Environmental and economic implications of emerging plastic recycling technologies

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bottle
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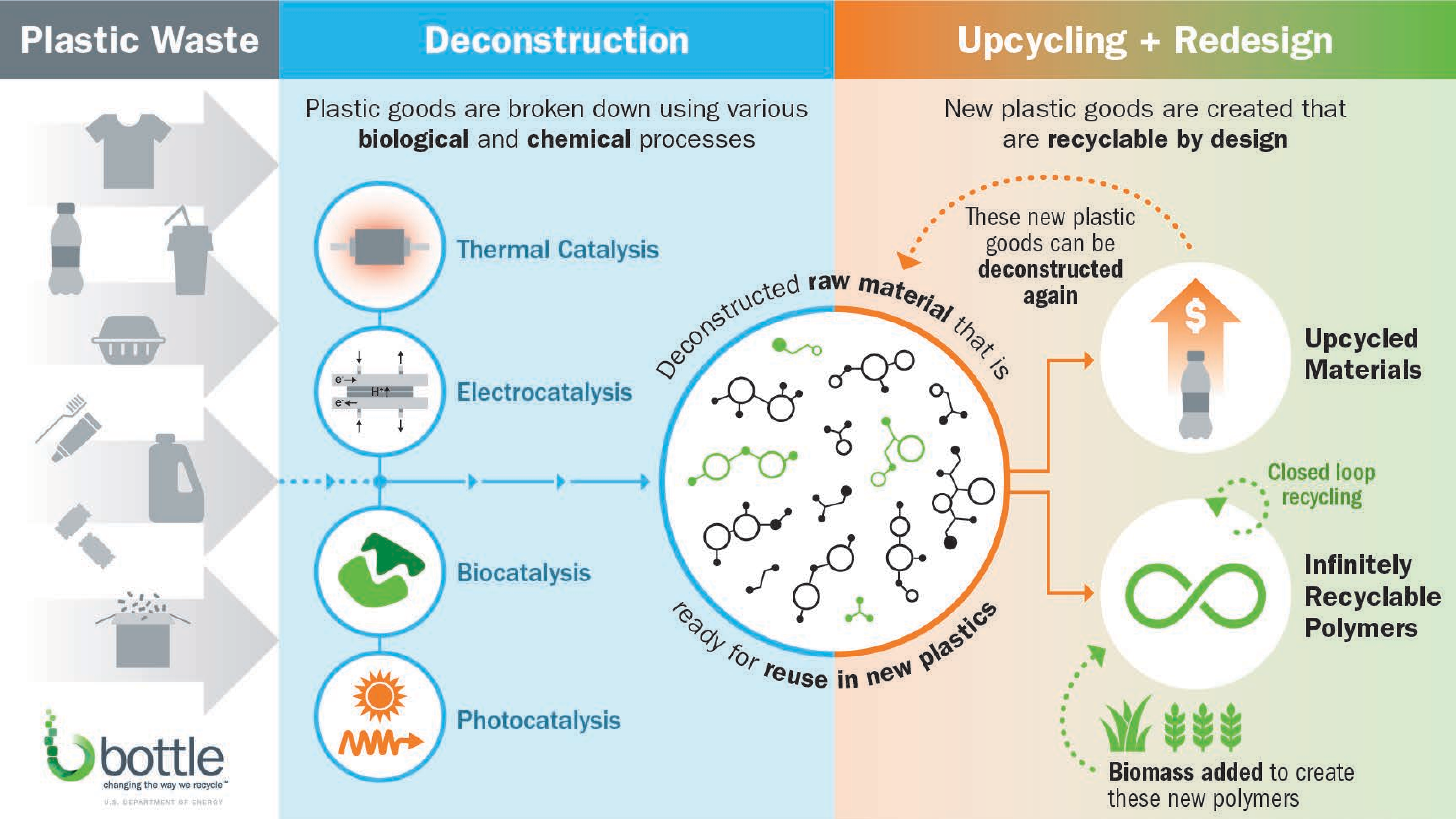
Plastic Waste
Deconstruction
Upcycling + Redesign
Plastic goods are broken down using various **biological** and **chemical** processes
New plastic goods are created that are **recyclable by design**
Thermal Catalysis
Electrocatalysis
Biocatalysis
Photocatalysis
Deconstructed **raw material** that is ready for **reuse in new plastics**
These new plastic goods can be **deconstructed again**
Upcycled Materials
Closed loop recycling
Infinitely Recyclable Polymers
Biomass added to create these new polymers
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Why analysis?

Analysis is foundational to BOTTLE's mission

- Develop robust processes to upcycle existing waste plastics that meet key goals:
  - ≥50% energy savings relative to virgin material production
  - ≥75% carbon utilization from waste plastics
  - ≥ 2x economic incentive over reclaimed materials
- Analysis-guided R&D aligns with DOE's Strategy for Plastics Innovation

Economic, environmental, and comparative analysis

- Model new processes and analyze energy, carbon, cost, and GHG emissions metrics to determine their feasibility and key drivers.
- Compare these results against incumbent technologies.
- **Results and insights help inform decisions in a crowded solution space.**

