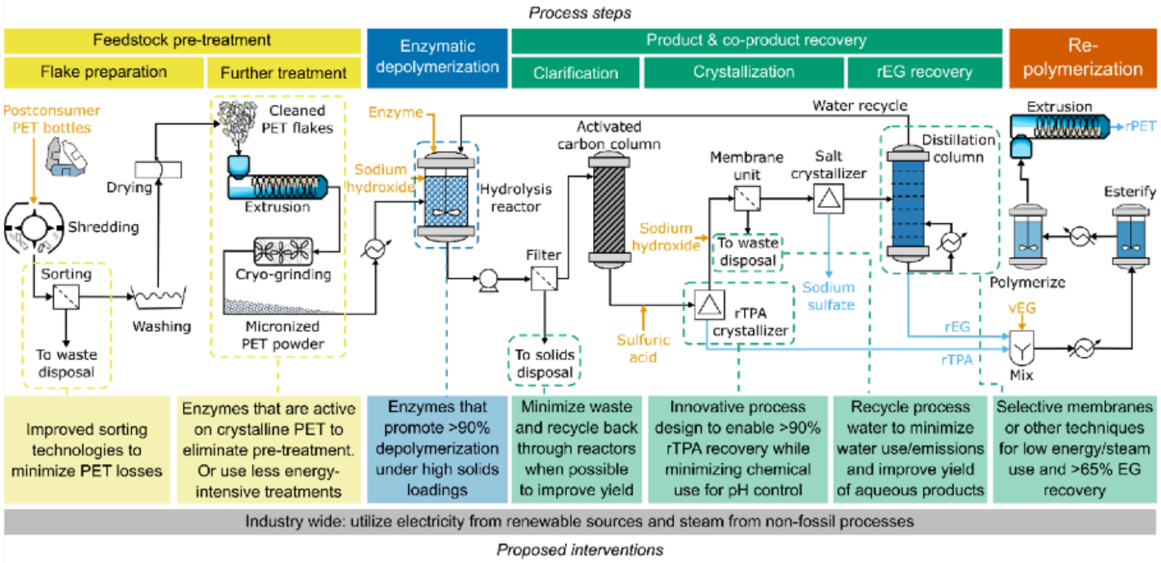
Enzymatic recycling of PET can reduce energy relative to virgin TPA manufacturing

- Supply-chain energy reduced by ~70%
- GHG emissions by ~17% per kg of TPA
- Major drivers: mechanical pretreatment, EG recovery

