U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

ADVANCED MATERIALS &
MANUFACTURING
TECHNOLOGIES OFFICE

Plastics Recycling and Circularity

September 24, 2024

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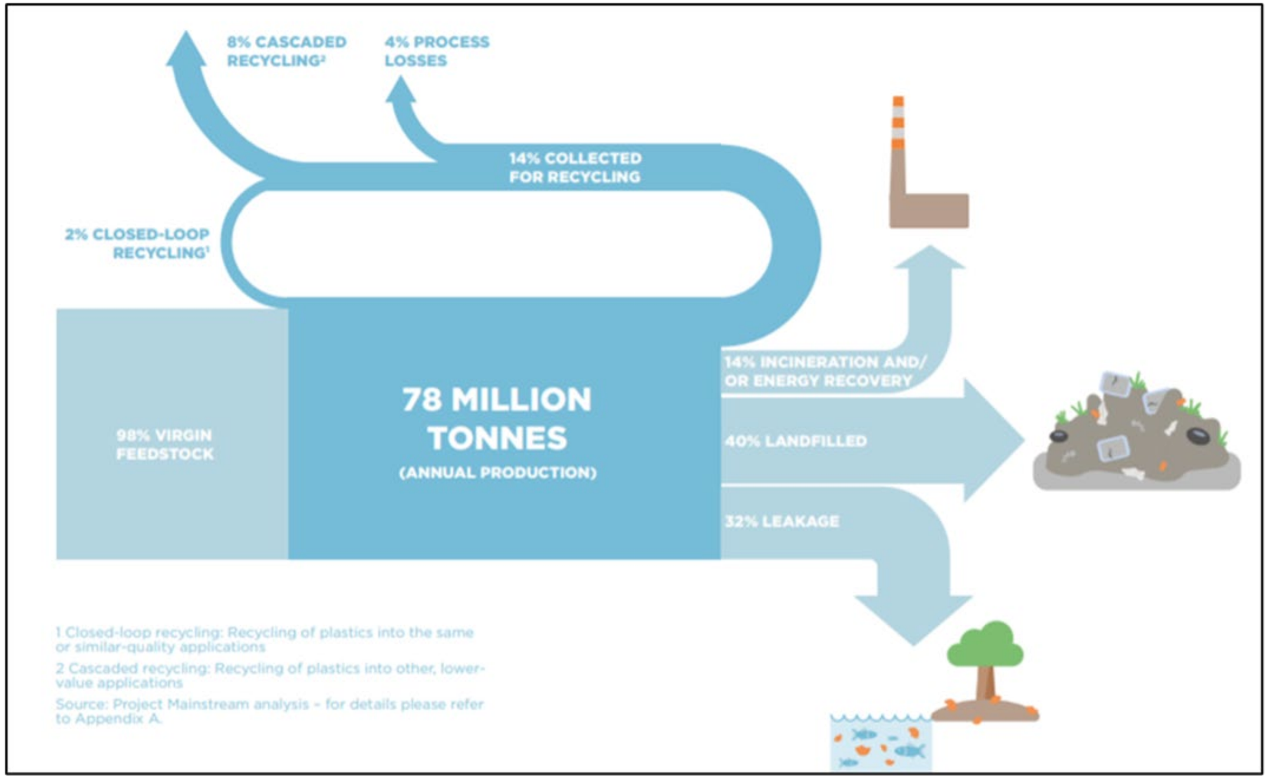
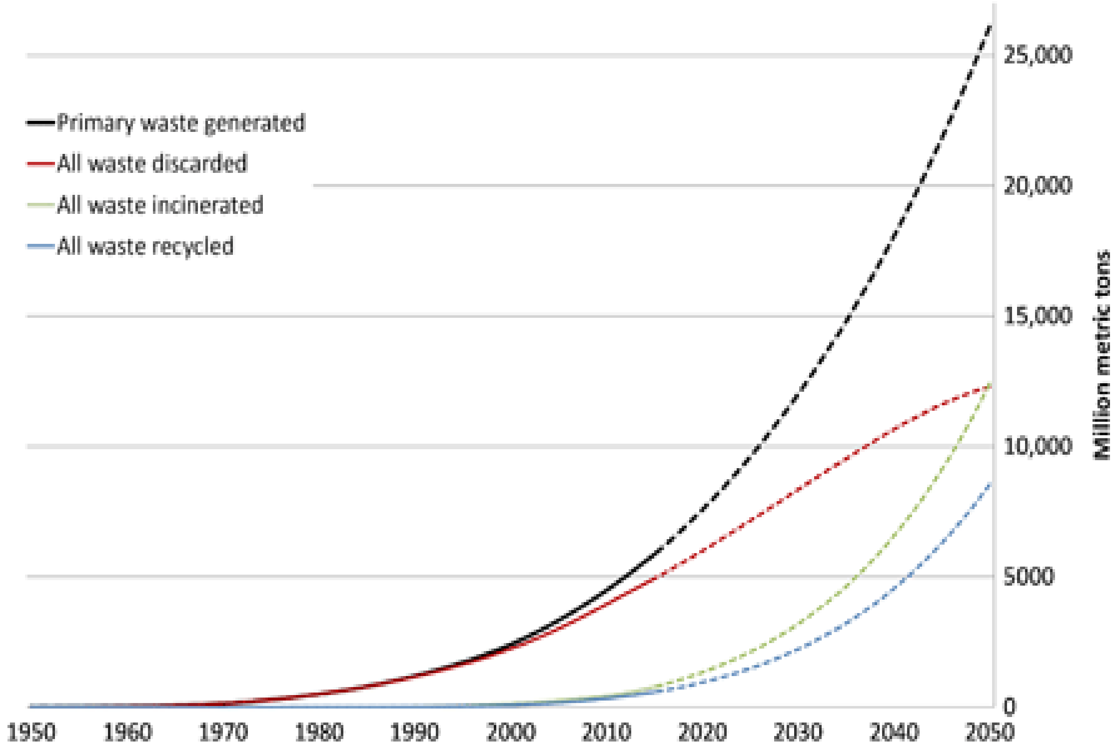
Why Plastic Waste?

