DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Multi-University Center for Chemical Upcycling of Waste Plastics (www.cuwp.org)

April 4, 2023

Technology Area Session

George W Huber
University of Wisconsin-Madison

Quad Chart Overview

Timeline

- *Project start date: October 1, 2020*
- Project end date: 1/1/2026

	FY22 Costed	Total Award
DOE Funding	*$2,677,707*	*$10 million federal funds*
Project Cost Share *	$729,534	$2.5 Million in cost share

TRL at Project Start: 2
TRL at Project End: 4 (for some parts)

*Only fill out if applicable.

Project Goal

The objective of CUWP is to develop the scientific and engineering principles that will enable the circular upcycling of plastic wastes into virgin plastic resins using chemical technology.

End of Project Milestone

- See slide 8

Funding Mechanism

DE-FOA-0002203

Project Partners*

- Iowa State University
- National Renewable Laboratory
- University of Massachusetts
- 23 companies and 3 other universities

1 Approach
CUWP Research Team:

18 – Principal Investigators
29 Industrial Advisory Board Members
5 – Post-Doctoral Researchers
18 – Graduate Students
7+ - Undergraduate Students

GW Huber has a financial interest in Anellotech.

1 Approach

CUWP

Chemical Upcycling of Waste Plastics

CUWP by the Numbers:
- $12.5 Million 5-year center
- 6 Universities (3 Domestic, 2 Mexico, and 1 Canada)
- 1 National Laboratory
- 23 Companies
- 2 Industry Associations

PLASTICS INDUSTRY ASSOCIATION
BETTER INDUSTRY. BETTER WORLD.

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
BIOENERGY TECHNOLOGIES OFFICE

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

STATE

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

UAM Casa abierta al tiempo Iztapalapa

ATANDO CABOS

Asistencia Ambiental

UASLP
Universidad Autónoma de San Luis Potosí

UNIVERSITY of GUELPH

Anellotech

Ketjen

GBIG
GREEN BAY INNOVATION GROUP

Revolution
BELIEVE IN BETTER PLASTICS

GSF The Upcycling Leap!

CONAGRA BRANDS

DOW

FRONTLINE BIOENERGY, LL
Capture the energy ⚡ Release t

freepoint ECO-SYSTEMS

VALGROUP
SUSTAINABLE INNOVATION

epac flexible packaging

ESTĒE LAUDER COMPANIES

سابك sabic

cpfd

Braskem

RPD Technologies

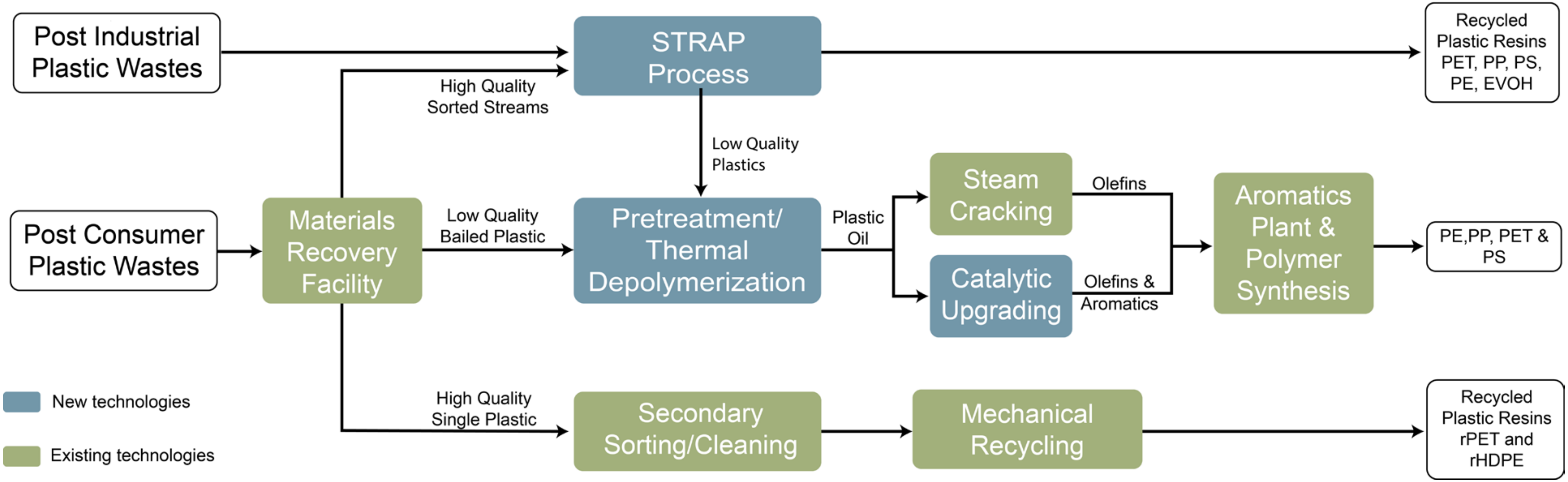
PLACON®
Simply Better Packaging®

amcor

DANE COUNTY DEPARTMENT OF WASTE & RENEWABLES

Center for Chemical Upcycling of Waste Plastics

Chemical Recycling in Circular Economy



Post Industrial Plastic Wastes

STRAP Process

High Quality Sorted Streams

Recycled Plastic Resins PET, PP, PS, PE, EVOH

Low Quality Plastics

Post Consumer Plastic Wastes

Materials Recovery Facility

Low Quality Bailed Plastic

Pretreatment/ Thermal Depolymerization

Plastic Oil

Steam Cracking

Olefins

Catalytic Upgrading

Olefins & Aromatics

Aromatics Plant & Polymer Synthesis

PE,PP, PET & PS

High Quality Single Plastic

Secondary Sorting/Cleaning

Mechanical Recycling

Recycled Plastic Resins rPET and rHDPE

🟦 New technologies

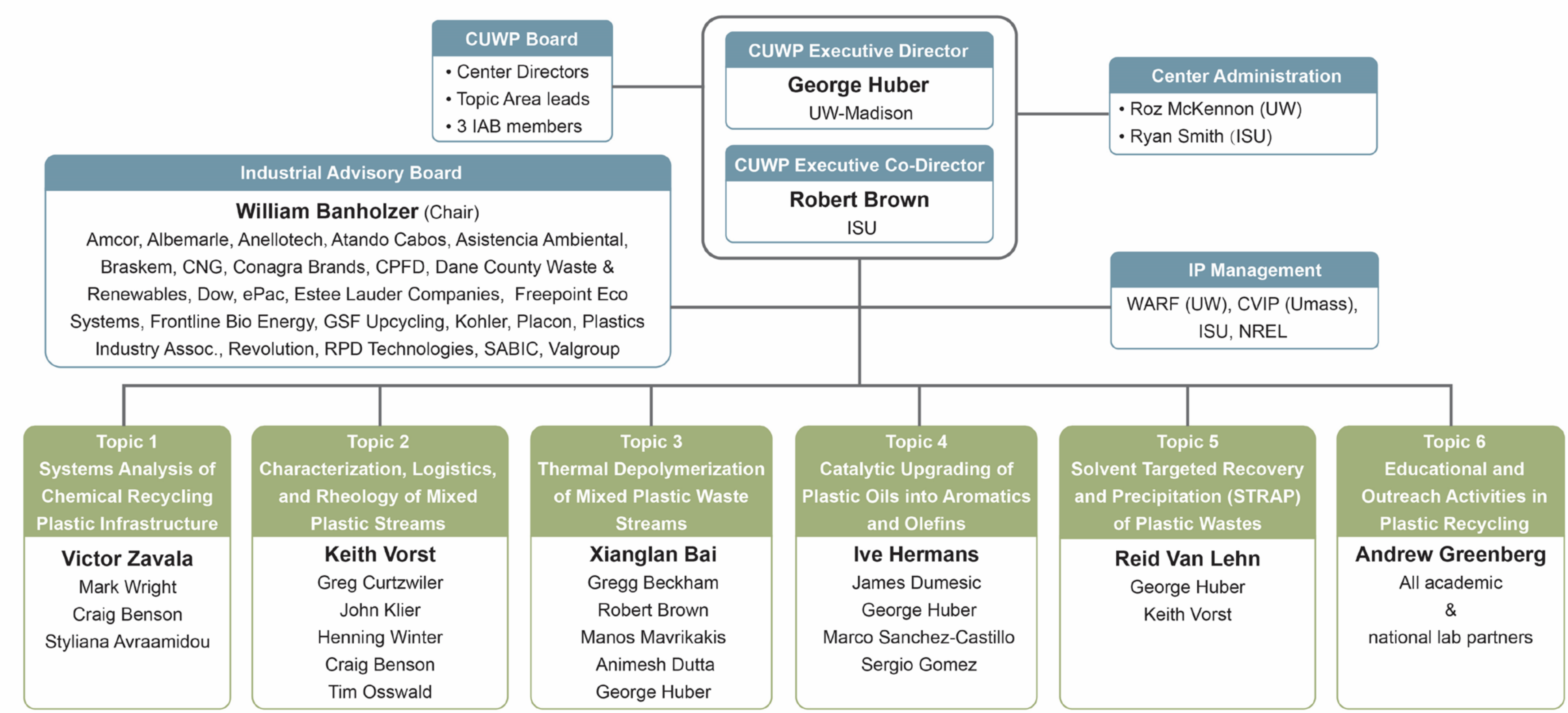
🟩 Existing technologies

1. Approach

The objective of CUWP is to develop the scientific and engineering principles that will enable the circular upcycling of plastic wastes into virgin plastic resins using chemical technology.