A Singh *et al. Joule* 2021

Life cycle assessment of enzymatic PET recycling

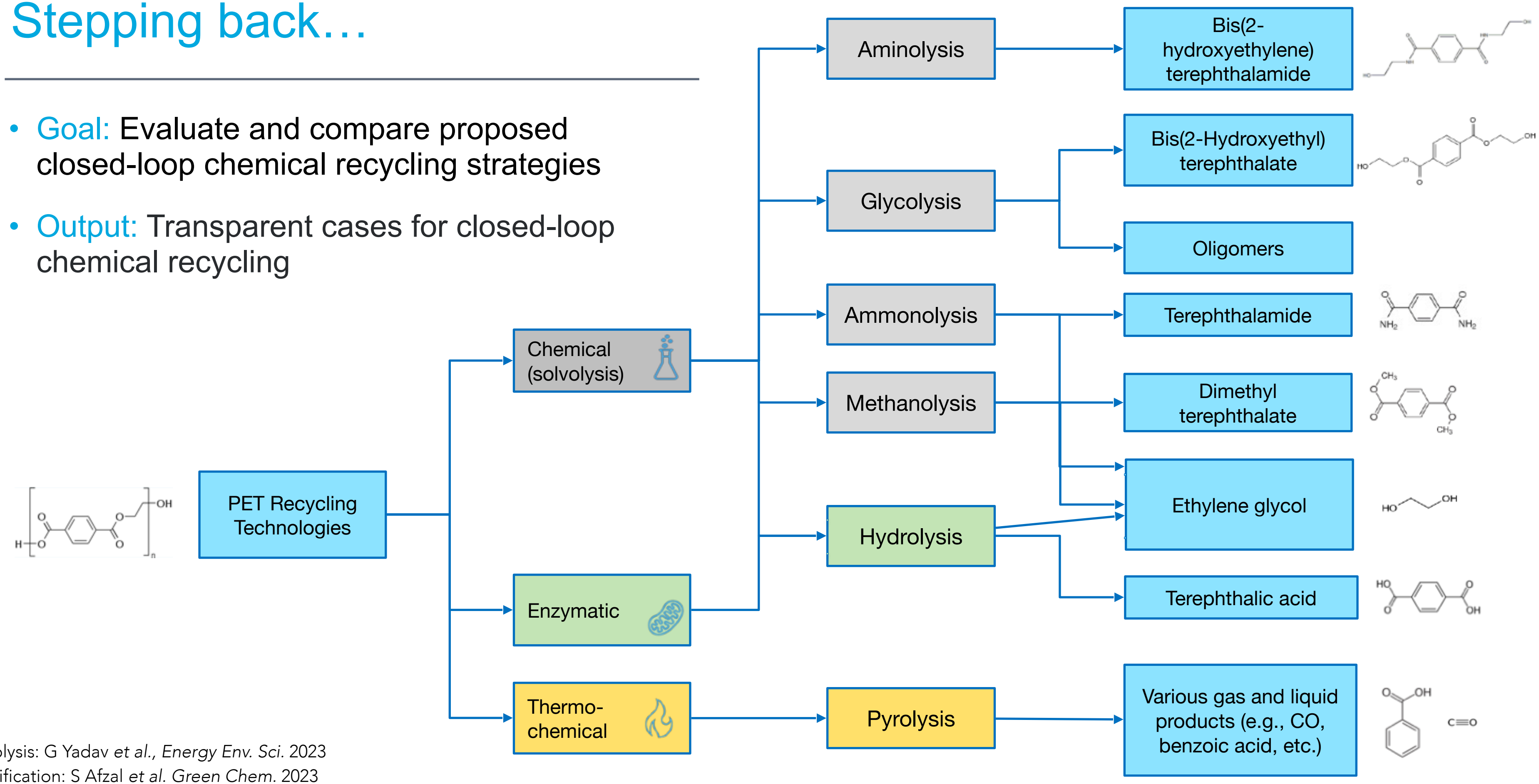




T Uekert *et al. Green Chem.* 2022

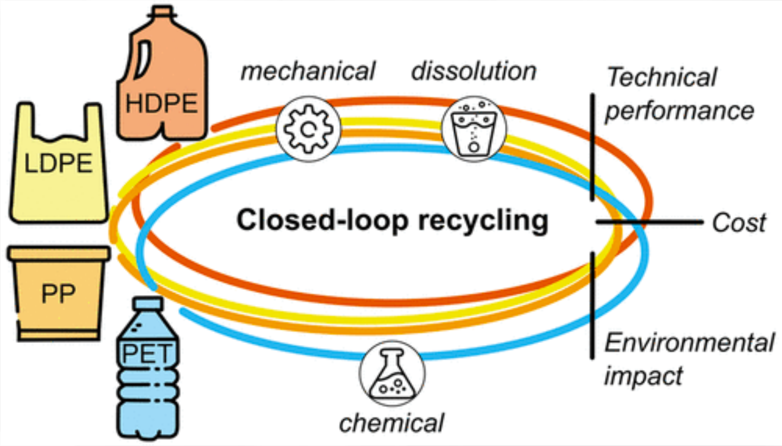
Stepping back…

- Goal: Evaluate and compare proposed closed-loop chemical recycling strategies
- Output: Transparent cases for closed-loop chemical recycling



