NREL
Transforming ENERGY

Polymer Recycling Opportunities and Challenges

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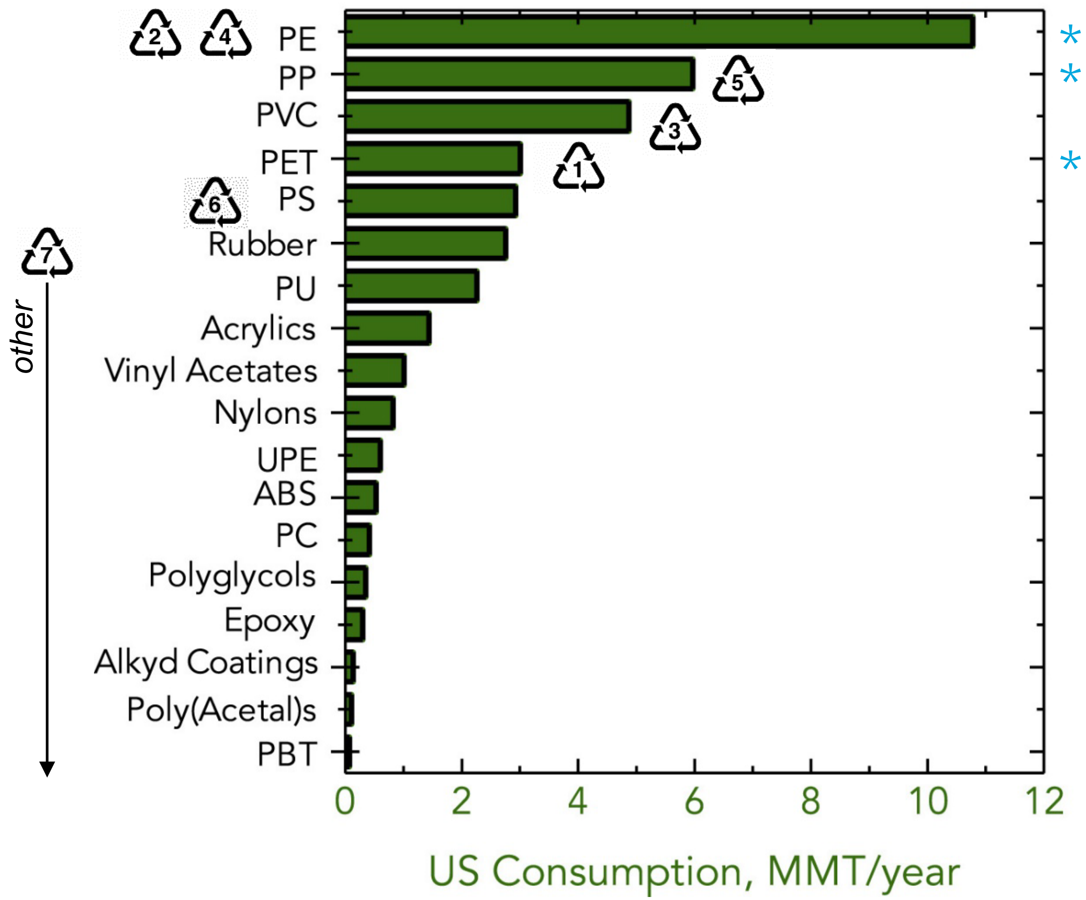
Photo from iStock-627281636

The Plastic Problem

5% of plastic waste in the U.S. is recycled.[1]

Image credit: Ellen MacArthur Foundation, *A New Plastics Economy: Rethinking the Future of Waste* **2016.** [1] Milbrandt et al., *Resourc. Conserv. Recycl.*, **2022**, *183*, 106363

Types of Polymers



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Today's focus

Nicholson, et al., *Joule*, **2021**, *5*, 673-686.