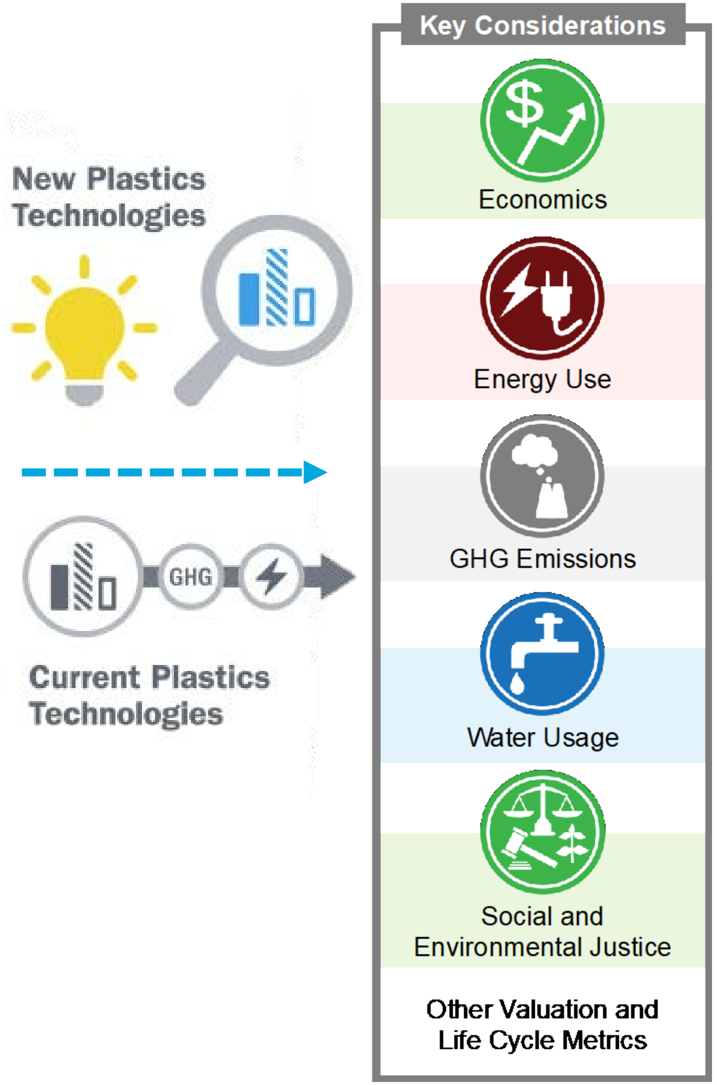
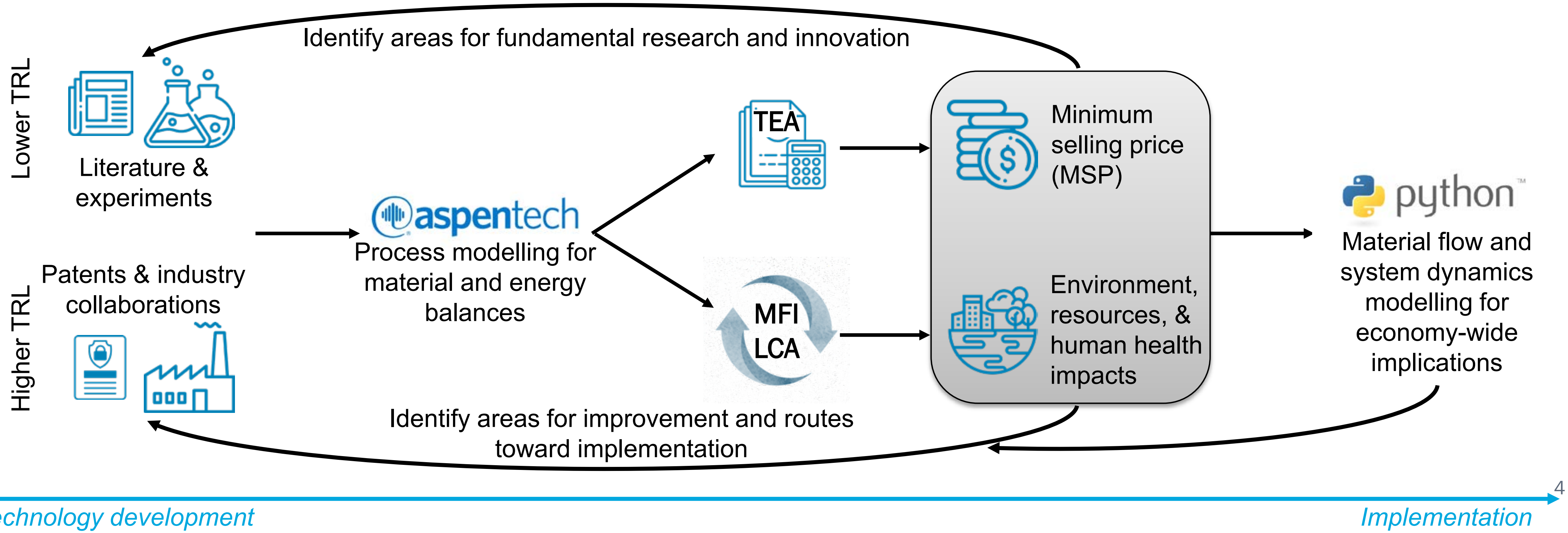


Image: S.R. Nicholson, N.A. Rorrer *et al.*, *Joule* 2021.

Analysis approach

- Techno-economic analysis (TEA) and life-cycle assessment (LCA) conducted across multiple scopes.
- Economics and sustainability assumptions follow transparent / open-source practices in EERE-funded R&D; framework published in a 2022 BOTTLE review.[1]
- Analysis is an iterative process that occurs in parallel to laboratory R&D.



[1] S. R. Nicholson *et al.*, *Annu. Rev. Chem. Biomolec. Eng.* 2022.