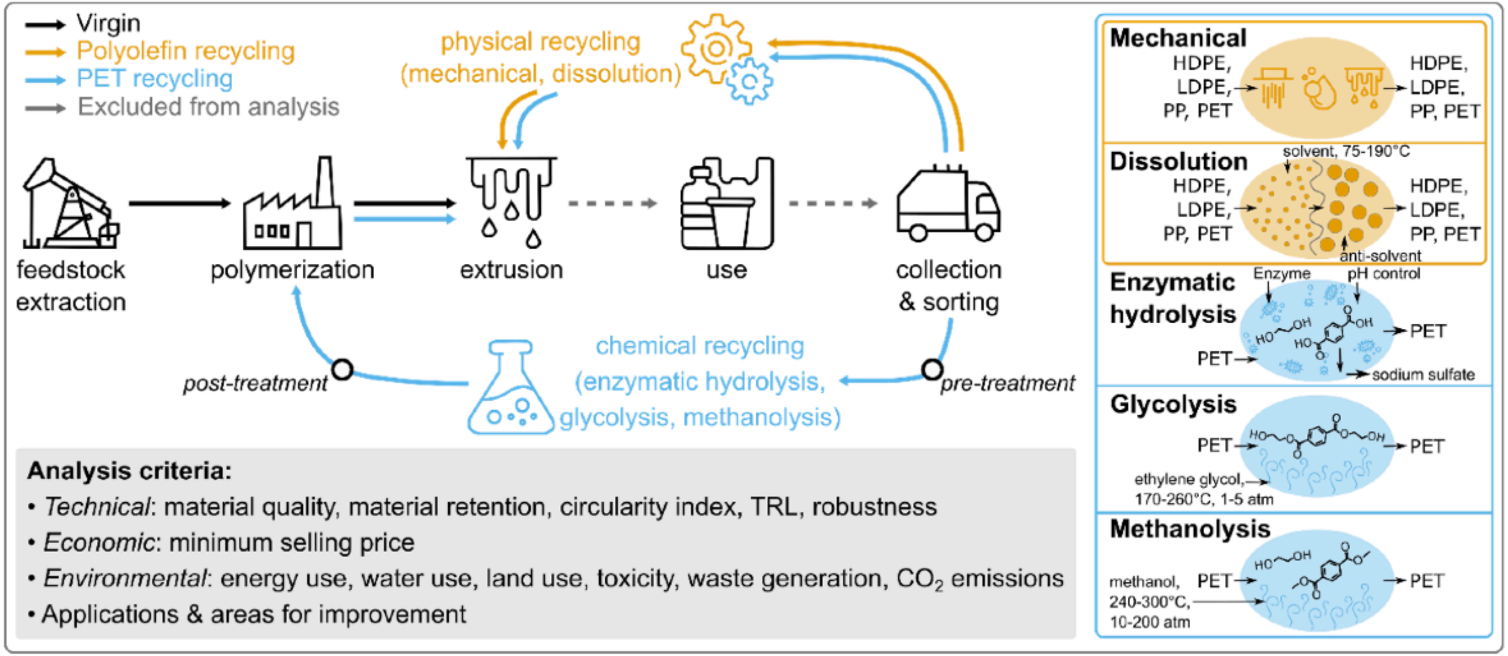
Pyrolysis: G Yadav *et al.*, *Energy Env. Sci.* 2023
Gasification: S Afzal *et al. Green Chem.* 2023
Enzymatic hydrolysis of PET: A Singh et al. Joule 2021; T Uekert *et al. Green Chem.* 2022
PET glycolysis, oxidation, hydrolysis, and methanolysis: A Singh, J DesVeaux, T Uekert *et al.* forthcoming

Comparison of closed-loop recycling approaches



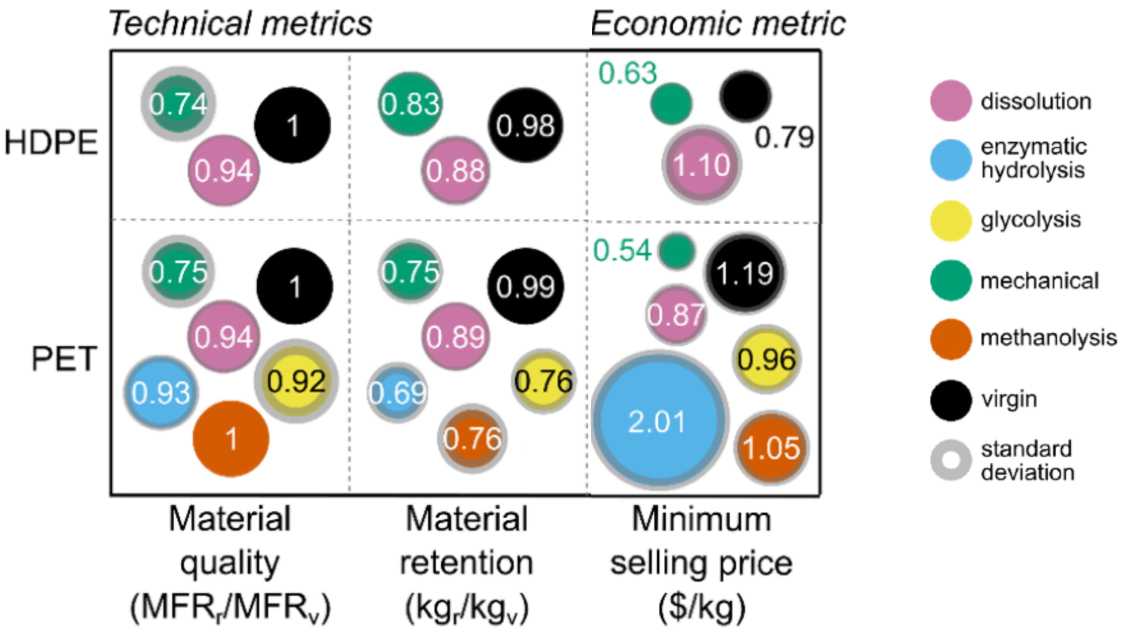
T Uekert *et al.*, *ACS SusChemEng*, 2023