Types of Recycling

Plastic Waste

↓

Collection

↓

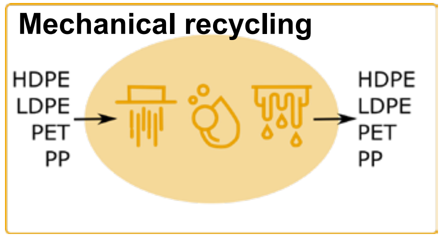
Sorting

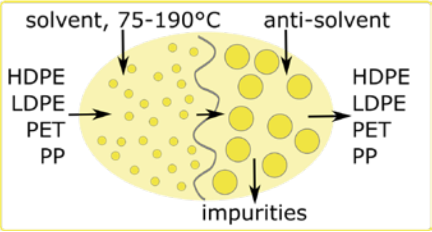
Plus energy recovery (incineration) and new upcycling technologies!

MECHANICAL RECYCLING

Change the physical form of plastic without changing its chemical structure

Today's technology



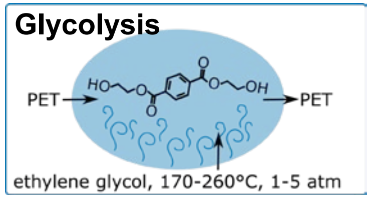


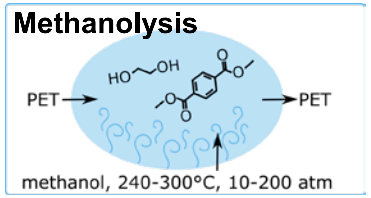
Dissolution recycling

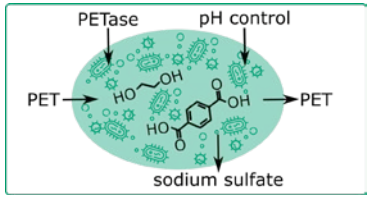
CHEMICAL RECYCLING

DEPOLYMERIZATION

Break plastic into "monomers" that are turned back into plastic



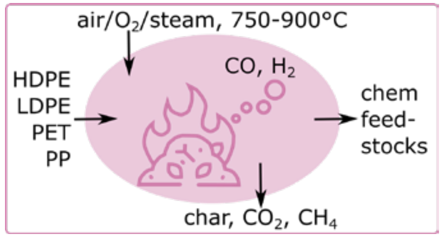