- Start Date: April 2021

1 Approach CUWP Org Chart



CUWP Board
- Center Directors
- Topic Area leads
- 3 IAB members

CUWP Executive Director
George Huber
UW-Madison

CUWP Executive Co-Director
Robert Brown
ISU

Center Administration
- Roz McKennon (UW)
- Ryan Smith (ISU)

Industrial Advisory Board
William Banholzer (Chair)
Amcor, Albemarle, Anellotech, Atando Cabos, Asistencia Ambiental, Braskem, CNG, Conagra Brands, CPFD, Dane County Waste & Renewables, Dow, ePac, Estee Lauder Companies, Freepoint Eco Systems, Frontline Bio Energy, GSF Upcycling, Kohler, Placon, Plastics Industry Assoc., Revolution, RPD Technologies, SABIC, Valgroup

IP Management
WARF (UW), CVIP (Umass), ISU, NREL

Topic 1
Systems Analysis of Chemical Recycling Plastic Infrastructure
Victor Zavala
Mark Wright
Craig Benson
Styliana Avraamidou

Topic 2
Characterization, Logistics, and Rheology of Mixed Plastic Streams
Keith Vorst
Greg Curtzwiler
John Klier
Henning Winter
Craig Benson
Tim Osswald

Topic 3
Thermal Depolymerization of Mixed Plastic Waste Streams
Xianglan Bai
Gregg Beckham
Robert Brown
Manos Mavrikakis
Animesh Dutta
George Huber

Topic 4
Catalytic Upgrading of Plastic Oils into Aromatics and Olefins
Ive Hermans
James Dumesic
George Huber
Marco Sanchez-Castillo
Sergio Gomez

Topic 5
Solvent Targeted Recovery and Precipitation (STRAP) of Plastic Wastes
Reid Van Lehn
George Huber
Keith Vorst

Topic 6
Educational and Outreach Activities in Plastic Recycling
Andrew Greenberg
All academic
&
national lab partners

PLASTIC SUPPLY CHAIN

Extraction Of Natural Gas & Crude Oil

Gasoline & Diesel Fuel

Petroleum Refineries/ Steam Crackers

Polymer Synthesis

Plastic Convertors

Brand Owners

Retailers

Consumers

Waste Management Companies/MRFs

Landfills

Recyclers

1 Approach: Project Objectives

1. Detailed process models for chemical and solvent-based upcycling of waste plastics.
2. Collection, sorting technology and practice that improve the volume, composition, and quality of bailed plastics from Material Recovery Facilities (MRFs).
3. Production of plastic-derived oils from thermal depolymerization of mixed plastic waste streams in laboratory and pilot plant scale.
4. Catalytic upgrading of plastics-derived oils into aromatics and olefins (plastic monomers) in a continuous flow reactor.
5. Use of solvent-based recycling strategies for converting multi-layer films into pure resins.
6. Development of undergraduate and graduate curriculum material for plastic recycling.