Comparative analysis of existing and emerging recycling methods



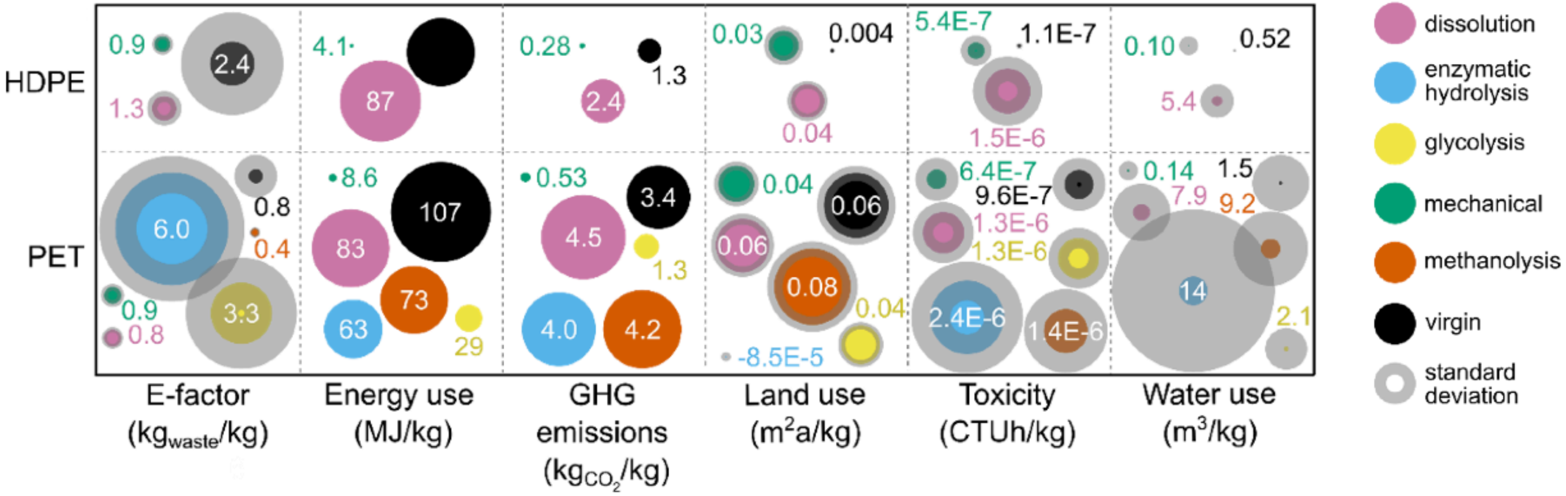
T Uekert *et al.*, *ACS SusChemEng*, 2023