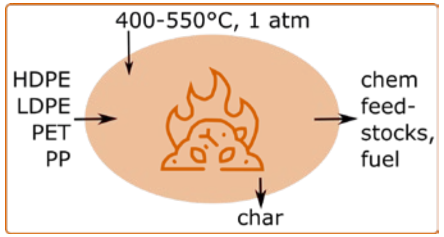
Enzymatic hydrolysis

THERMAL RECYCLING

Break plastic into feedstock chemicals or fuels



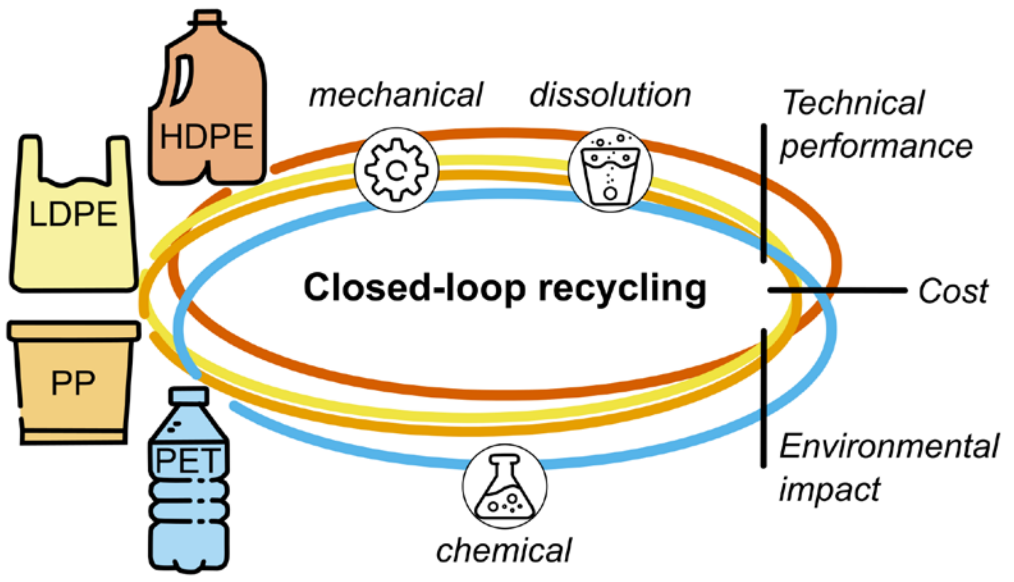
Gasification



Pyrolysis

Quantifying Opportunities & Challenges

- How do plastic recycling technologies stack up? Where are the key issues and gaps?
- Our approach: compare closed-loop (plastic-to-plastic) recycling technologies consistently and quantitatively across cost, environmental impacts, and technical performance.



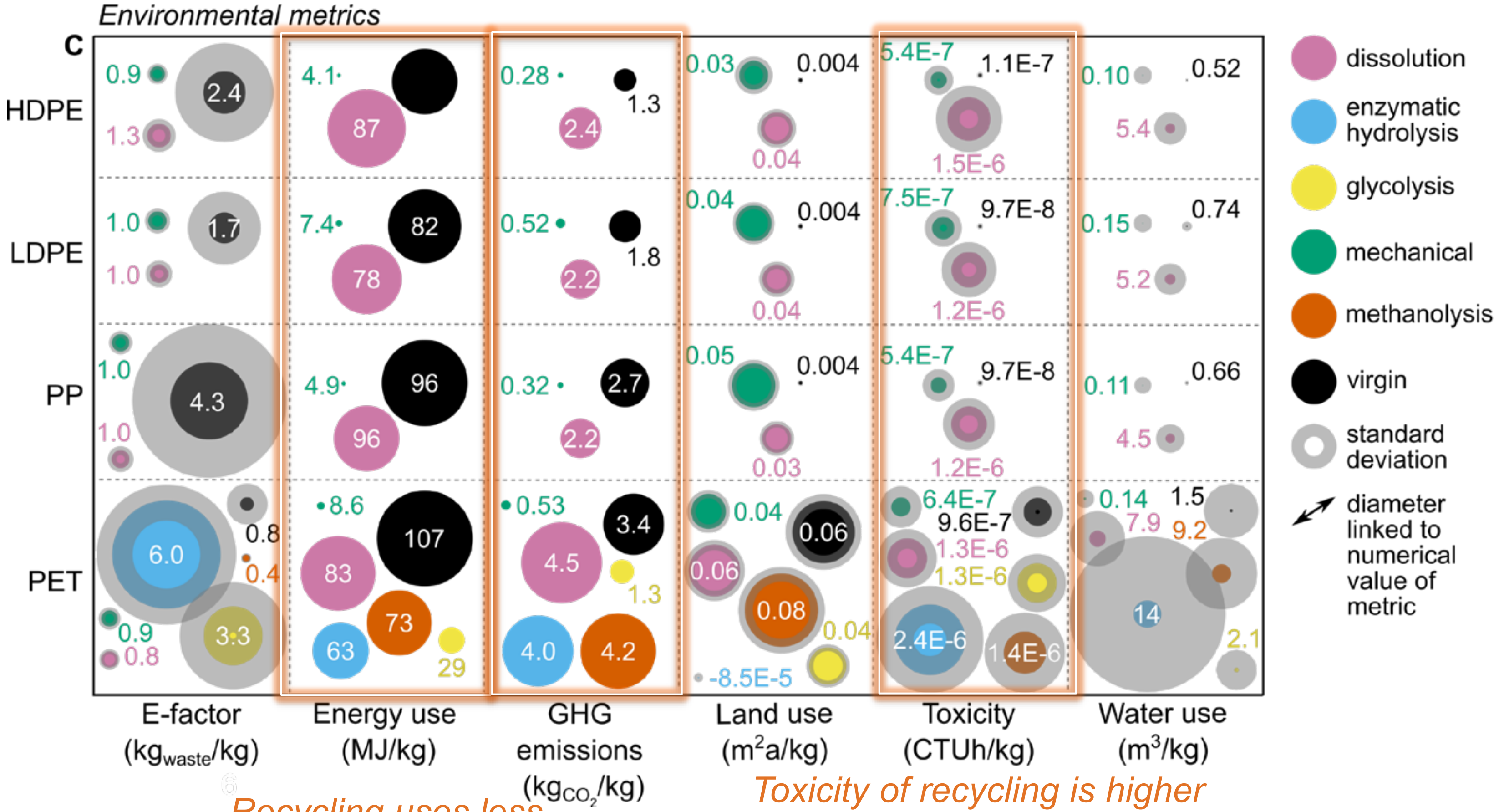
Uekert, et al. *ACS Sustain. Chem. Eng.* **2023**, *11*, 965-978.