Today's topics

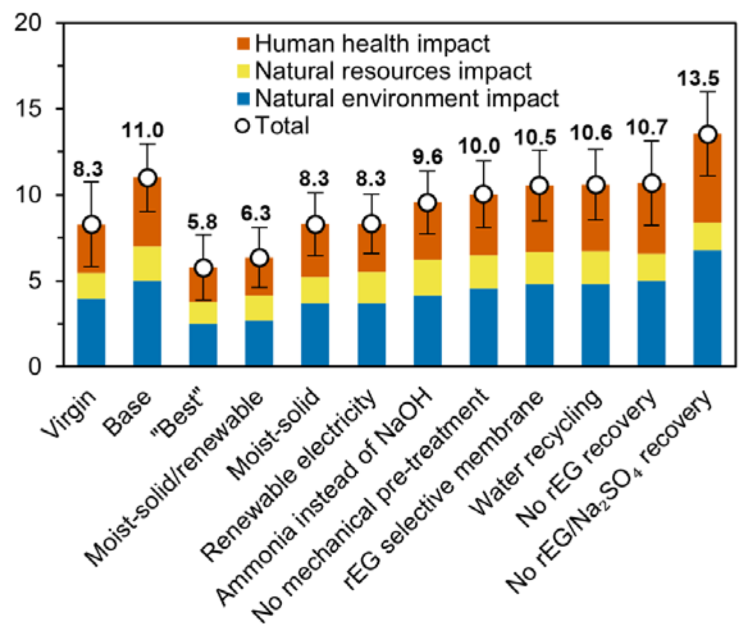
1. Leveraging TEA/LCA to identify areas for improvement in emerging chemical recycling technologies
   - Enzymatic hydrolysis
   - Pyrolysis
   - Gasification
2. Comparing across technologies and identifying opportunities for combining end-of-life pathways
   - Closed-loop recycling comparison
   - Multi-pathway optimization
3. Looking towards social analysis
   - Individual recycling behavior
   - Social and environmental justice

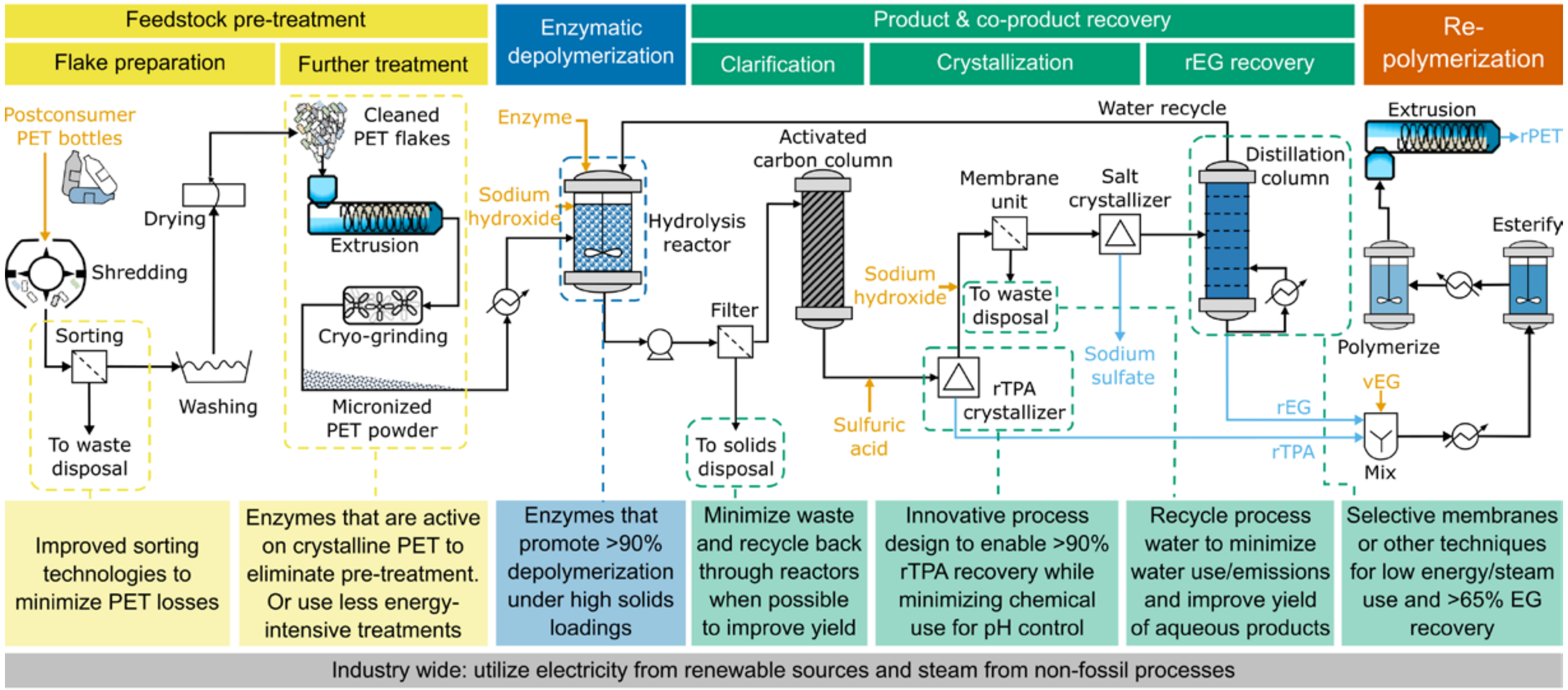
Identifying technologies that need improvement

Enzymatic hydrolysis

LCA → improvements across many process areas will be necessary for realization of enzymatic recycling

- Opportunities to better design this technology:
  - *Remove or replace energy intensive process steps* like amorphization pre-treatment, distillation, moist-solid case
  - *Reuse consumables* as with water recycling, moist-solid cases
  - *Use lower impact consumables* like ammonia instead of NaOH, renewable electricity