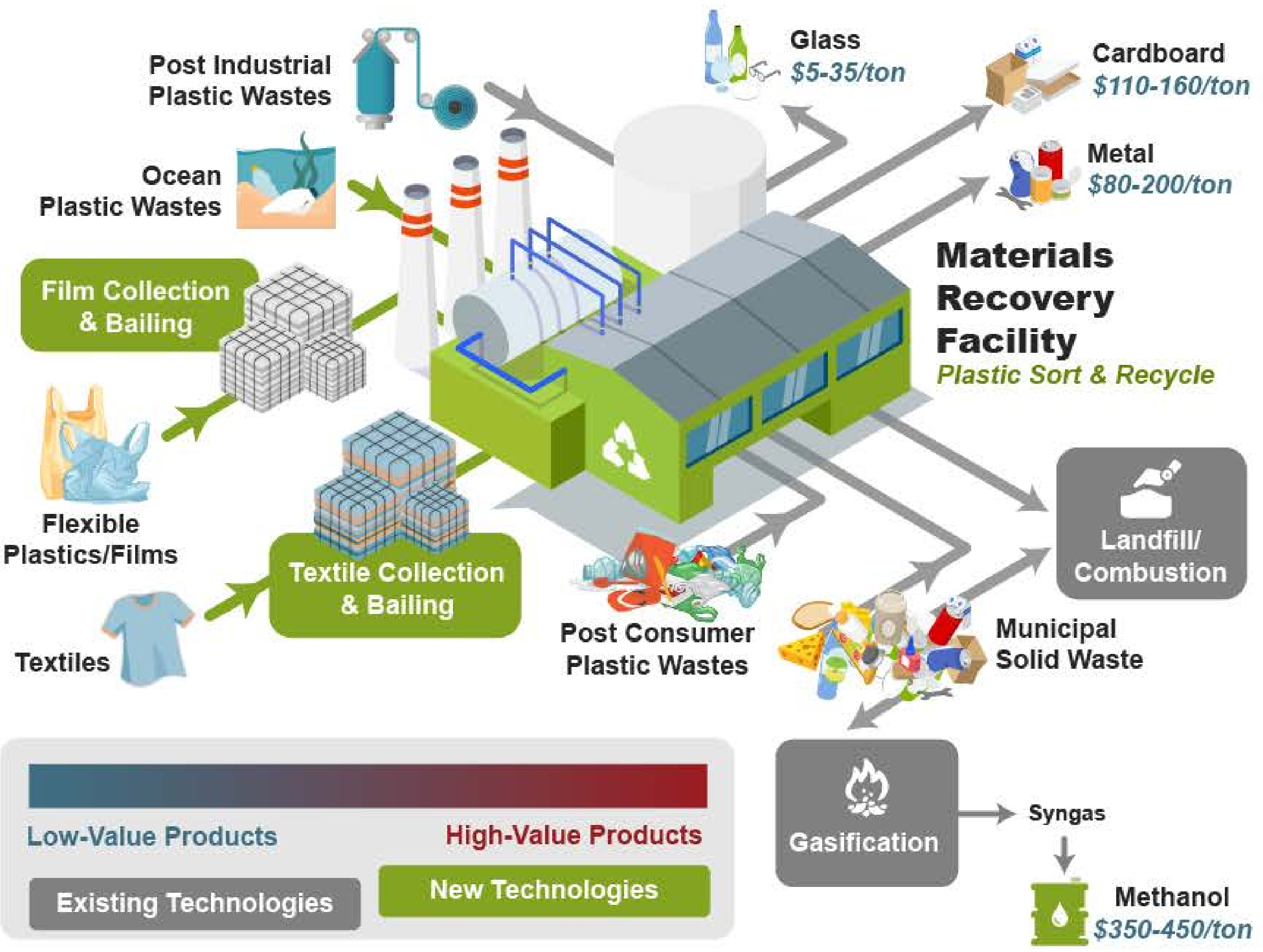
1 Approach: End of Project Goals

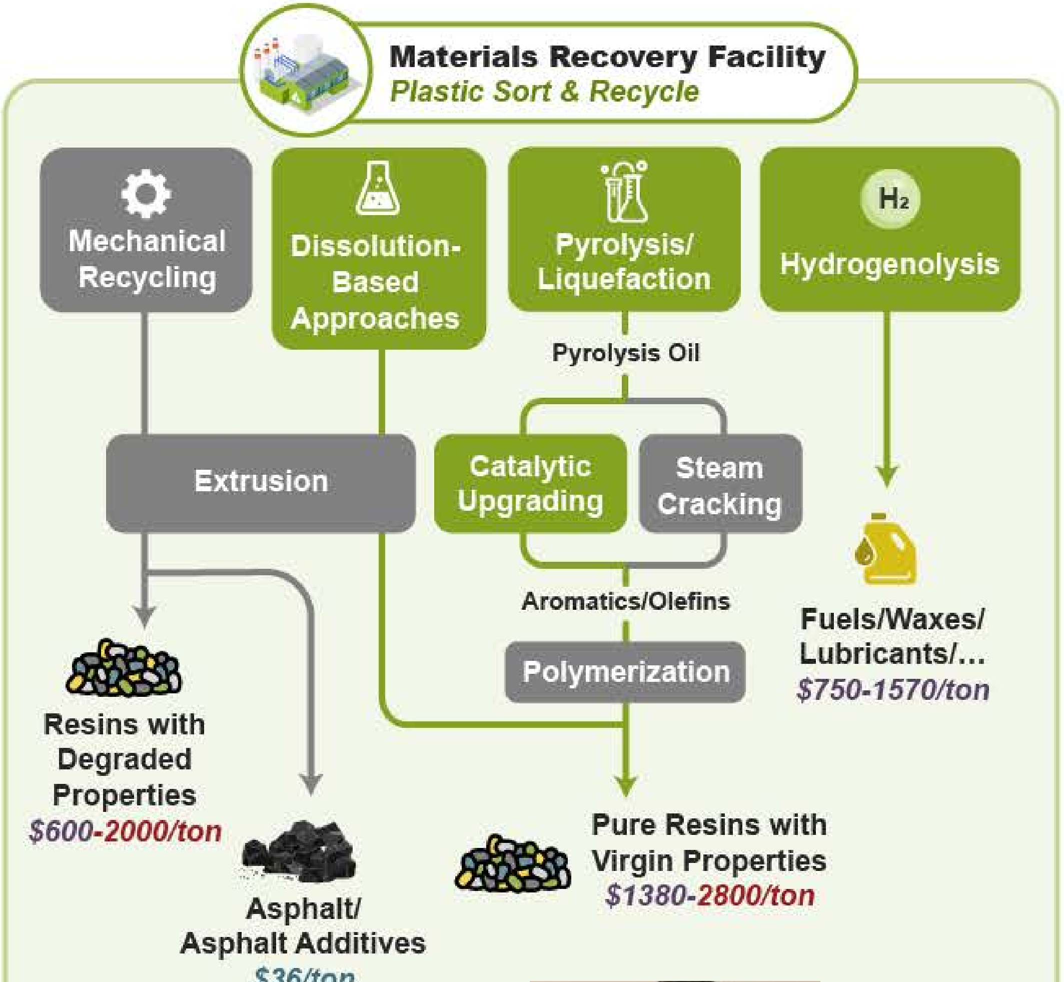
- **Milestone 4.1.4** (**End of Project goal**)**:** Completed database to provide industry with material selection criteria that will optimize subsequent upcycling and reuse of starting materials (Q19).
- **Milestone 4.2.3 (End of Project Goal):** Provide machine learning based digital tool as a resource for industry….(Q19).
- **Milestone 4.3.5 (End of Project Goal):** Pilot reactor is continuously operated for at least 24 hours without plugging. At least 1L of plastic-derived oil products …..shipped to Topic 4 team (Q19).
- **Milestone 4.4.4 (End of Project Goal):** Produce >80 wt% of the plastic monomers from plastics-derived wastes and oils (Q19).
- **Milestone 4.5.3 (End of Project Goal):** Recover >90% of the polymer components of PCW stream and obtain resins that can be mechanically recycled (Q19).

2 Progress and Outcomes: Completed BP2 Go/No-Go Decision Points

- **Milestone 2.3.3 (Go/No-Go).** Prewashed individual polymer constituents from PCW plastics will be thermally depolymerized using a lab-scale continuous reactor at steady state for at least 24 hours of cumulative TOS achieving >70% yield of waxes and oils from PE, PP and PS constituents…..(Q8).
- **Milestone 2.3.4 (Decision Point).** Results of thermal oxo-degradation and pyrolysis are compared to determine the method that is more suitable to degrade plastic feedstock. (Q8)
- **Milestone 2.5.4 (Go/No-Go):** Recover >90 wt% of two different commercial rigid films and demonstrate that recovered resins have properties similar to pure resins (Q8).

2 Progress and Outcomes: Review Plastic Recycling

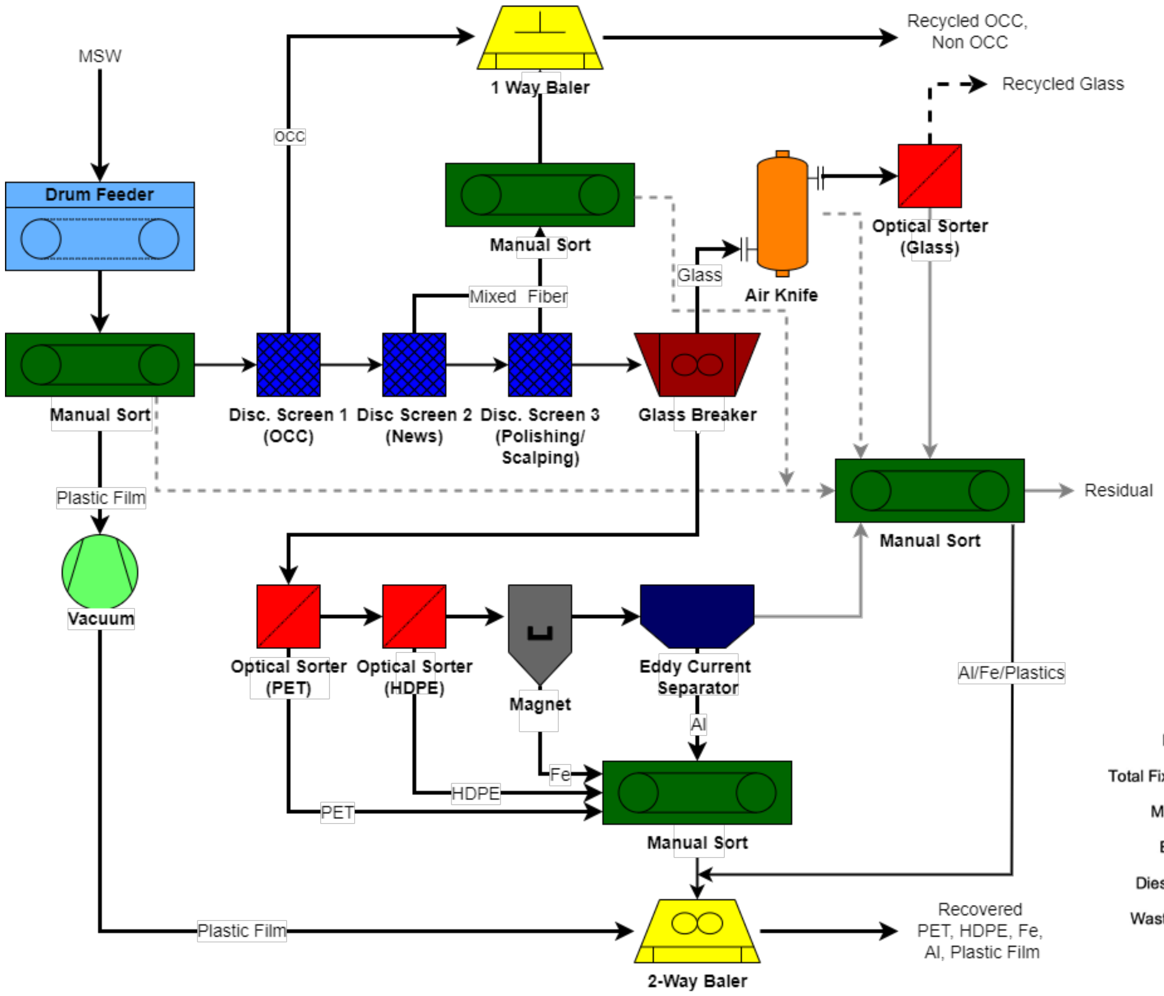




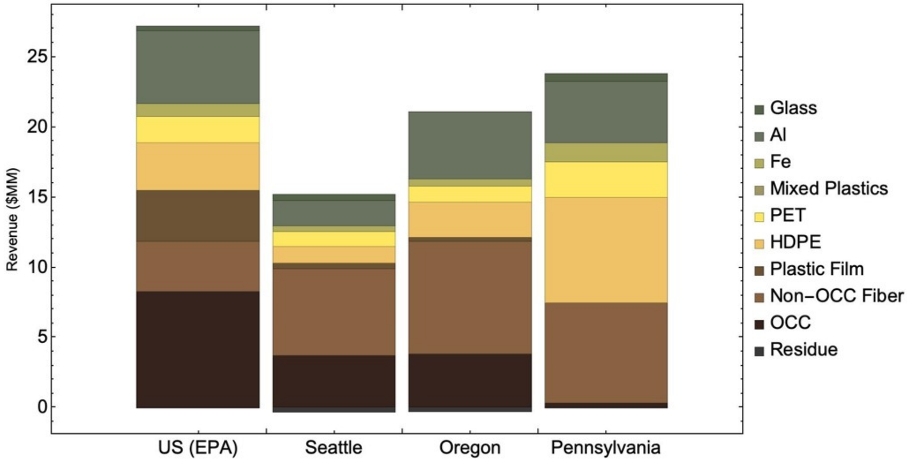
Houqian Li

H Li et al, Expanding Plastics Recycling Technologies: Chemical Aspects, Technology Status and Challenges, Green Chemistry (2022)