Opportunity 1: Lowering Environmental Impacts

Mechanical recycling & glycolysis have lowest greenhouse gas emissions

Electricity, steam, and solvents are biggest contributors to impacts

Yield is a major determining factor

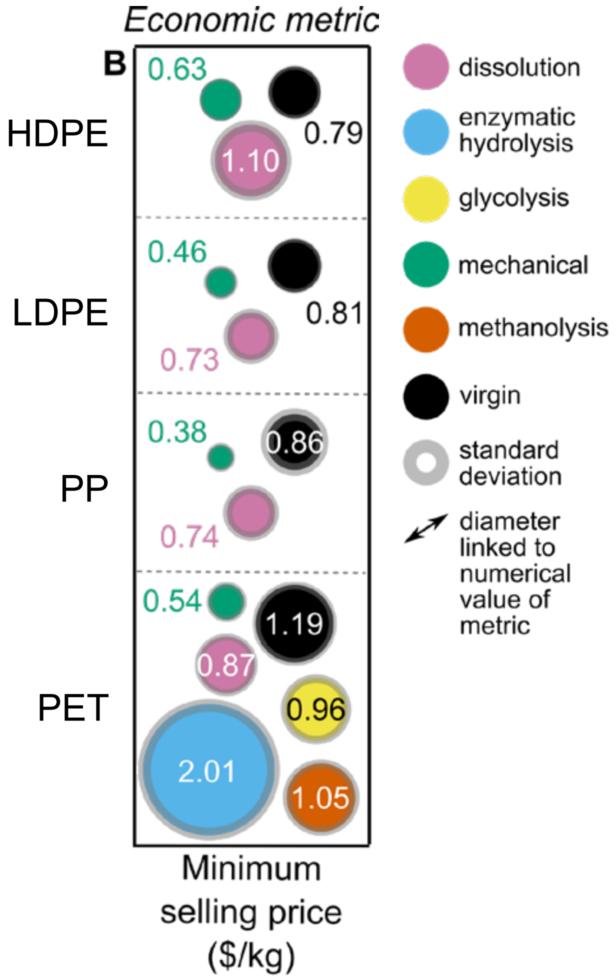


Recycling uses less energy than virgin

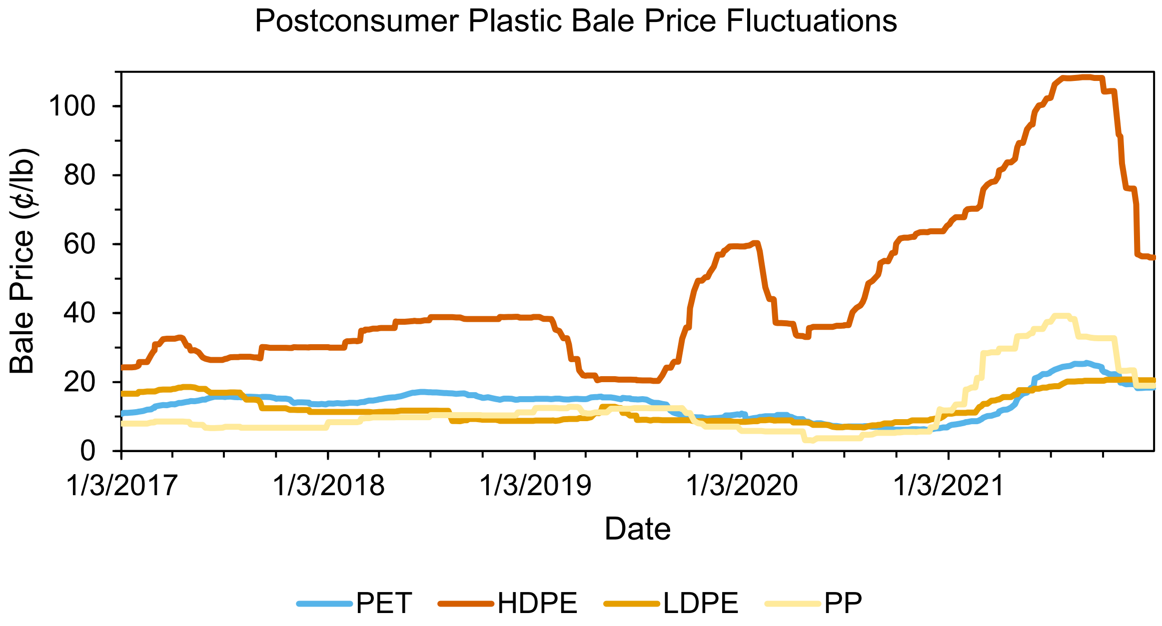
Toxicity of recycling is higher than virgin production, but similar to landfill