In 2019, the United States recycled 5% of its plastics and disposed of 86%, resulting in market value losses totaling $7.2 billion. Plastic consumption accounts for 3% of US GHG Emissions and, globally, plastic waste is projected to triple by 2060.



Cumulative Global Plastic Waste



[1]Geyer et al. Science Advances 2017. [2]Zheng and Suh. Nature Climate Change 2019. [3]Beckham and co. Joule 2021

Biden-Harris Climate Goals

Reduce 2005 GHG emissions by 50% in 2030

Reach net zero economy-wide by 2050

Critical to Administration Priorities

Climate

- Plastics contribute ~3% of global GHG emissions[1]
  - Improving the footprint of plastics is essential to decarbonize the industrial sector
- Recycling and making renewable plastics can reduce GHG emissions significantly[2]

Economy

- 95% of plastic waste is discarded, and the value of the material is lost[3]
- Transitioning from business as usual to green waste processing can add up to 730,000 jobs[4]

Environmental Justice

EERE is working to gain better understanding of impacts.

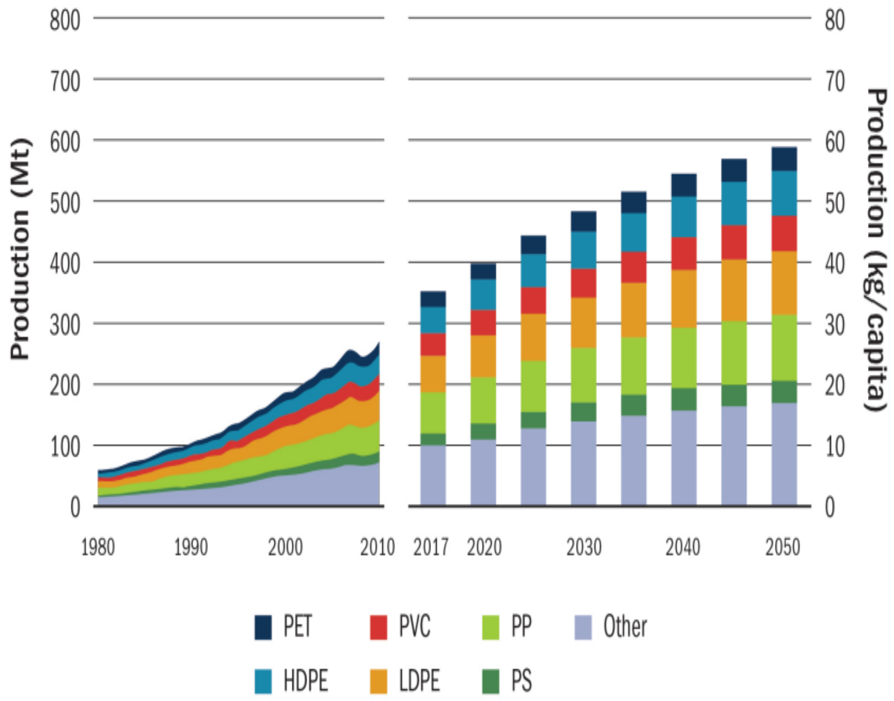
- Plastic-related GHG → climate change.[1] Effects of climate change are unequal.
- The US generates the most plastic waste of any country, and is one of the biggest coastal polluters[5]
- Net plastic exports go to developing countries[6]
- Irreversible environmental damage from plastic waste in the ocean is estimated to cost $2.5 trillion a year[7]

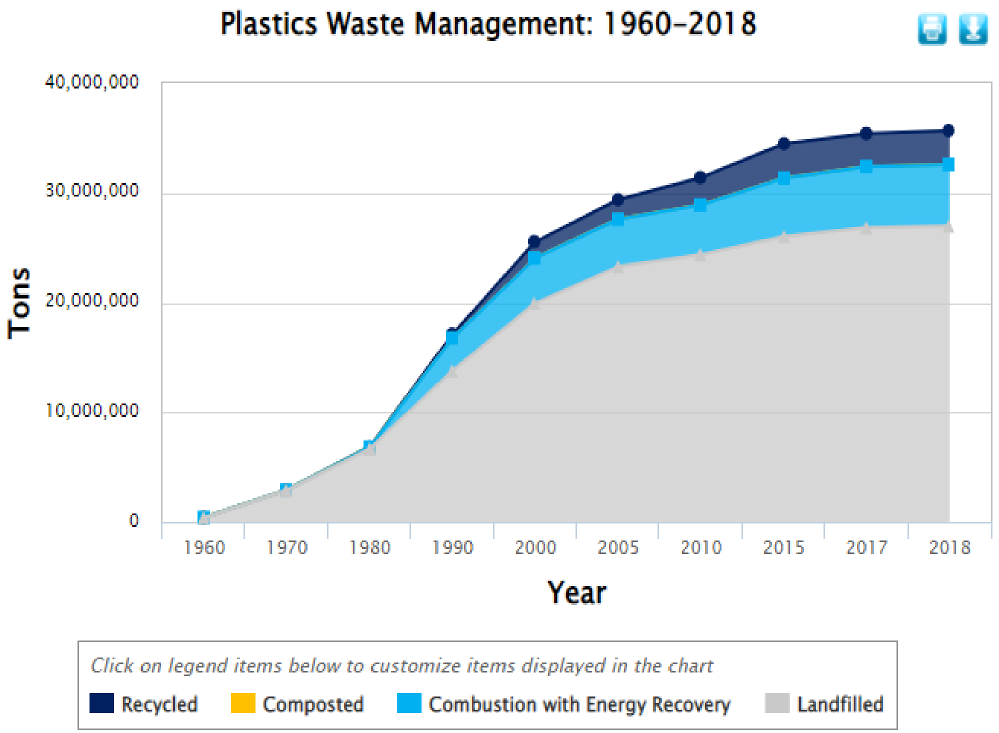
Solutions

- Recycling plastics saves >50% of GHG emissions[8]
- Making recyclable-by-design or biodegradable plastics from renewables saves GHG and energy from production to end of life[1]
- These new industries require domestic labor, providing new jobs