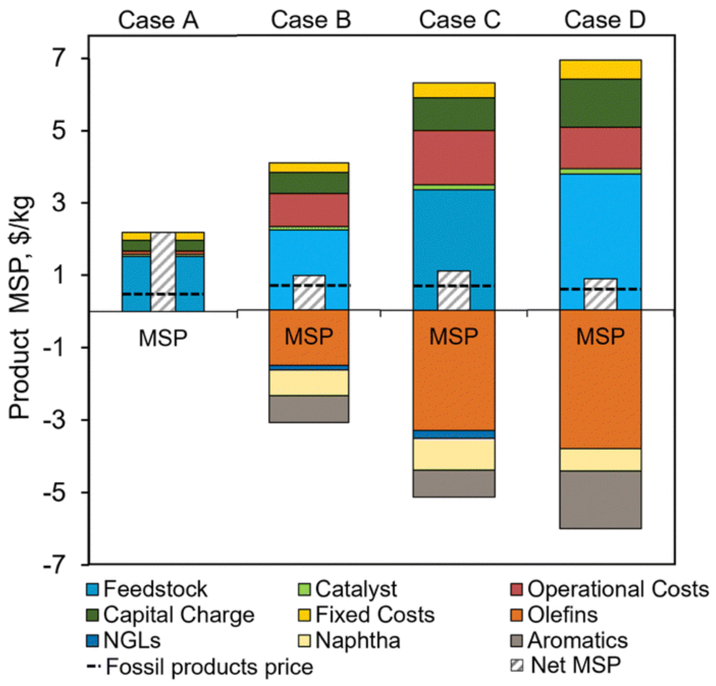


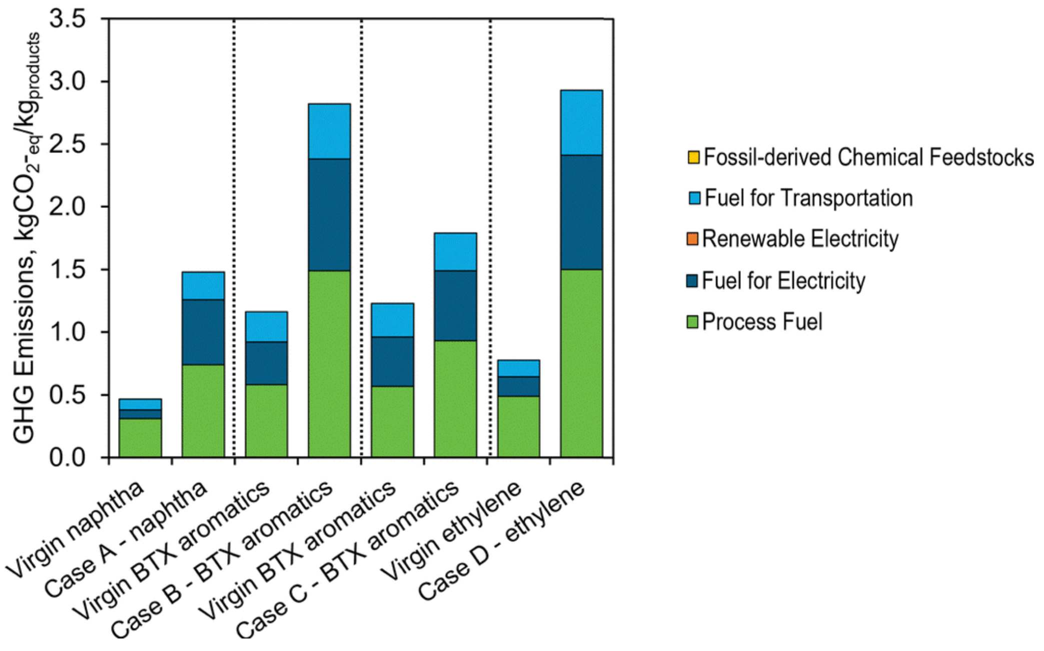
T. Uekert et al., *Green Chem.*, 2022

Mixed plastic pyrolysis

TEA/LCA → pyrolysis to various aromatics or olefins is 1.4-4x more expensive and 2-4x more environmentally impactful than conventional production, even with "cheap" mixed plastic feedstock

- Opportunities: source cheaper feedstocks, eliminate need for significant size reduction, avoid compromising high yields