Technical and economic metrics



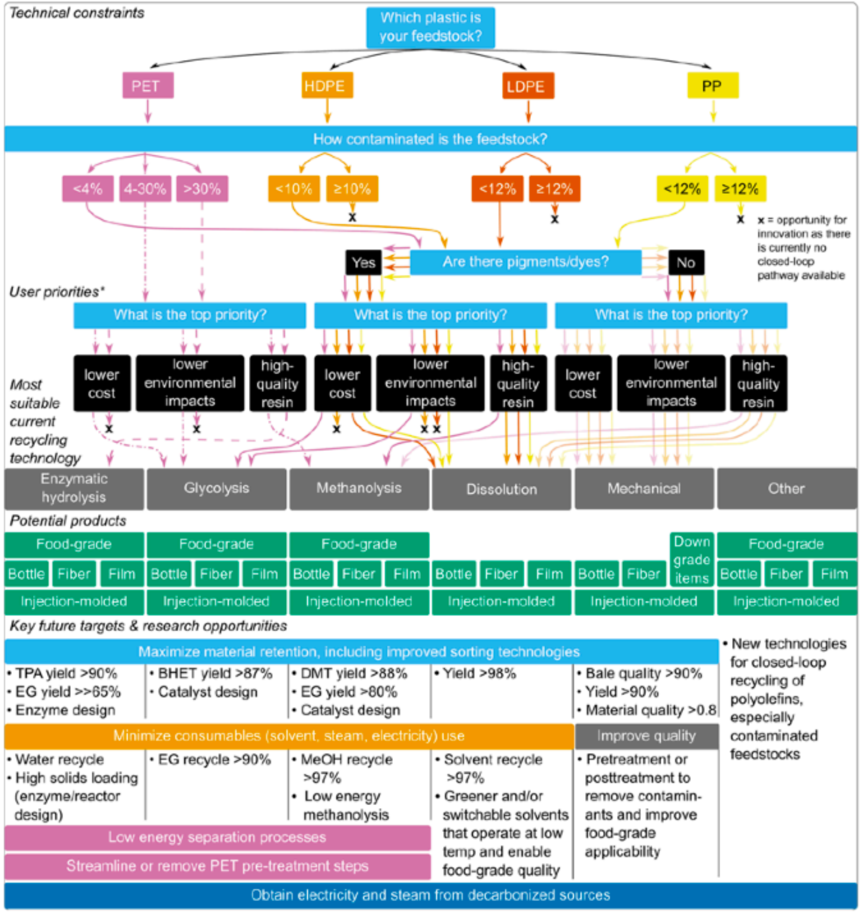
T Uekert *et al.*, *ACS SusChemEng*, 2023

Environmental metrics



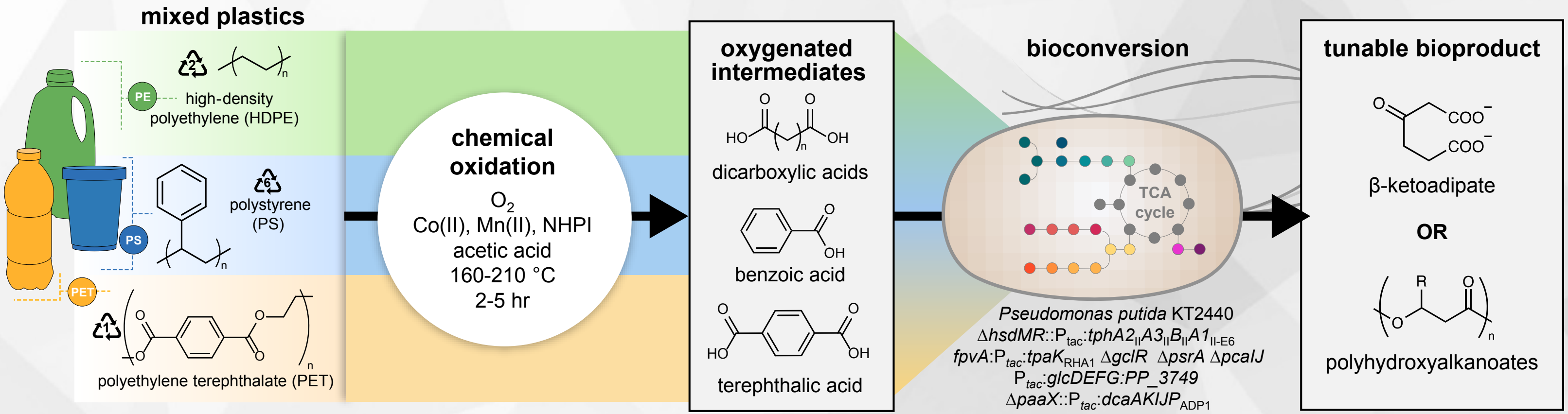
T Uekert *et al.*, *ACS SusChemEng*, 2023