Recycling is Difficult and the Challenge is Growing

- Plastic waste presents many technical challenges
- Plastic production is projected to continue to increase substantially through 2050[1-2]
- Plastic recycling rates have plateaued[3]





Addressing barriers to recycling can unlock greater waste reduction and energy and emissions savings

1.. International Renewable Energy Agency (IRENA). 2018. Global Energy Transformation: A Roadmap to 2015. Abu Dhabi: IRENA.; 2. International Energy Agency (IEA). 2018. The Future of Petrochemicals. Paris: IEA.; 3. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

Strategy for Plastics Innovation Objectives

Vision

For the United States to lead the world in developing and deploying technologies that minimize plastic waste and promote energy-efficient and economic plastic and bioplastic design, production, reuse, and recycling.

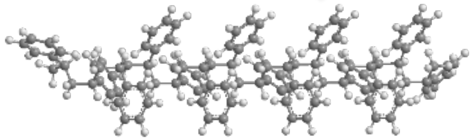
Objectives/Metrics

- Address **end-of-life fate for >90%** of plastics
- **≥50% energy savings** relative to virgin material production
- Achieve **≥75% carbon utilization** from waste plastics
- Develop **cost-competitive** recyclable-by-design plastic
- Design recycling strategies that **mitigate ≥50% GHG emissions** relative to virgin resin or plastic intermediates

Strategy for Plastics Innovation | Department of Energy

Complex challenge with promising R&D opportunities

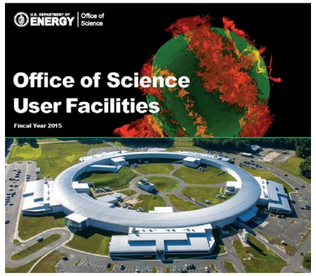
- Plastic waste presents many technical challenges
- Research is needed to overcome these challenges
- DOE user facilities and capabilities are equipped to provide solutions



Selective deconstruction & reassembly

Example research direction

Example deconstruction challenge



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Research Directions

PIC Goals	Challenges	Thermal Processes	Chemical Processes	Biological Processes	Physical Recycling and Recovery	Design for Circularity
Deconstruction	Retain value	●	●	●	●	●
	Feedstock heterogeneity		●	●	●	
	Contaminant removal	●	●	●	●	
	Multicomponent materials		●	●		●
Upcycling	Recover value		●	●	●	●
	New material design		●	●		●
Recyclable by Design	Design for reuse		●	●		●
	Compatibility with recycling infrastructure	●	●	●	●	●
Scale and Deploy	Life cycle assessment implications	●	●	●	●	●
	Management of distributed resource	●	●	●	●	●
	Circularity	●	●	●	●	●
	Scale of plastics challenge	●	●	●		●

What Are Practical Solutions for Plastic Waste?

- **Improved recycling processes**
  - Material efficient upcycling processes
  - Tolerant of contaminants
  - Energy and material efficient
  - Works with unsorted plastics
  - Non-traditional feedstocks

- **Plastic designed to address end-of-life concerns**
  - Highly recyclable
  - Biodegradable/compostable for some applications
  - Compatible with current infrastructure
  - Performance-advantaged
  - Lower global warming potential using bio-based materials

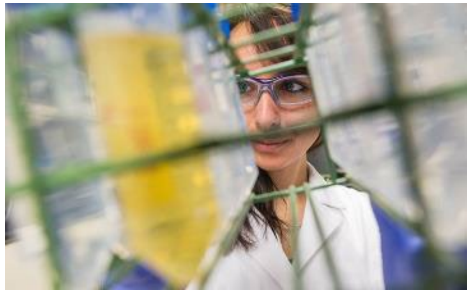
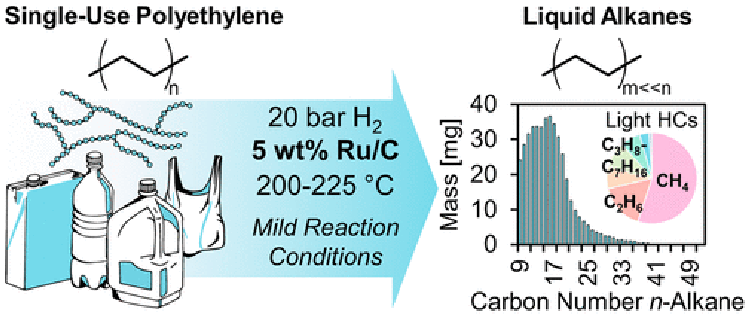


Photo: NREL



JACS Au **2021** 1 (1) 8–12

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AMMTO's Plastic Portfolio

- **AMMTO is funding a variety of work focused on plastics, most of which is jointly sponsored by the Bioenergy Technologies Office (BETO)**
  - BOTTLE Consortium
  - BOTTLE FOA
  - Single Use Plastic Recycling (SUPR) FOA
- **The REMADE Institute also includes polymers in their scope, and has ongoing work in the plastics space**
- **The BOTTLE and SUPR FOAs were designed to improve plastic circularity by developing deconstruction and upcycling pathways for plastic waste and redesign polymers for circularity. Efforts were designed to be complementary to the BOTTLE™ Consortium and the REMADE Institute.**

BOTTLE Consortium vision, mission, goals, and DEI

Vision

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

Mission

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

Goals

- **Work with industry** to catalyze new recycling and redesign paradigms
- Leverage DOE investments in process development, catalysis, materials, and **analysis-driven R&D**