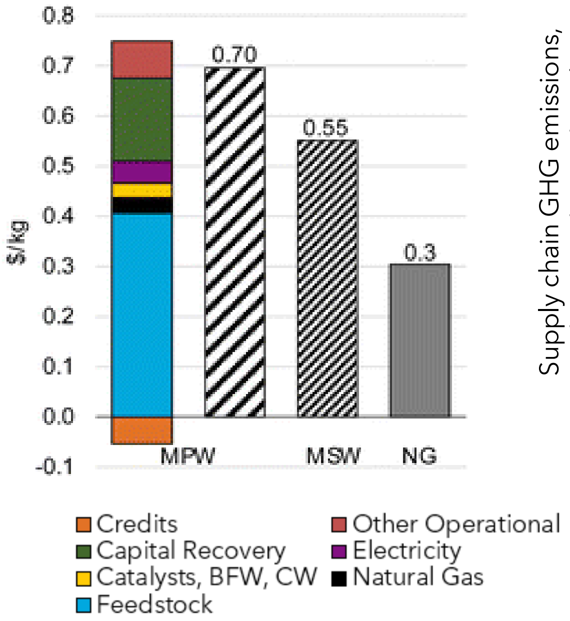


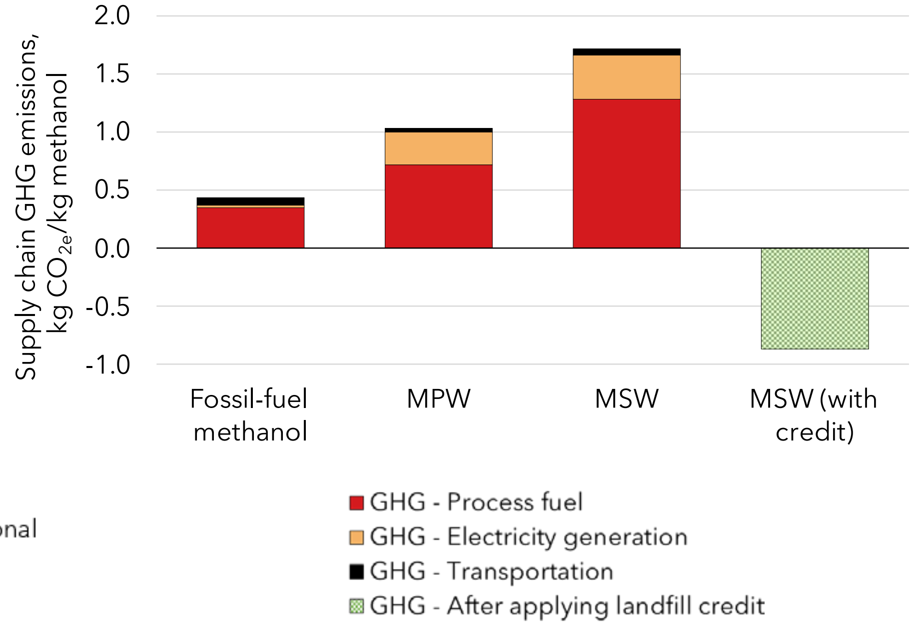
G. Yadav *et al. Energy Environ. Sci.* 2023

Mixed plastic gasification

TEA/LCA → gasification to methanol or H_2 is 2-3x more expensive and 1.5-4x more environmentally impactful than conventional production

- Opportunities: source cheaper feedstocks while increasing yields of the target products, couple with existing facilities





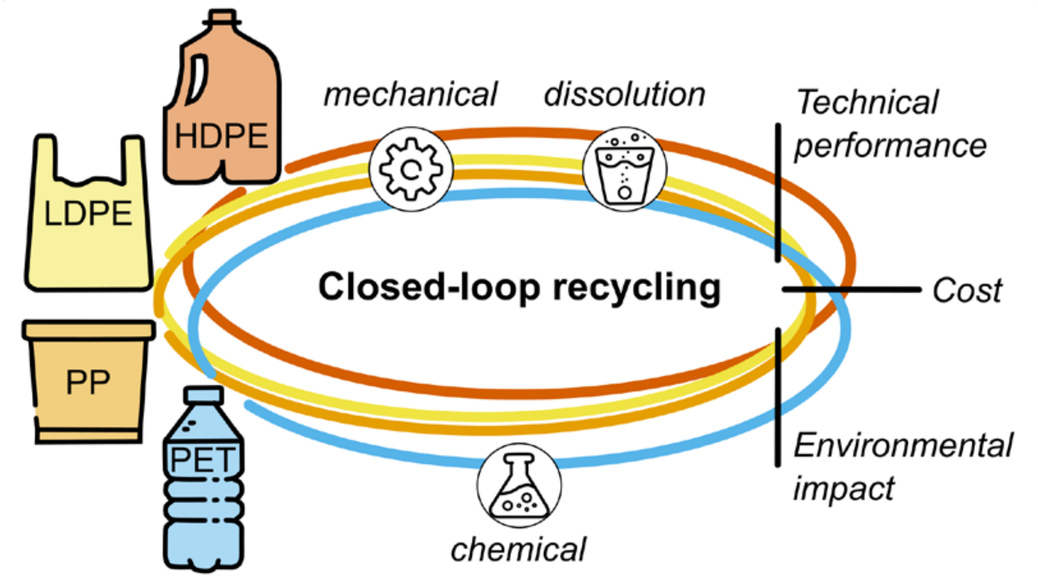
S. Afzal *et al. Green Chem.* 2023

Comparing recycling options and parallel application opportunities

From stand-alone to comparative

How can we identify gaps and synergies **across** recycling technologies?

- Our approach: comparative analysis of closed-loop (plastic-to-plastic) recycling technologies across cost, environmental impacts, and technical performance.
  - Combination of literature review (material quality, retention, contamination tolerance), process modelling (Aspen Plus software), TEA (minimum selling price), and LCA (GHG emissions, energy use, toxicity, water use, E-factor).