2 Progress and Outcomes: Material Recovery Facility



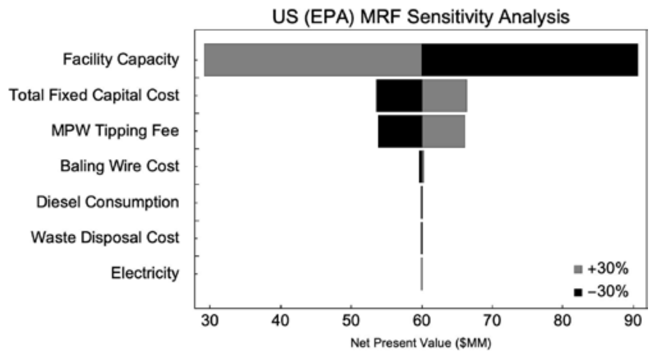
MRF Revenue by

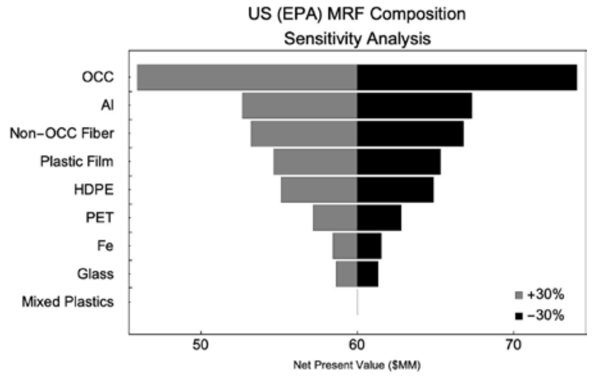


Dr. Mark Mba-Wright

Olumide Olafasaki

Techno-Economic Analysis NPV Sensitivity Analysis





Some key assumptions and results

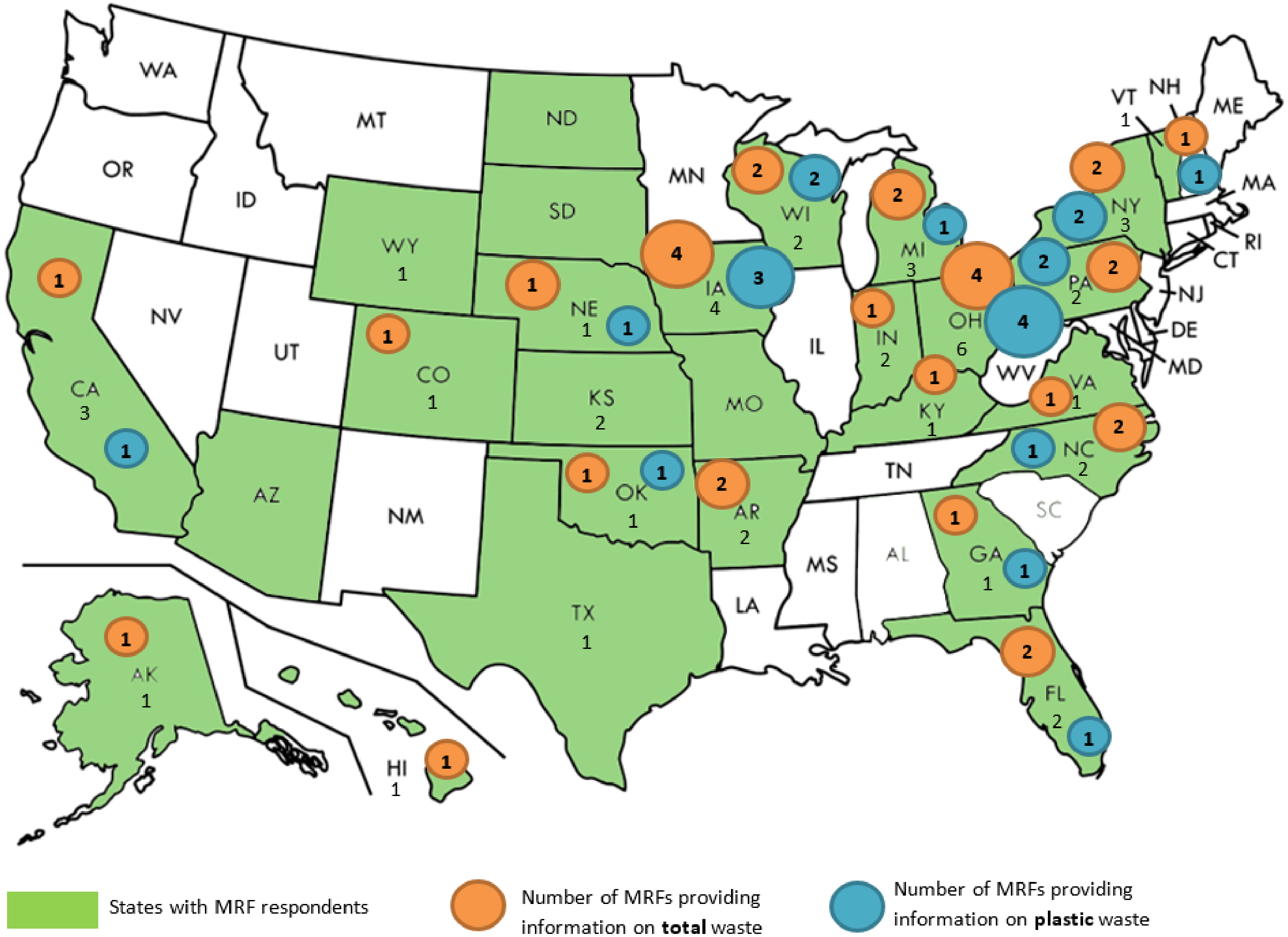
- Capacity: 120,000 MT/year
- Total Fixed Capital Cost: $5.15 MM
- Operating Cost: $Operating hours: 4160 hours/year (2 8-hours shift, 5 days a week)
- Net Present Value (NPV): 3.57 – 60 MM USD

Composition reference

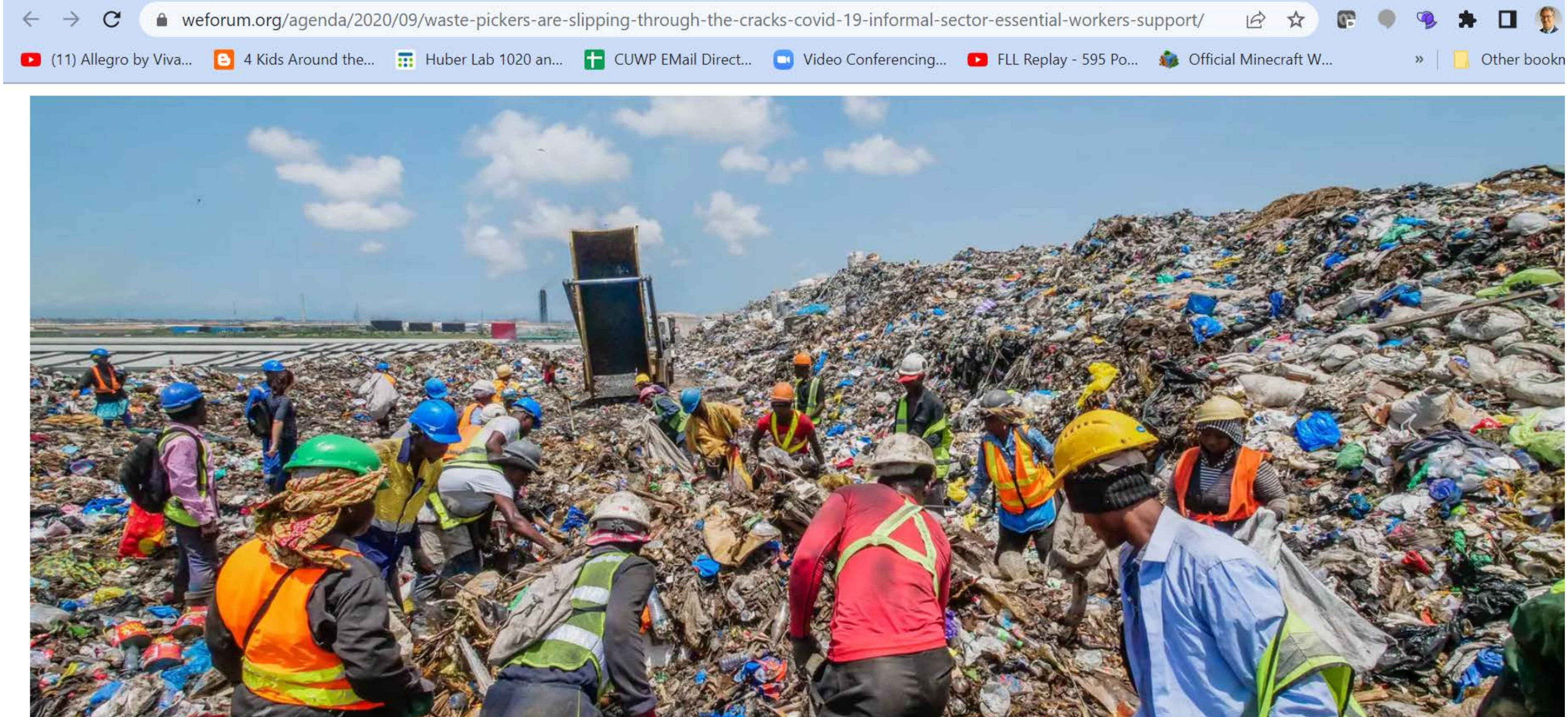
- US EPA, “Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010 https://www.epa.gov/sites/production/files/2015-09/documents/2010_msw_fs.pdf,” US Environ. Prot. Agency, no. February, p. 63, 2010.
- R.W. Beck Inc., “Pennsylvania Recovered Material Composition Study,” 2005.
- P. Spendelow, “Composition of Commingled Recyclables Before and After Processing,” no. March, 2011.
- C. C. Group, S. Public, and U. Staff, “Seattle Public Utilities Residential Waste Stream Composition Study FINAL Report,” no. November, 2007.