Decision tree for recycling methods



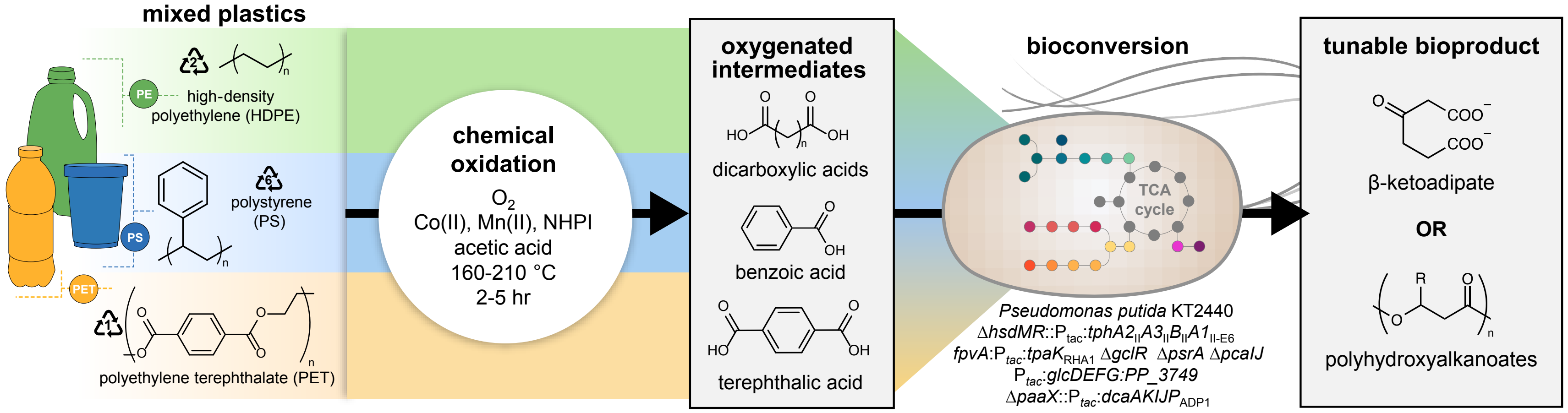
T Uekert *et al.*, *ACS SusChemEng*, 2023

Valorization of mixed waste plastics



Sullivan, Werner, Ramirez, Ellis, *Science*, 2022

Hybrid processes allow mixed polymers to be converted to a single product



- Hybrid catalytic oxidation and bioconversion can offer a new route to valorize mixed plastics
- This approach works for polyester textiles, food packaging, PVC-contaminated materials, etc.
- Products include be monomers for recyclable-by-design polymers (**next slide**)