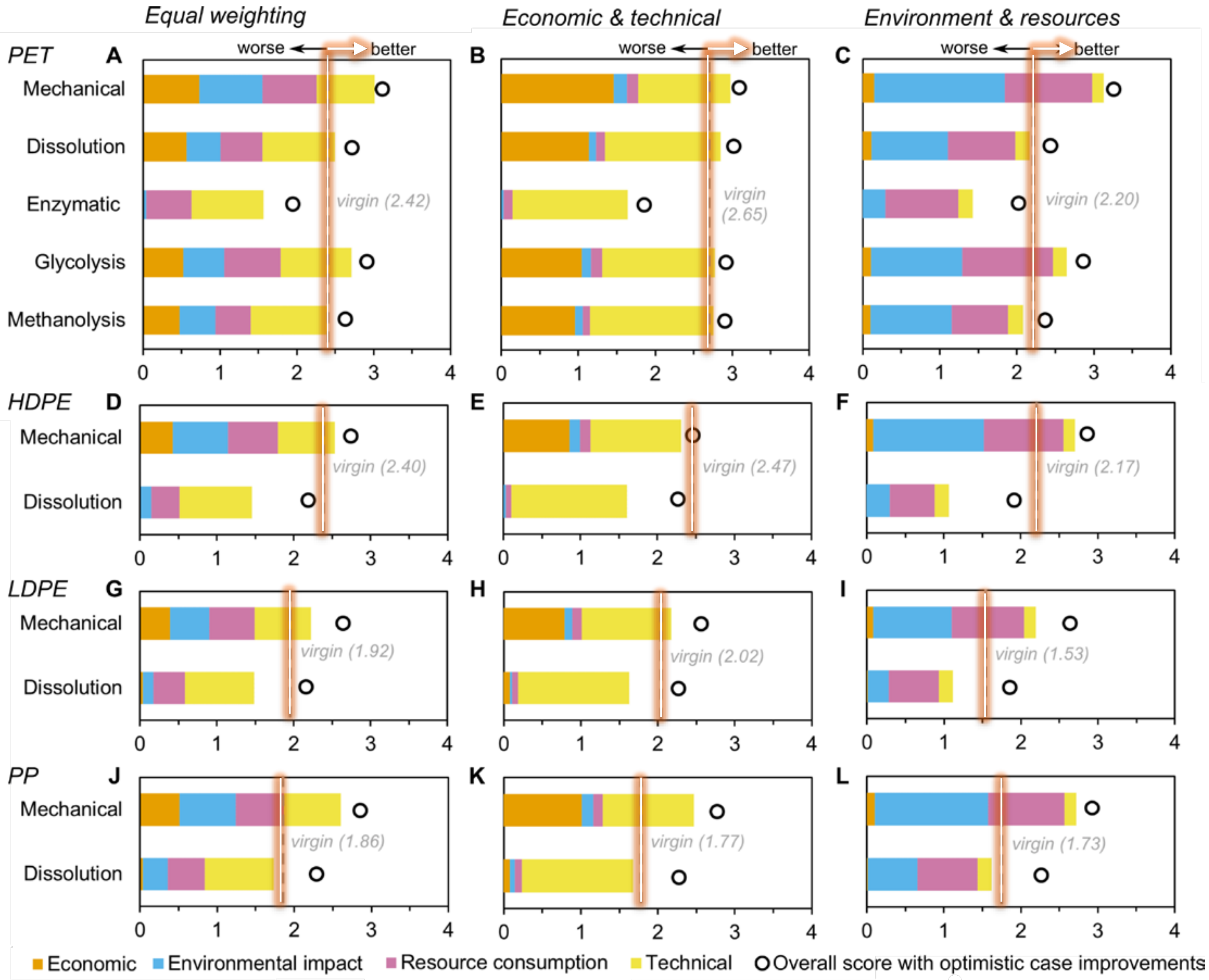


T. Uekert *et al*. *ACS Sustain. Chem. Eng.* 2023

Multi-criteria decision analysis (MCDA)

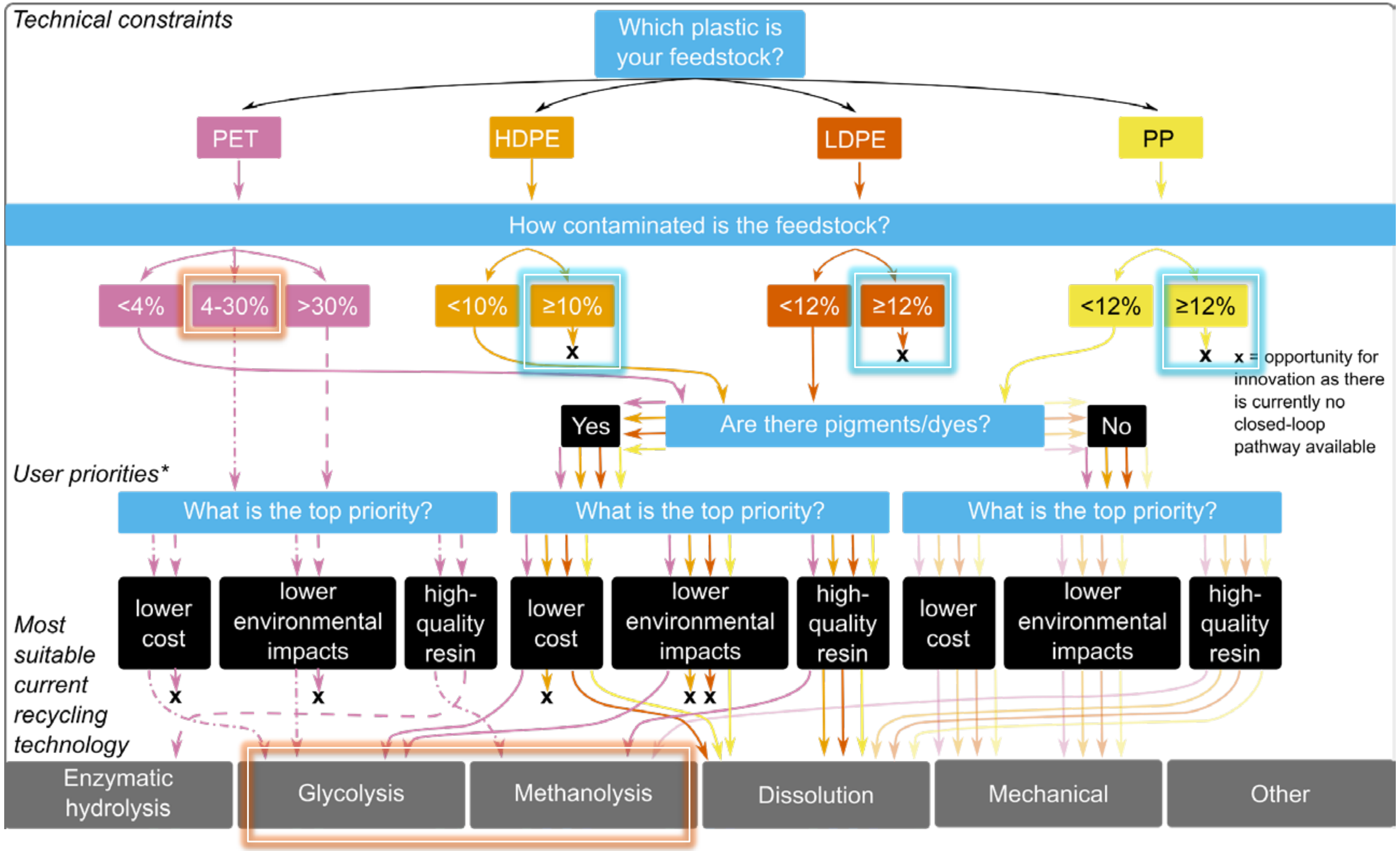
MCDA → evaluation of conflicting criteria

- Mechanical recycling & glycolysis already offer better alternative than virgin plastic.
- Many emerging technologies perform worse under environmental weighting → need streamlining
- Technologies with low scores are not necessarily "bad" – many can improve to similar or better than virgin plastic manufacturing.