2 Progress and Outcomes: National MRF Survey

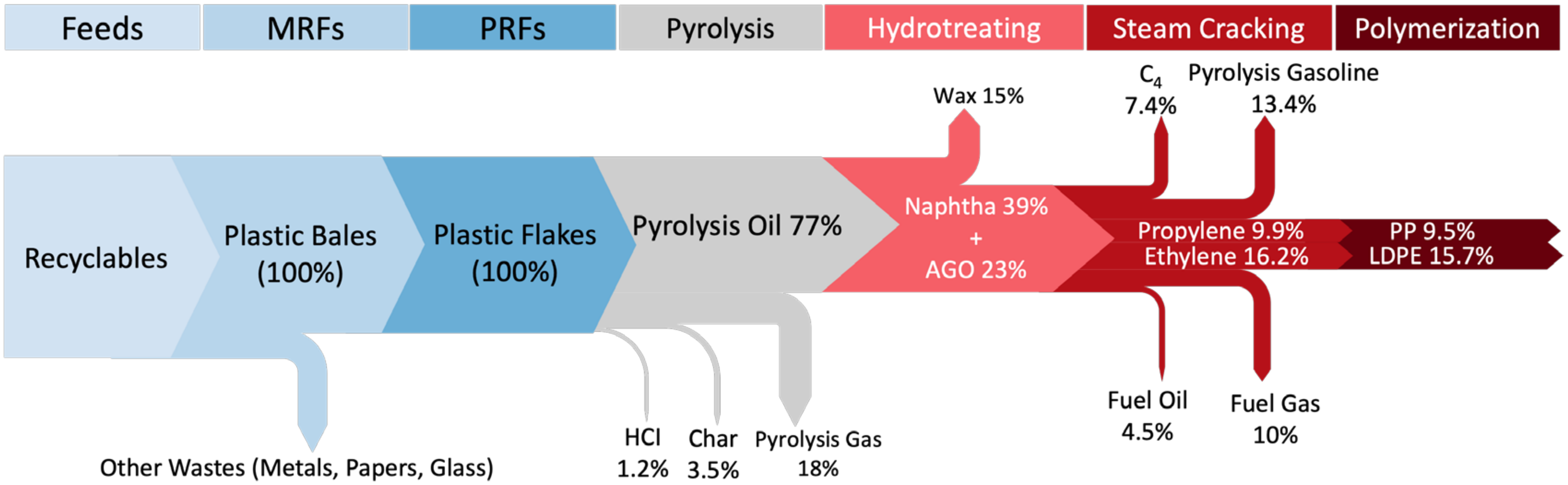
- Partnered with Environmental Research and Education Foundation.
- Questions: MRF type, waste source, handled materials (type and quantity), % revenue, type of equipment.
- 49 responses, but only 38 provided waste mass information, and 23 provided plastics information.



2 Progress and Outcomes: 20 million people world-wide are waste pickers and manually collect and sort recyclables

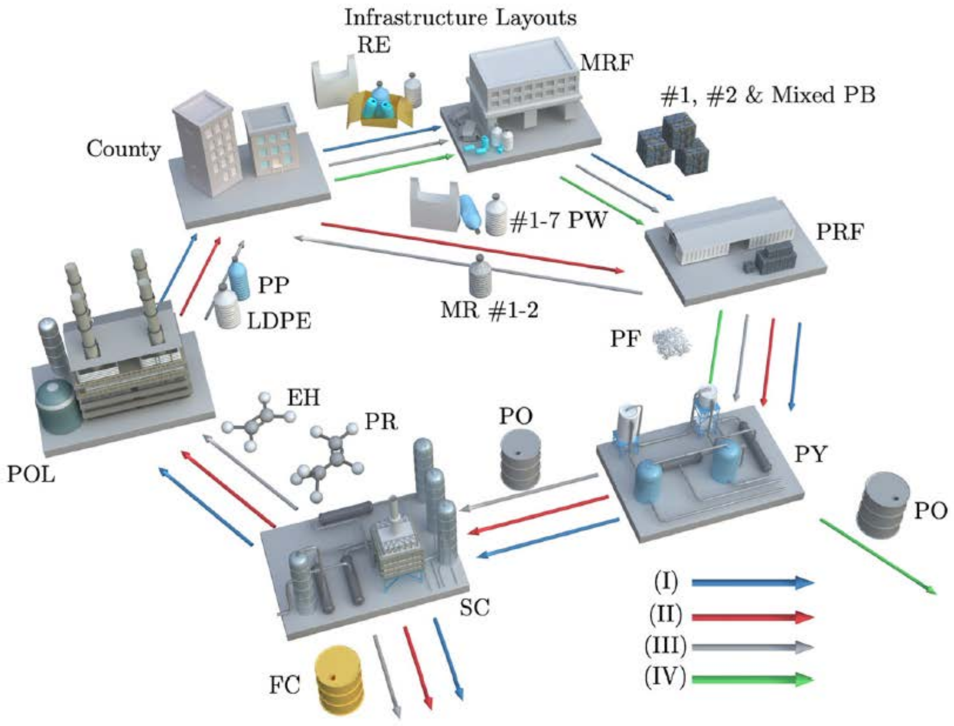


2 Progress and Outcomes: Pyrolysis Technology Requires a Very Complex, Expensive Infrastructure (>$3.5 billion)



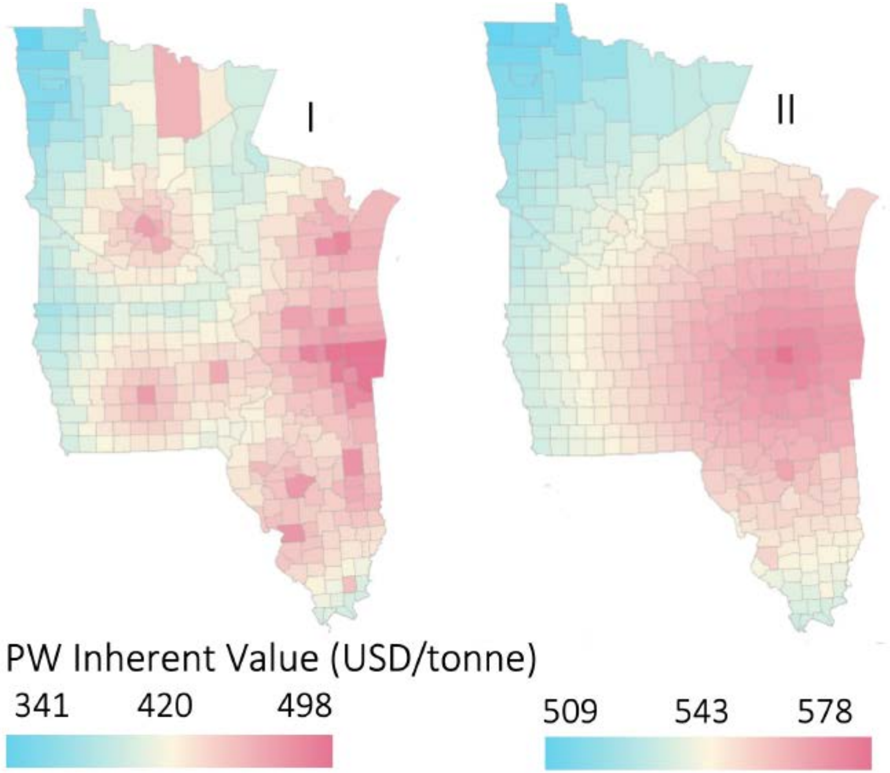
Jiaze Ma, Philip Tominac, Olumide Olafasakin, Horacio Aguirre-Villegas, Mark Mba Wright, Craig H Benson, George W Huber, Victor M Zavala, Economic Evaluation of Infrastructures for Thermochemical Upcycling of Post-Consumer Plastic Waste, Green Chemistry, in-press.