DEI

- A **diverse and inclusive** consortium that fosters the growth of researchers across their career, engages broadly to **educate the public** on our work, and ultimately contributes to the local community and the world broadly

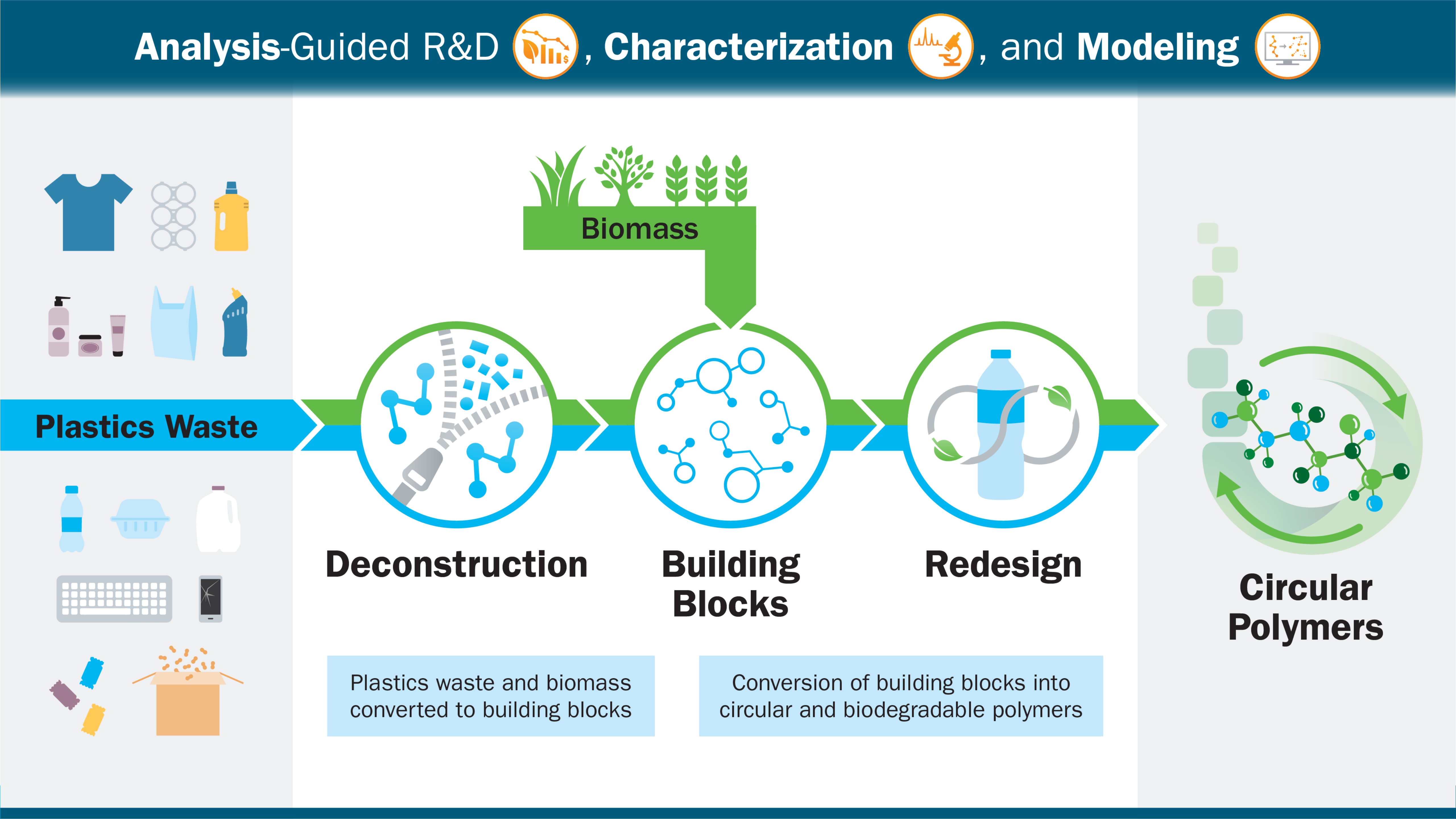
Strategic Goals

1. **Deconstruction:** Create new chemical, thermal, and biological/hybrid pathways to deconstruct plastics efficiently into useful chemical intermediates.
2. **Upcycling:** Advance the scientific and technological foundations that will underpin new technologies for upcycling chemical intermediates from plastic waste into high-value products.
3. **Recyclable by Design:** Design new and renewable plastics and bioplastics that have the properties of today's plastics, are easily upcycled, and can be manufactured at scale domestically.
4. **Scale and Deploy:** Support an energy- and material-efficient domestic plastics supply chain by helping companies scale and deploy new technologies in domestic and global markets, while improving existing recycling technologies such as collection, sorting, and mechanical recycling.

Aligning BOTTLE tasks:

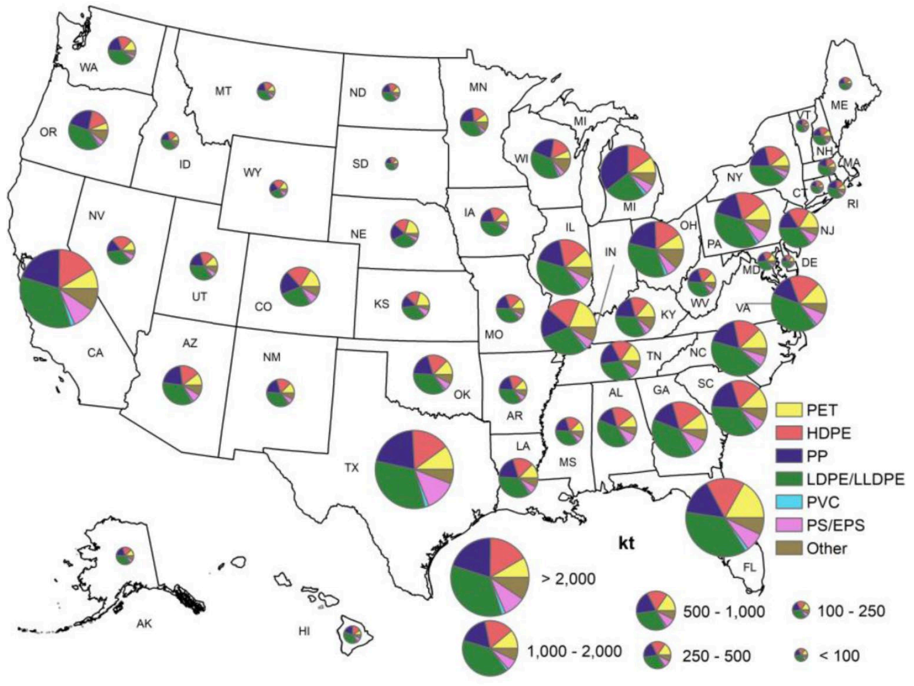
Deconstruction | Upcycling | Redesign | Industry Engagement