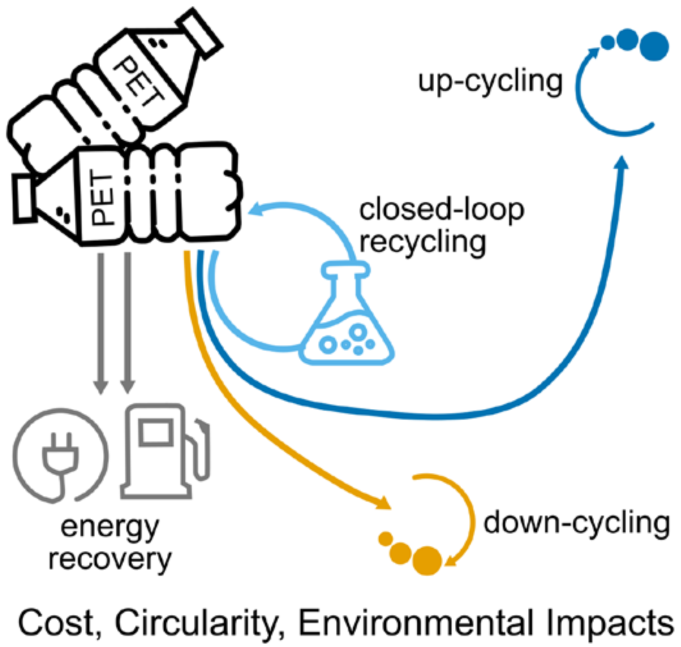
T. Uekert *et al. ACS Sustain. Chem. Eng.* 2023

Feedstock → priority pathways



T. Uekert *et al.* *ACS Sustain. Chem. Eng.* 2023

Beyond closed-loop recycling



How can we compare plastic-to-x options and determine how to combine them to minimize impacts and maximize circularity?

- Methodology:

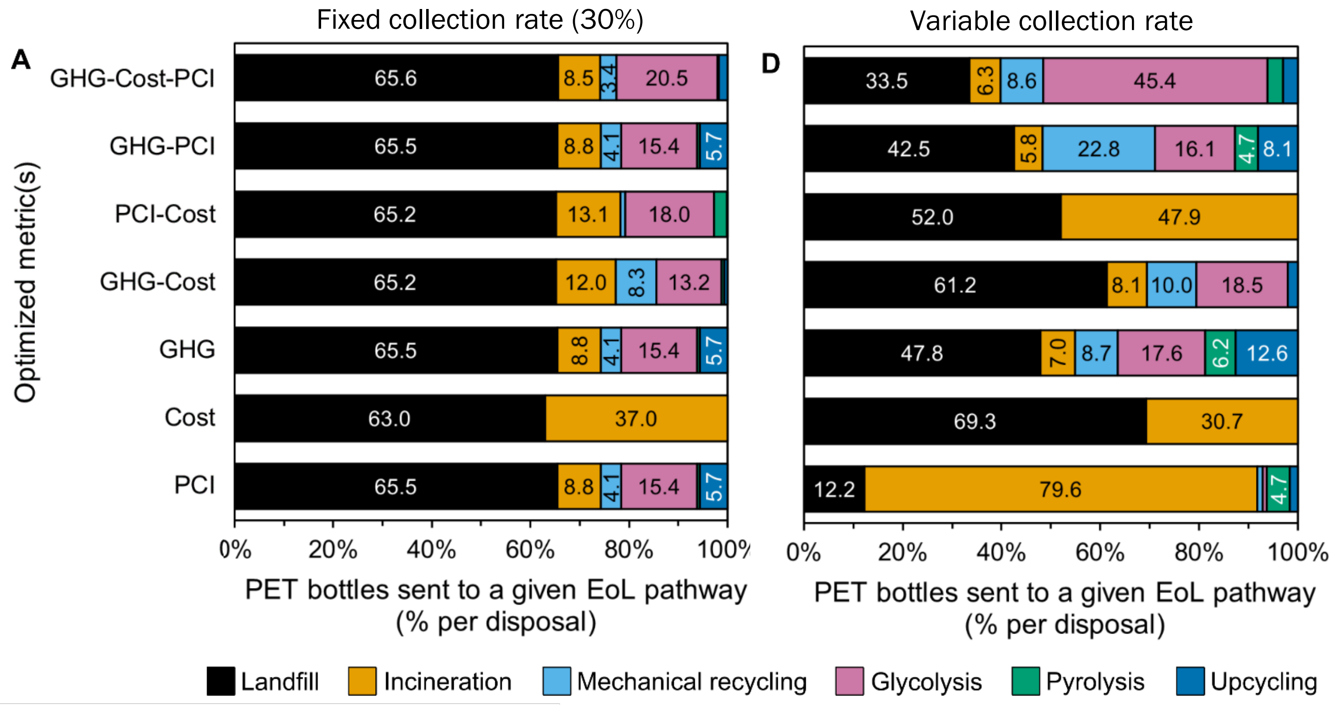
Develop United States economy wide PET material flow model → Add detailed modules for each end-of-life option → Calculate life cycle impacts, cost, and circularity of total system