Uekert, et al. *ACS Sustain. Chem. Eng.* **2023**, *11*, 965-978.

Opportunity 2: Lowering Cost



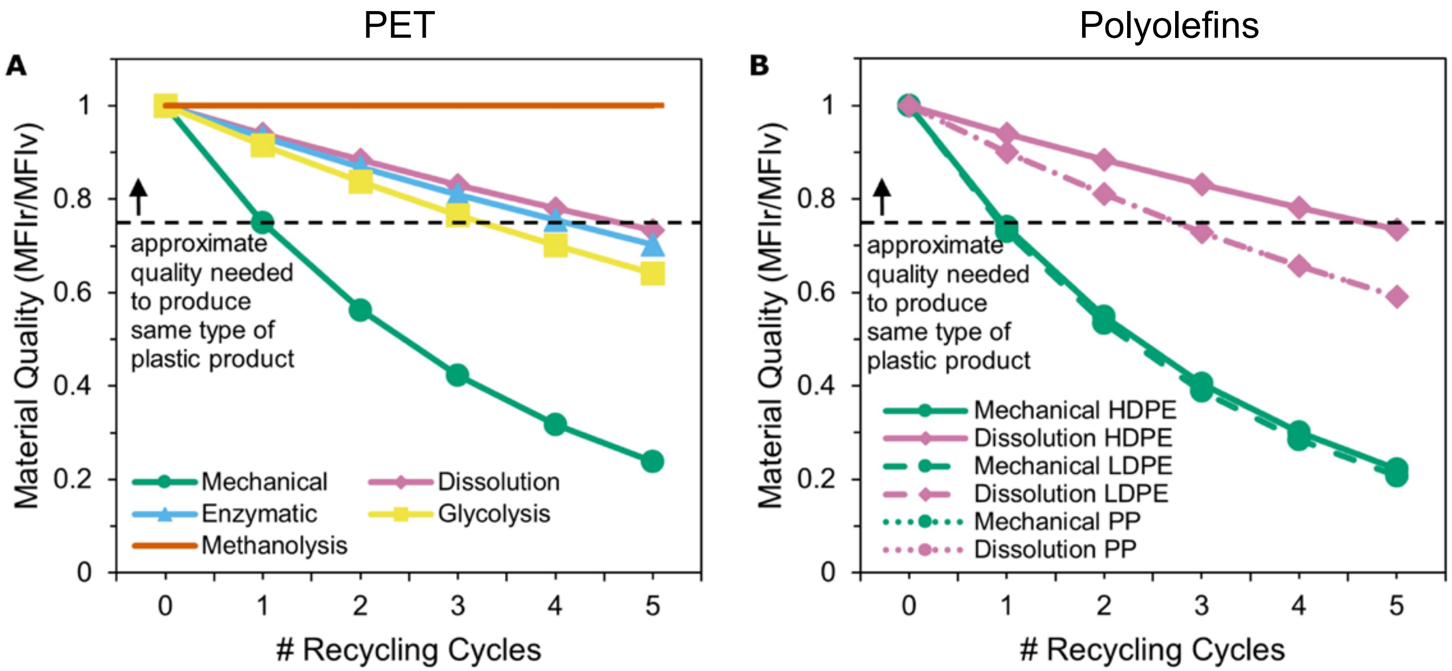
- Mechanical recycling always **less expensive** than virgin plastic
- Glycolysis, methanolysis and dissolution also less expensive than virgin plastic manufacturing
- **Plastic bale price** is the biggest contributor to recycling costs and is highly variable → **Yield** is again a major determining factor