2 Progress and Outcomes: Waste Plastic has an Inherent Value



Jiaze Ma

Victor Zavala



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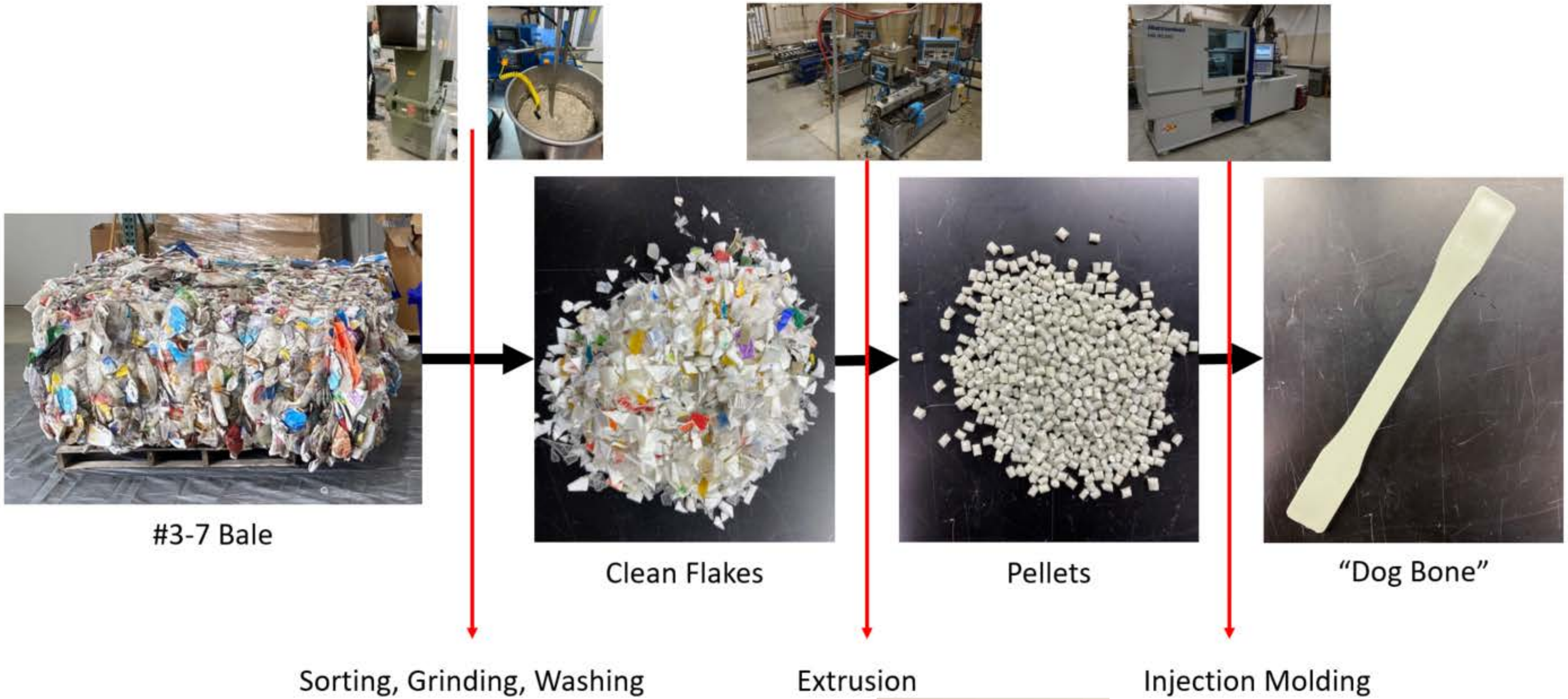
2 Progress and Outcomes: #3-7 Plastic Bale Composition from MRFs



#3-7 Bale

Clean Flakes

Pellets

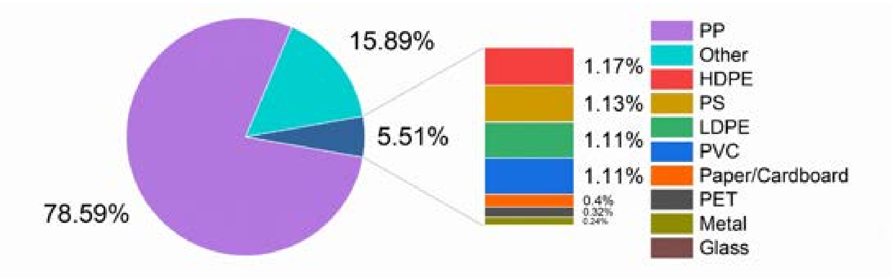
“Dog Bone”

Sorting, Grinding, Washing

Extrusion

Injection Molding

MRF 1



Victor Cecone Greg Curtzwiler Keith Vorst

2 Progress and Outcomes: Pyrolysis is not burning plastics

Plastic combustion products are CO_2, H_2O, and heat

Plastic Pyrolysis products are an oil and light gases

Combustion = Burning = Incineration

Pyrolysis or thermal depolymerization (also liquefaction)

1. Pyrolysis of plastic has a significantly lower carbon footprint compared to incineration
   GHG emission of pyrolyzing one tonne of plastic waste is 500-1000kg CO_2e.[a]
   GHG emission of combusting one tonne of plastic waste is 2200-3000kg/CO_2e.[b]
2. Pyrolysis enables a circular economy for plastic

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a. RTI International. (2012). Environmental and Economic Analysis of Emerging Plastics Conversion Technologies.

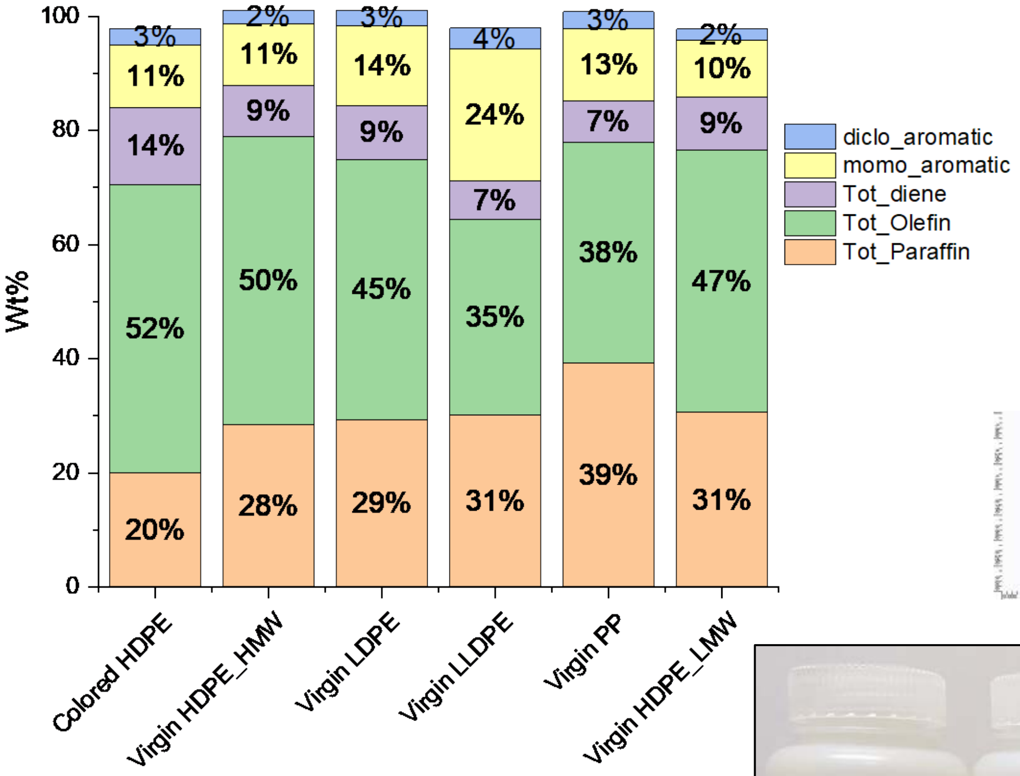
b. Rudolph, N., Kiesel, R., & Aumnate, C. (2020). Understanding plastics recycling: Economic, ecological, and technical aspects of plastic waste handling.

2 Progress and Outcomes: 8+ Companies have made Announcement on Plastic Pyrolysis/thermal depolymerization Commercial Facilities

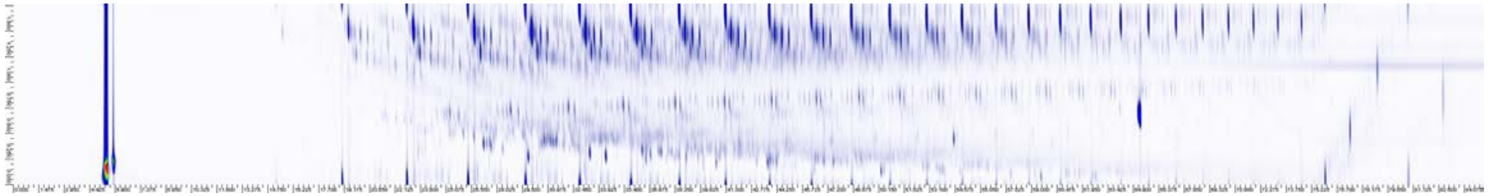
Company name	Plant location	Scale (kton/year)	Status	Reactor type	Feedstocks	Product	Collaborators
Agilyx	Tigard	3	Operational since 2018	Stirred tank reactor	PS	Styrene monomer	Toyo, ExxonMobil, Braskem, AmSty, Lucite, and NextChem
QuantaFuel	Skive	20	Operational since 2017	Fluidized bed reactor	HDPE, LDPE, PP, PS, and PET	Liquid oil, non-condensable gas, and carbon rich ash	BASF, VITOL, and VITTI
	Amsterdam	100	2023-2024				
	Sunderland	100	2024				
Pryme	Rotterdam	40-60	Plan to start up in 2022	Stirred tank reactor	PS, PE, and PP	Kerosine, naphtha, and wax	Shell
Brightmark	Asheley	100	Not reported	Auger Rector	PET, HDPE, PVC, LDPE, PP, and PS	Ultra-low sulfur diesel, naphtha and wax	BP, Chevron, Clean fuel Partners, and Northeast Indiana Solid Waste Management District
Plastic Energy	Seville	5	Operational since 2017	Stirred tank reactor	LDPE, HDPE, PP, PS	Diesel and Naphtha	SABIC, ExxonMobil, and Freepoint Eco-Systems
	Le Havre	25	Design phase planned to start up in 2023				
	Almeria	Not reported	Operational since 2014				
Freepoint Eco-Systems	Houston	33	Start up in Mid-2024	Not reported	LDPE, HDPE, PP, PS	Synthetic oil	Plastic Energy, and TotalEnergies
	Obetz	90	Start up in 2023				
Shell	Pulau Bukom	50	2022	Not reported	Not reported	Not reported	Pryme
ExxonMobil	Baytown	30	Start up in End 2022	Fluidized Bed Reactor	Not reported	Not reported	Cyclyx, Agilyx, and Plastic Energy