Department of Energy, 2023. Strategy for Plastics Innovation


Analysis-Guided R&D, Characterization, and Modeling
Biomass
Plastics Waste
Deconstruction
Building Blocks
Redesign
Circular Polymers
Plastics waste and biomass converted to building blocks
Conversion of building blocks into circular and biodegradable polymers

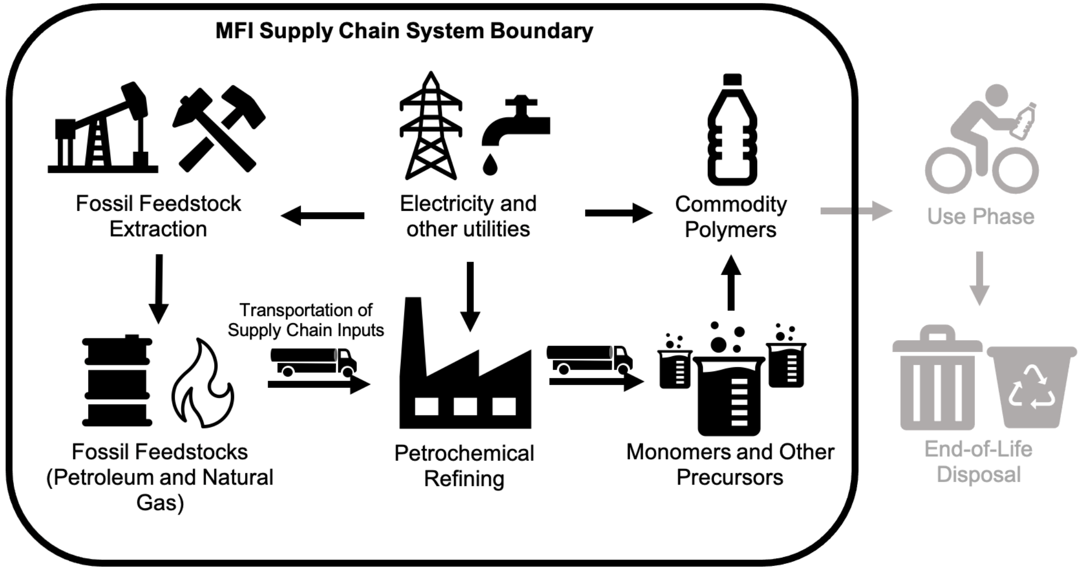
BOTTLE has strong analysis and benchmarking focus

- Updated estimates for plastics entering US landfills
  - 2019 US recycling rate was 5%
  - 2019 US landfilling rate was 86%
  - $7.2 B lost market value