Uekert, et al. *ACS Sustain. Chem. Eng.* **2023**, *11*, 965-978.

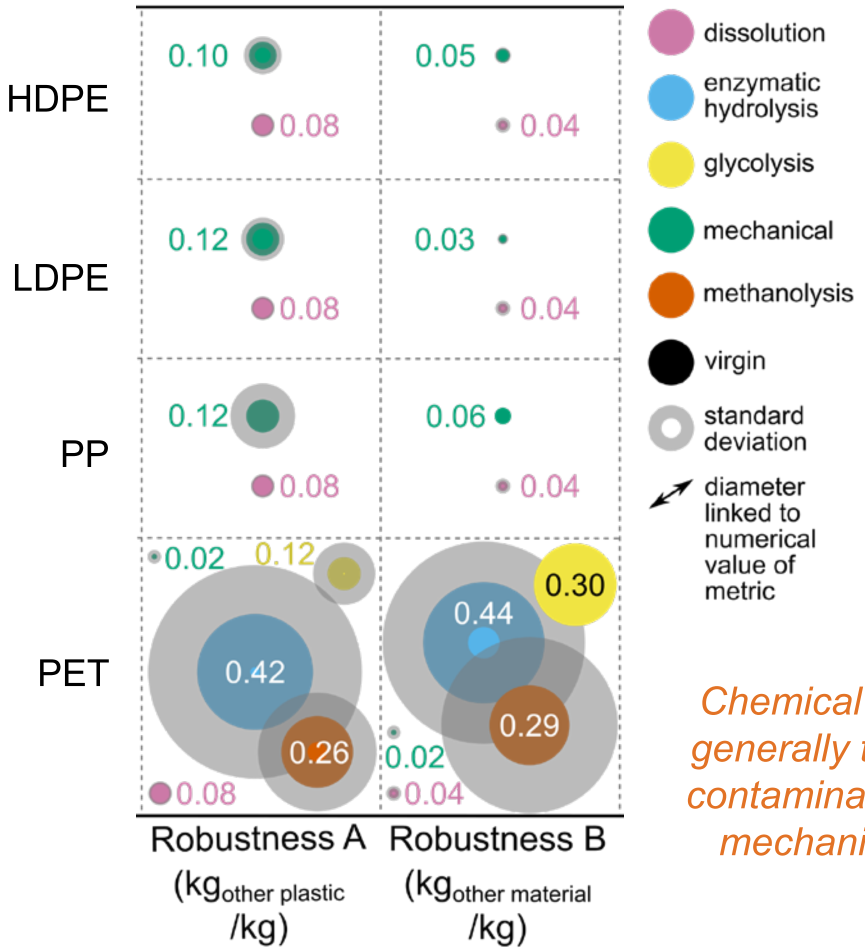
Challenge 1: Material Quality

- **Material quality** = melt flow rate (MFR) of recycled plastic divided by MRF of virgin plastic
- Mechanical recycling → heat + shearing during extrusion → chain scission, branching & cross-linking → must supplement with virgin plastic to improve quality
- Quality is rarely characterized for chemical recycling techniques but tends to be higher than mechanical



Uekert, et al. *ACS Sustain. Chem. Eng.* **2023**, *11*, 965-978.