"Credits" for avoided manu-facture

T. Ghosh and T. Uekert *et al. Adv. Sustain. Syst.* 2023

System optimization

- Glycolysis + upcycling to glass fiber reinforced resin + mechanical recycling → GHG emissions reduce by 1.1 MMT, costs increase by 2.5x, circularity increases from 0 to 0.13, virgin bottle demand decreases by 16% relative to landfilling only
- Improved collection rate (30% → 69%) can lead to further reduction GHG emissions (up to 1.2 MMT) and increase the circularity index (up to 0.47)



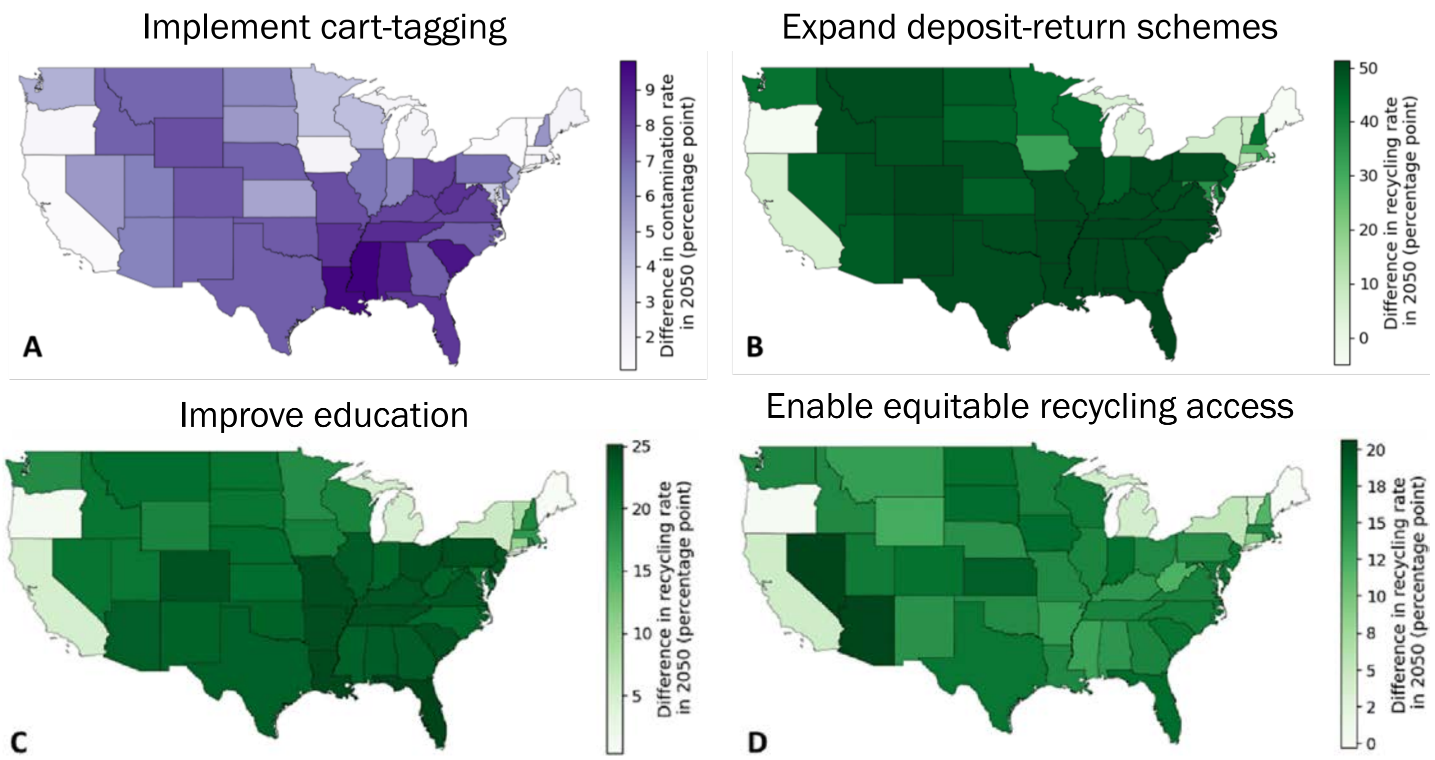
T. Ghosh and T. Uekert *et al. Adv. Sustain. Syst.* 2023

Opportunities in social analysis

Addressing collection

We can't recycle if plastic isn't collected…so how do we improve collection rate?

- Agent-based model explores effect of interventions on households' disposal behavior.
- Cart tagging, deposit return schemes, education, and equitable access could increase U.S. PET bottle collection by 13-41%.



J. Walzberg *et al. Energy Res. Soc. Sci.* 2023

Social & environmental justice

How can we incorporate social and environmental justice into analysis of early-stage research?

- Explore health and environment, affordability and consumer rights, and jobs and worker rights – qualitative for early-TRL, quantitative for mid-TRL
- Enzymatic hydrolysis case study → sulfuric acid and ethylene glycol emissions are “hotspots”

Try our EJ/SJ worksheet for your own technology!

Image credit: Clore Social Leadership

Key takeaways

- Analysis is crucial for benchmarking recycling technologies and determining research priorities to ensure that circularity = sustainability.
- There is no “silver bullet” – we need combinations of end-of-life technologies.
- Lots more to come on recyclable by design polymers, biodegradable plastic recycling, and more!

THINK BEYOND THE LAB: RECYCLE AT HOME!

Tips at:
https://www.washingtonpost.com/climate-solutions/interactive/2023/recycling-tips-mistakes-quiz

Thank you! Questions?

Reach out to taylor.uekert@nrel.gov
Visit https://www.bottle.org/

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