A Milbrandtet etal. Resources, Conservation & recycling 2022

- Plastic recycling technologies require accurate baselines

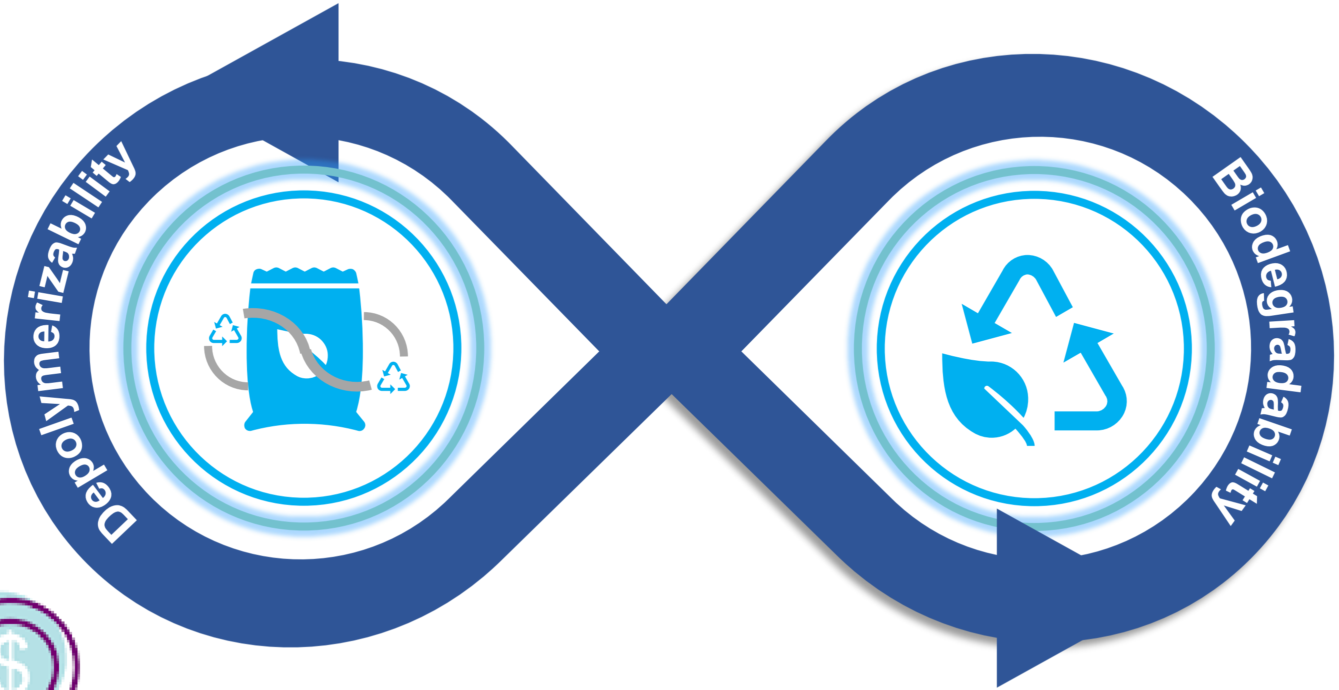


Estimate supply chain energy and GHG emissions from US-based plastics consumption for polymers with global consumption > 1 MMT per year

SR Nicholson, NA Rorrer et al.Joule 2021

Recyclable-by-design: The balance

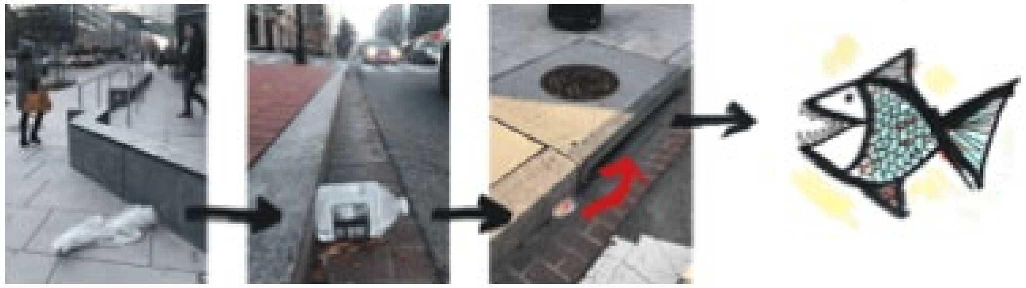
Can be infinitely depolymerized and repolymerized without loss in properties



Will naturally break down into H_2O, CO_2, and biomass

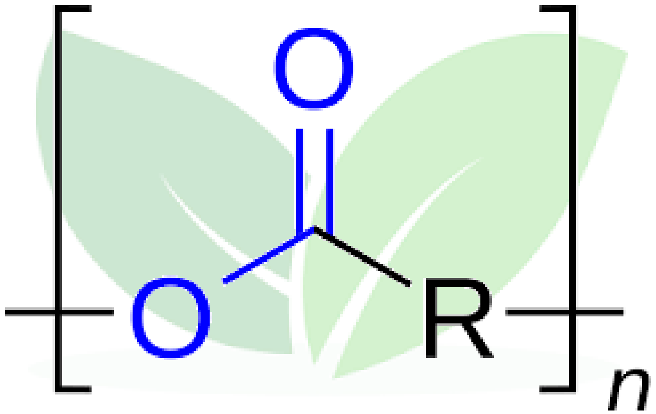
Economics

Back-up plan

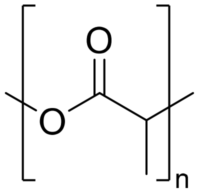


Westlie, Shen, Holland *et al. Macro. Rap. Comm*, 2022

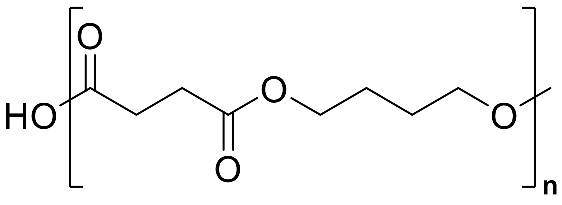
Could bio-based polyesters be an alternative?



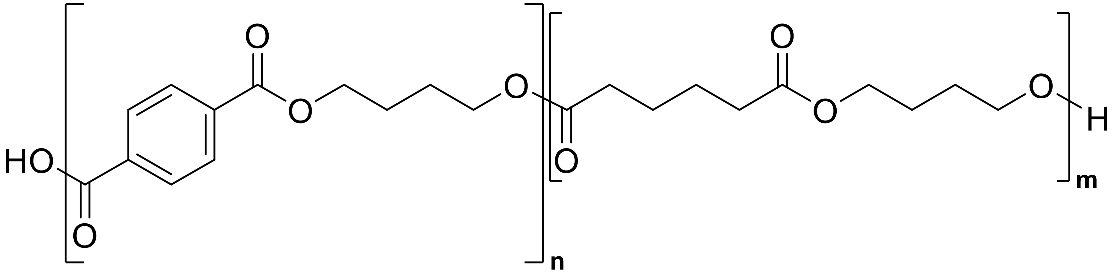
- Lightweight, durable, tunable
- Can be derived from biogenic carbon (or other waste-based feedstocks)
- Ester bonds are easier to break than C-C bonds
- Half lives in the natural environment <5 years
- Ester bond allows for one shot sortation