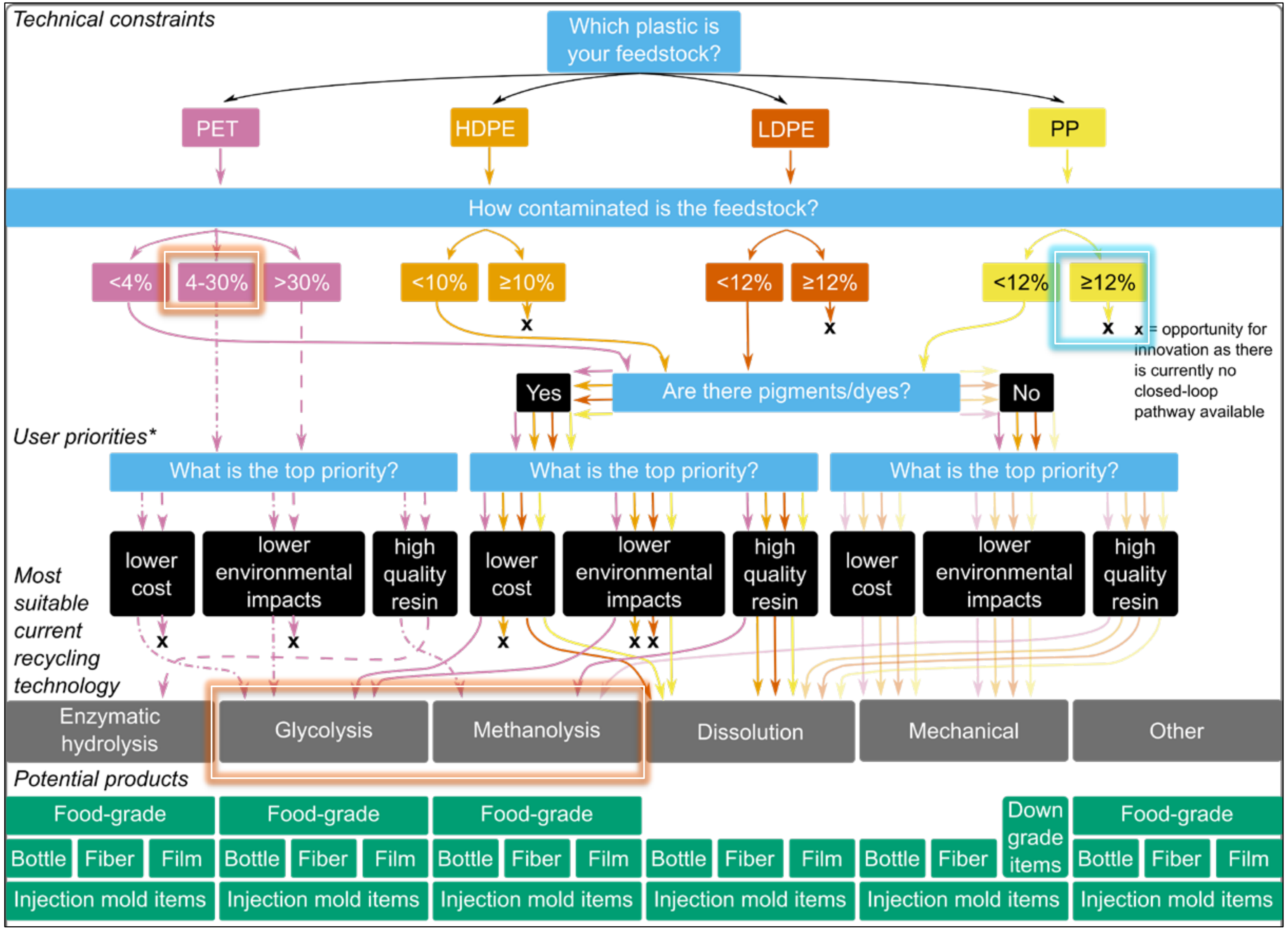
Challenge 2: Contamination Tolerance



Chemical recycling can generally tolerate higher contamination rates than mechanical recycling

- **Robustness A** = quantity of other plastic contamination tolerable by process
- **Robustness B** = quantity of other material (e.g., paper, metals) contamination tolerable by process
- Better sorting at collection and at material recovery facilities could address some contamination issues