H Li et al, Expanding Plastics Recycling Technologies: Chemical Aspects, Technology Status and Challenges, Green Chemistry (2022)

2 Progress and Outcomes: Detailed Understanding of Plastic Pyrolysis OIls



Product Yields (C%)	Virgin HDPE	PC HDPE	Virgin LDPE	PC LDPE	Virgin PP	PC PP
Gas	3.9	6.6	6.7	10.7	11.2	13.4
Solid Residue	0	2.8	0	0.6	0	1.2
Total Liquid/Wax	96.1	90.6	93.3	88.7	88.8	85.4
Gasoline (C5-C12)	24.1	23.8	24.3	27.7	31.5	28.4
Diesel (C13-C20)	23.4	19.7	23.4	19.9	17.5	16
Wax (C20+)	48.6	47	45.6	41.1	39.4	41



Harish Radhakrishnan
Saad Aftab
Xianglan Bai

Jiayang
Wu

2 Progress and Outcomes: PCR Plastics Pyrolyze differently than Virgin Materials

Product distributions & mass loss profiles

Product Yields (C%)	Virgin HDPE	PC HDPE	Virgin LDPE	PC LDPE	Virgin PP	PC PP
Gas	3.9	6.6	6.7	10.7	11.2	13.4
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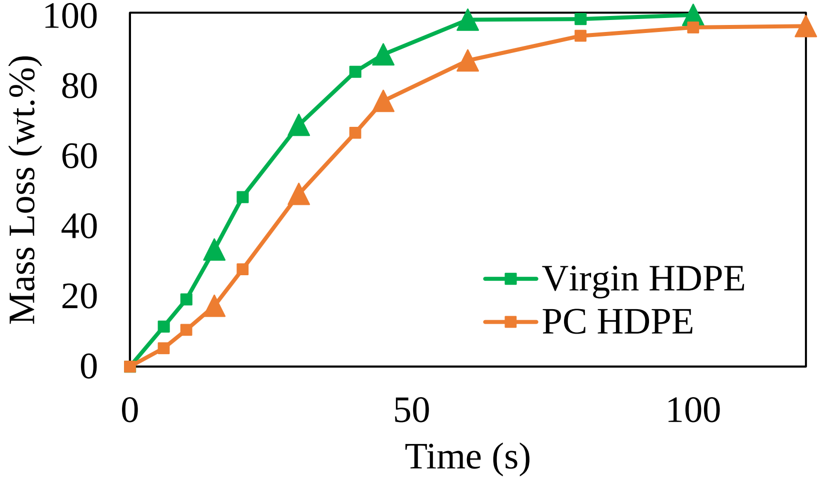
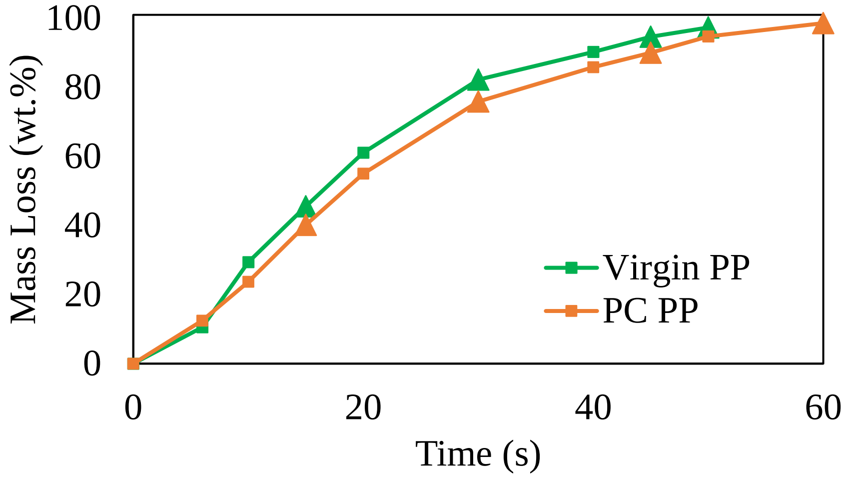
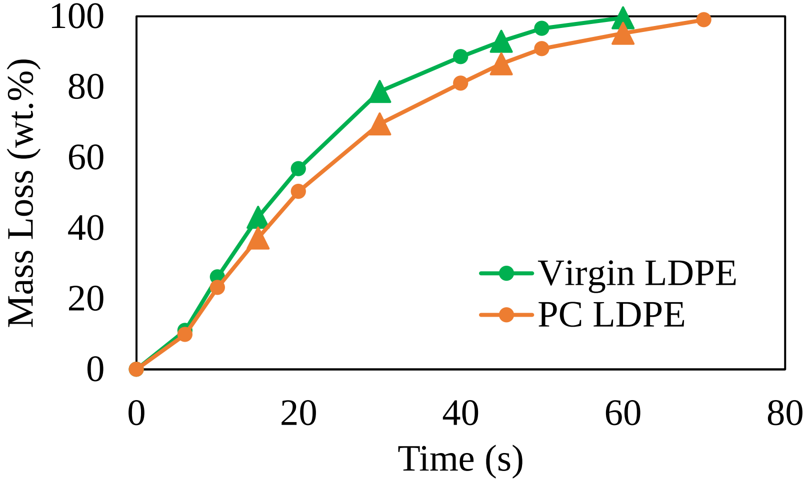
T= 550℃



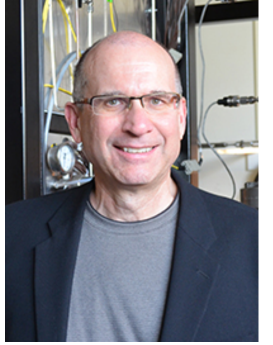




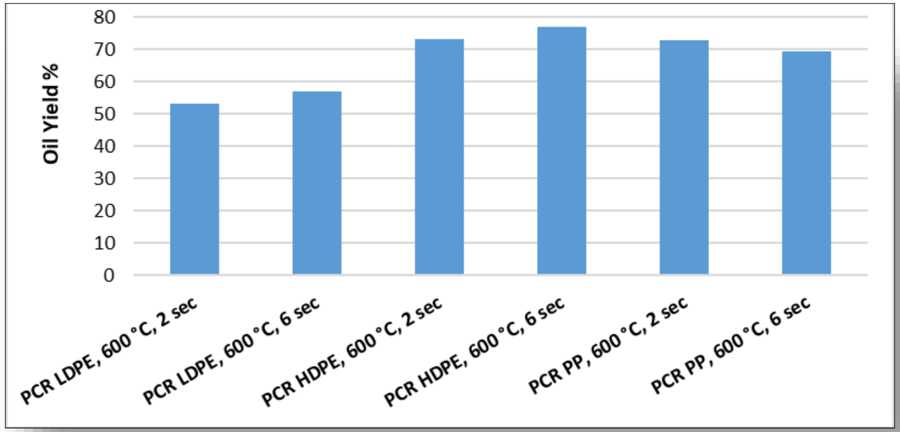
Xianglan Bai
Harish Radhakrishnan

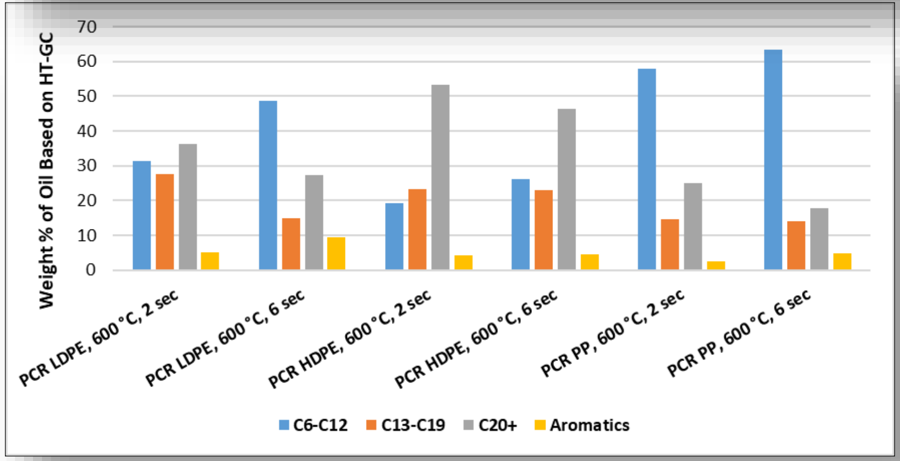
2 Progress and Outcomes: Impact of secondary reactions on the products of pyrolysis