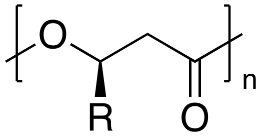
PLA



PBS



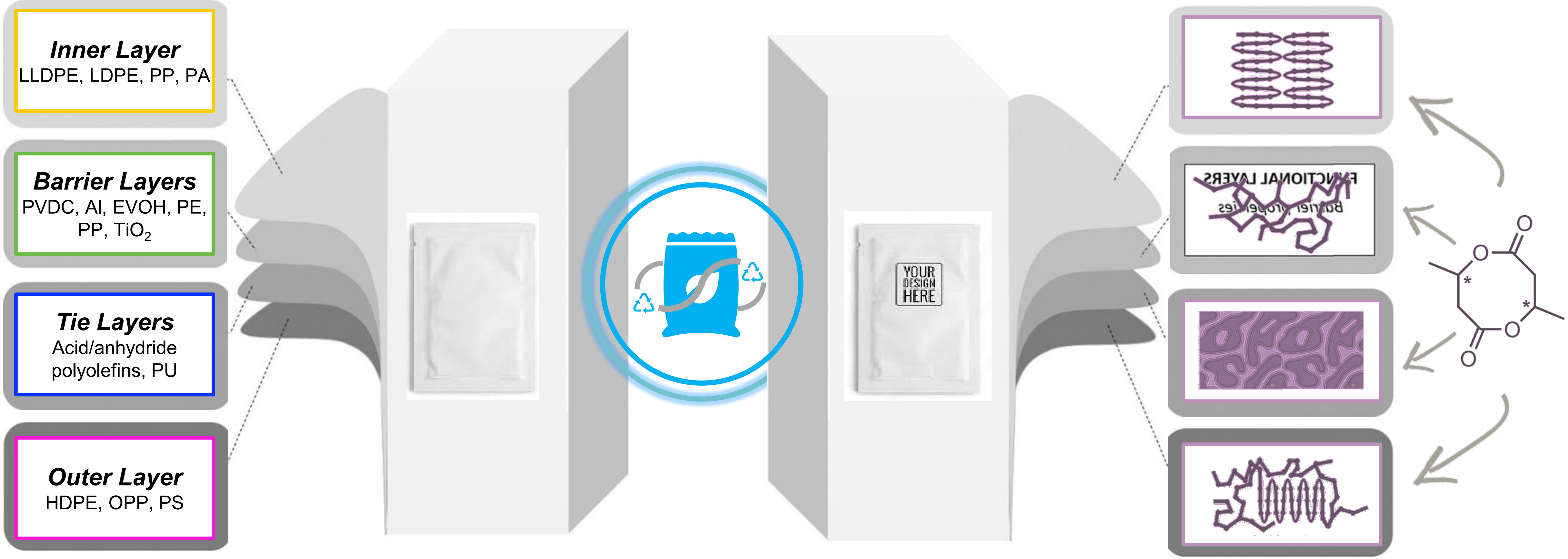
PBAT



PHA

Clarke *et al. RSC Material Advances* 2024

Monomaterial design based on PHAs

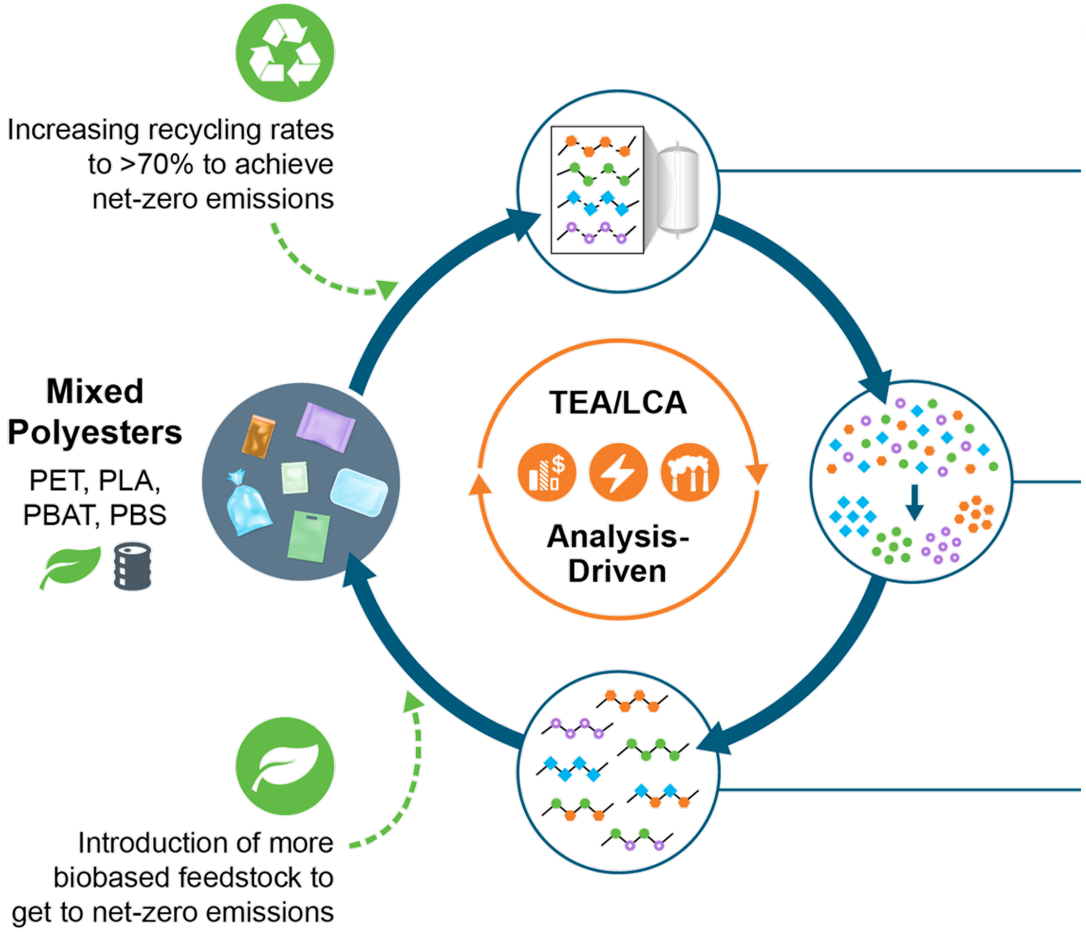


Multi-material multi-layer film design

Mono-material multi-layer film design

Quinn, E. *et al. One Earth* 2023

BOTTLE's polyester agnostic recycling technology



amazon

EsterCycle

Polyester agnostic recycling

Machine learning tools to predict new materials


Brandon Knott, NREL


Nolan Wilson, Exxon

Using PolyID to identify potential new packaging materials

- Layers independently optimized for High O_2 and H_2O barrier performance
- Model as series of resistances
- Solubility (sorption) and crystallinity (diffusion) can be tuned independently

PolyID
Polymer Inverse Design

PLGA & polyglycolides

Aliphatic polyesters

Identified polyglycolides and aliphatic polyesters as materials for further evaluation

- Promising predicted barrier properties
- Can be sourced from renewable feedstocks
- Have known biodegradation pathways

Wilson *et al. Macromolecules* 2023

BOTTLE FOA – jointly sponsored with BETO

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

Developed to support DOE's Plastics Innovation Challenge, which aims to accelerate innovations to significantly reduce plastic waste and position the U.S. as a global leader in plastics recycling technologies and in the development and manufacturing of plastics that are recyclable by design.