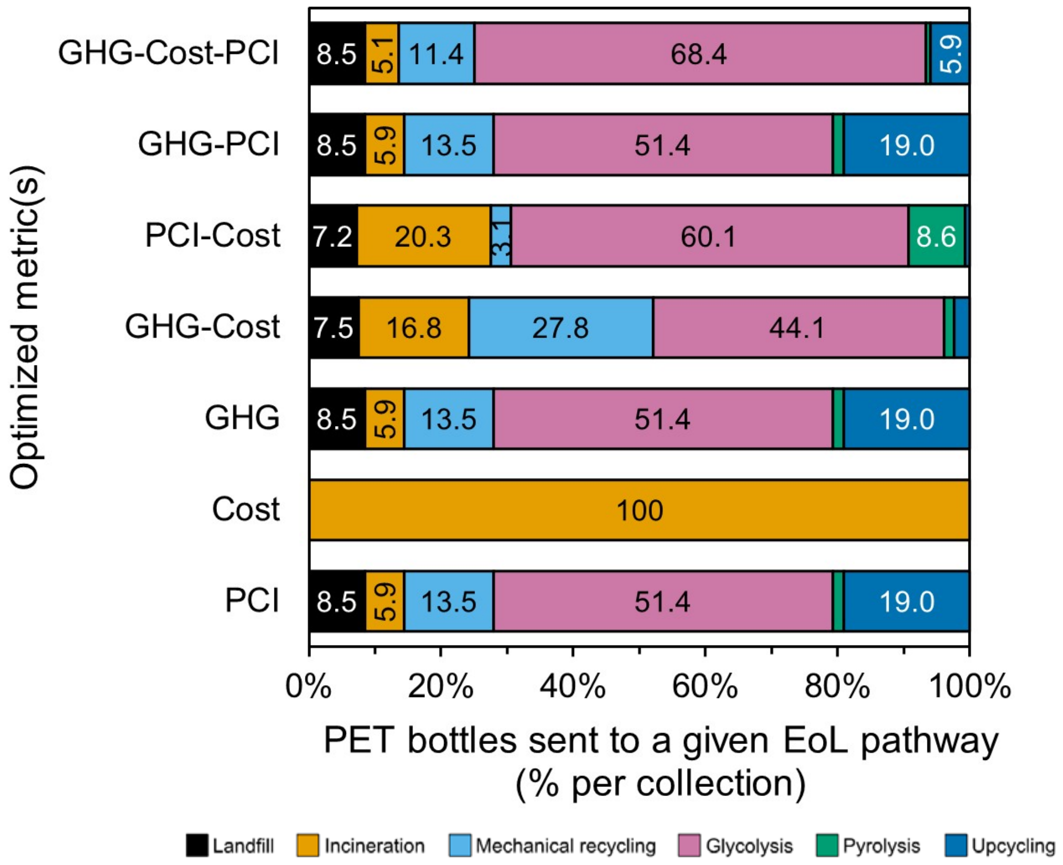
Mapping Challenges & Opportunities to Applications



Uekert, et al. *ACS Sustain. Chem. Eng.* **2023**, *11*, 965-978.

Leveraging Opportunities to Combine Recycling Pathways

- No single technology can fix everything, so how can we **optimally combine technologies**?
- Approach: Material flow model of all PET bottles in the U.S. combined with brute force algorithm for end-of-life optimization across multiple metrics
- Mechanical recycling + glycolysis + up-cycling → reduce GHG emissions by 1.1 million metric tons CO_2, increase costs by 2.5x, improve circularity from 0 to 0.13, and reduce virgin bottle demand by 16% relative to landfilling



Ghosh, et al. *Adv. Sustain. Systems* **2023**, 2300068

Summary

- Quantitative analysis identifies clear trade-offs between technical performance and environmental and economic impacts across plastic recycling technologies.
- Mechanical recycling still outperforms its competitors across most metrics but cannot handle all materials.
- Chemical recycling will be important for multi-material or contaminated plastic, but not all technologies are created equal, and all require improvement.
- Combining solutions could help achieve a more circular and sustainable plastic economy.

Uekert, et al. *ACS Sustain. Chem. Eng.* **2023**, *11*, 965-978.

Thank you! Questions?

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