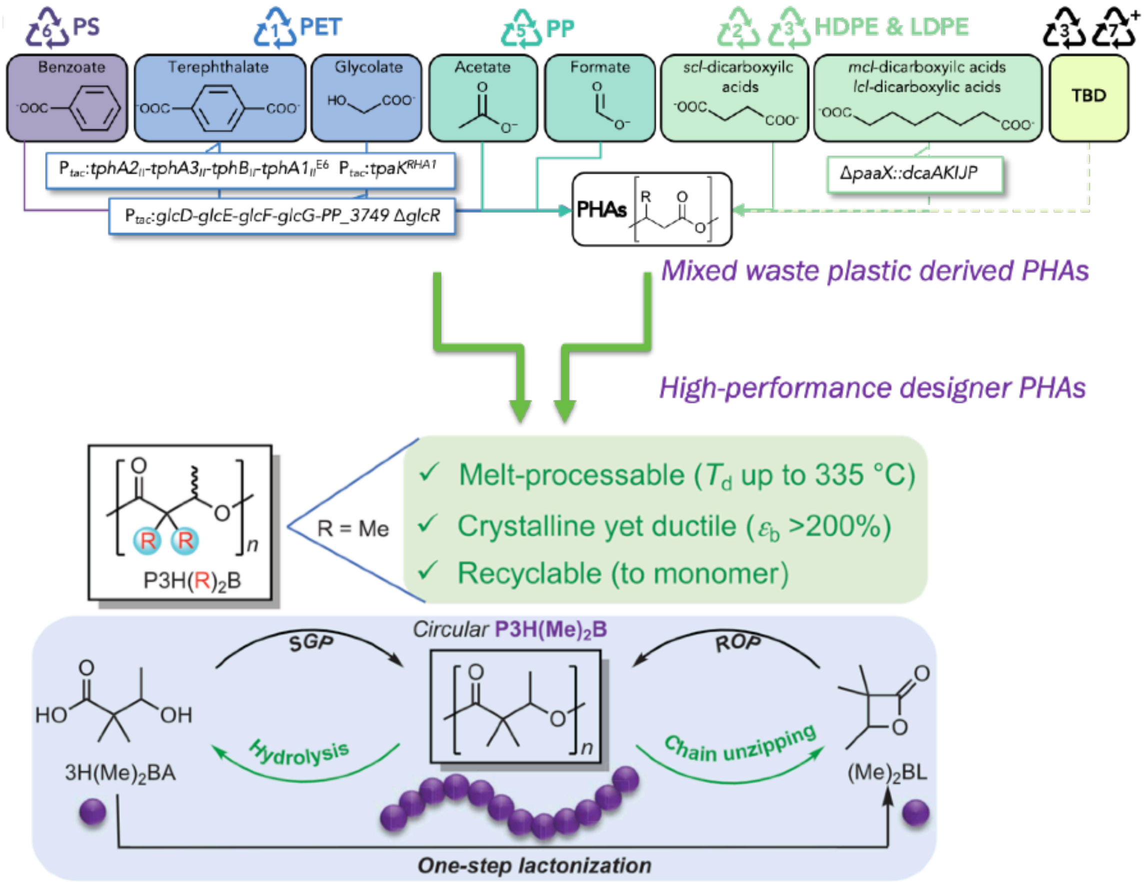
Colorado State University

Massachusetts Institute of Technology

Wisconsin University of Wisconsin–Madison

Sullivan, Werner, Ramirez, Ellis, *Science*, 2022

Today's waste plastics to tomorrow's recyclable mono-materials



Eugene Chen

Kat Knauer

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Zhou, Zhang, Shi *et al.*, *Science* 2023

Quinn, Knauer, Beckham, Chen, *One Earth*, 2023

Main messages:

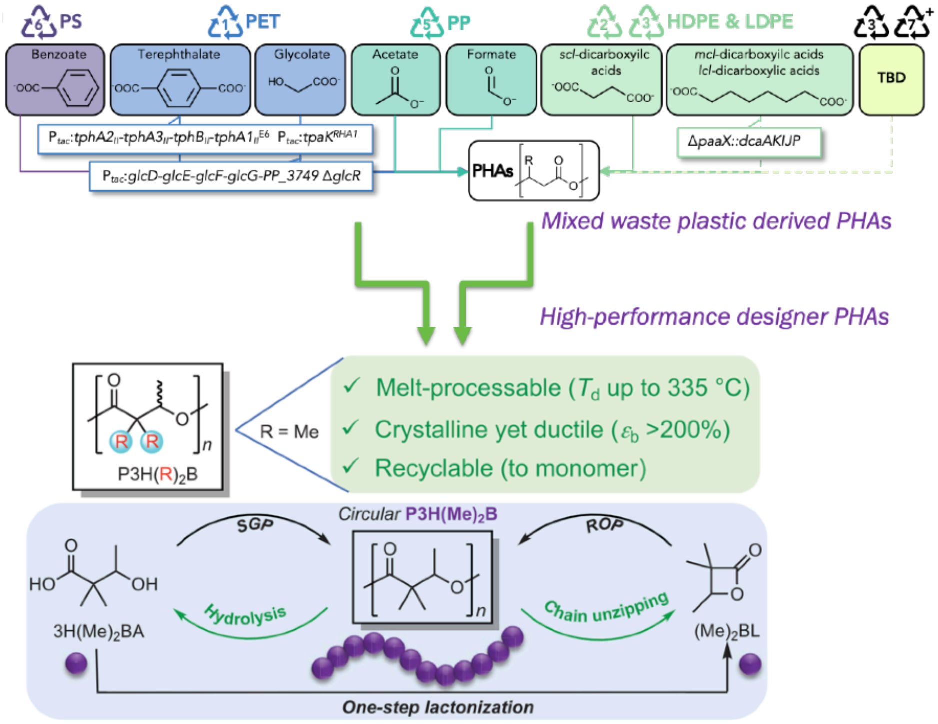
- If we can keep a polymer a polymer to recycle it, we should…

- Chemical recycling *might* make sense where no other options exist, especially for low-, zero-, or negative-value feedstocks

- Analysis for economics, energy, GHG emissions, and environmental impacts is critical to evaluate options relative to incumbent processes – new technologies should be evaluated early!

- The plastics recycling field has many parallels to biomass conversion – let's standardize substrates and methods to evaluate new processes

- We must also consider "Redesign" as a core concept of a plastics future



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