BOTTLE FOA – jointly sponsored with BETO

AMMTO and BETO's approach has been to both develop technologies for deconstruction and utilization of existing plastic waste and new materials that are recyclable by design.

Three Topic Areas in the BOTTLE FOA:

- **Highly recyclable or biodegradable plastics**
  - Novel bio-based plastics: designing highly recyclable or biodegradable bio-based plastics
  - Novel plastics: designing highly recyclable or biodegradable plastics
- **Novel methods for deconstructing and upcycling existing plastic waste**
- **BOTTLE consortium collaborations to tackle challenges in plastic waste**

SUPR FOA – jointly sponsored with BETO

Single-Use Plastic Recycling Funding Opportunity Announcement Topic Areas

Developed to address specific challenges with flexible films. This focused on both recycling conventional materials, as well as redesigning packaging (e.g. shifting to monomaterial multilayers or bio-based polymers) to simplify end of life processing.

SUPR FOA – jointly sponsored with BETO

AMMTO and BETO's approach has been to both develop technologies for deconstruction and utilization of existing plastic waste and new materials that are recyclable by design.

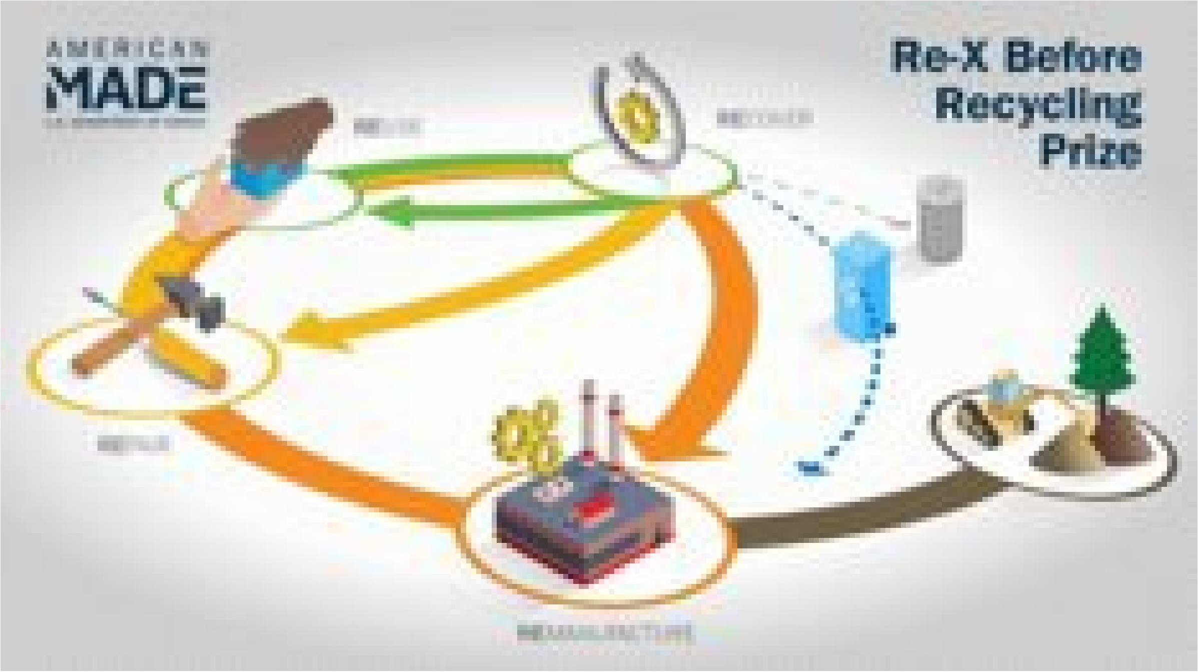
Two Topic Areas in the SUPR FOA:

- **Novel Approaches to Recycle and Upcycle Films**
  – Develop novel degradation, upcycling and/or recycling pathways for post-consumer films.
- **Redesign of Multi-layer Films for Infinite Recyclability or Biodegradability**
  – Multi-layered films are often used to achieve a multitude of properties that are difficult to achieve with a single component. This topic seeks new materials that are infinitely recyclable or biodegradable and meet all the required properties to replace multi-layered films

Future Efforts will also Target Other Re-X Pathways

In addition to our ongoing efforts in recycling and redesign, we are interested in developing other Re-X strategies to lower the lifecycle impacts of polymers, such as reuse.

- The Re-X Before Recycling Prize has this in its scope
- We plan to continue assessing how we can reduce the emissions and energy associated with plastics



BOTTLE Consortium Webinar on Analysis for Plastics Circularity Coming Soon!

“A Primer on Using Analysis To Guide Plastic Circularity” is planned for this fall, keep an eye out for registration details coming soon!

- This talk will introduce key analysis techniques such as techno-economic analysis, life cycle assessment, and environmental justice evaluation.
- Will discuss how these methods are conducted and interpreted and provide examples from the BOTTLE portfolio demonstrating their use in benchmarking and optimizing the costs and environmental impacts of new innovations in plastic circularity.

Questions?