Saad Afrab
Robert Brown



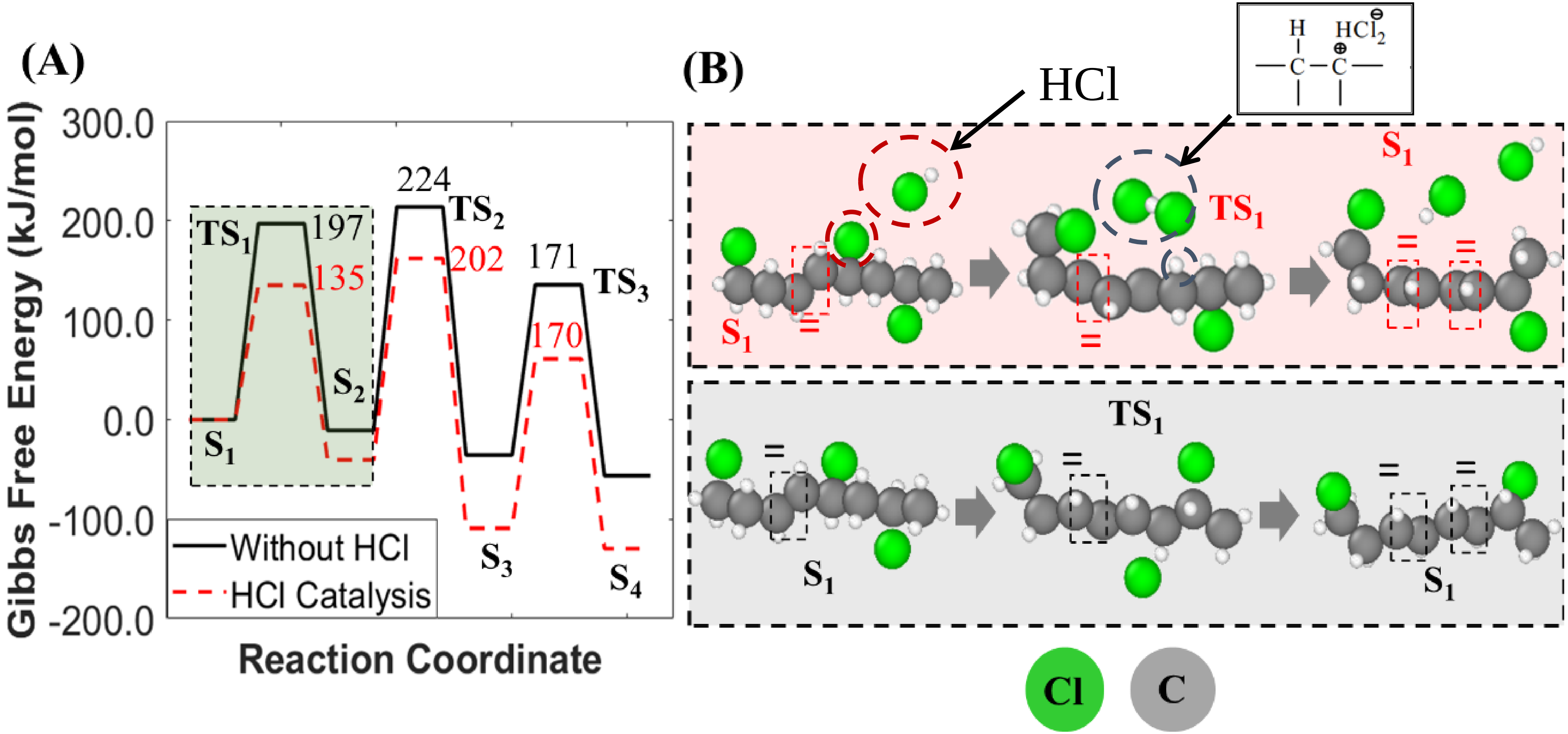
- Secondary reactions are those that occur in the gas phase after plastic has cracked to volatile species
- In general, increasing volatiles reaction time (VRT) produces less wax and more light oil, but at the expense of overall yield of condensable products (that is, producing more non-condensable gases)
- The VRT required to completely convert wax to oil and gas is varies among different kinds of plastics.
- A small amount of oxygen added during pyrolysis can enhance both primary and secondary reactions of pyrolysis





Feedstock	Rate Constant (s^{-1})	Projected Time (sec)
Post-consumer PP from MRF 1	0.085	~ 35
Post-consumer LDPE from MRF 1	0.071	~ 42
Post-consumer HDPE from Mexico	0.035	**~ 85**

2 Progress and Outcomes: DFT Shows HCl catalyzes dehydrochlorination of PVC

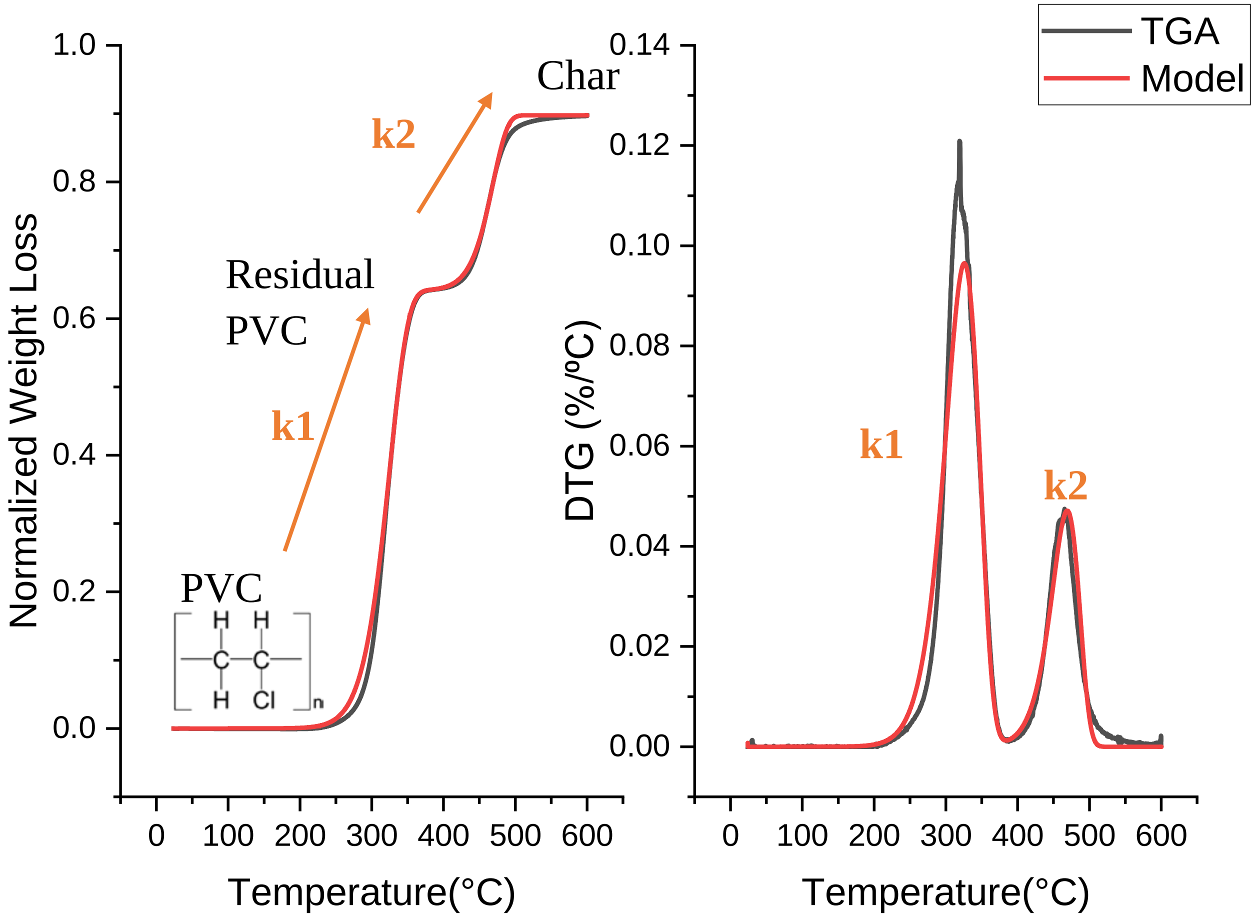


Konstantinos Papanikolaou

- HCl reduced around **60 kJ/mol** apparent activation energy for Cl removal
- Tested with 20 carbon backbone, the result was similar

Konstantinos G Papanikolaou, Jiayang Wu, George W Huber, Manos Mavrikakis, Mechanistic Insights into the Pyrolysis of Poly(Vinyl Chloride), Journal of Polymer Research, (2023) 30, 1-16.

2 Progress and Outcomes: Autocatalysis and Kinetics of the PVC Degradation Obtained from TGA



PVC degradation kinetic parameters

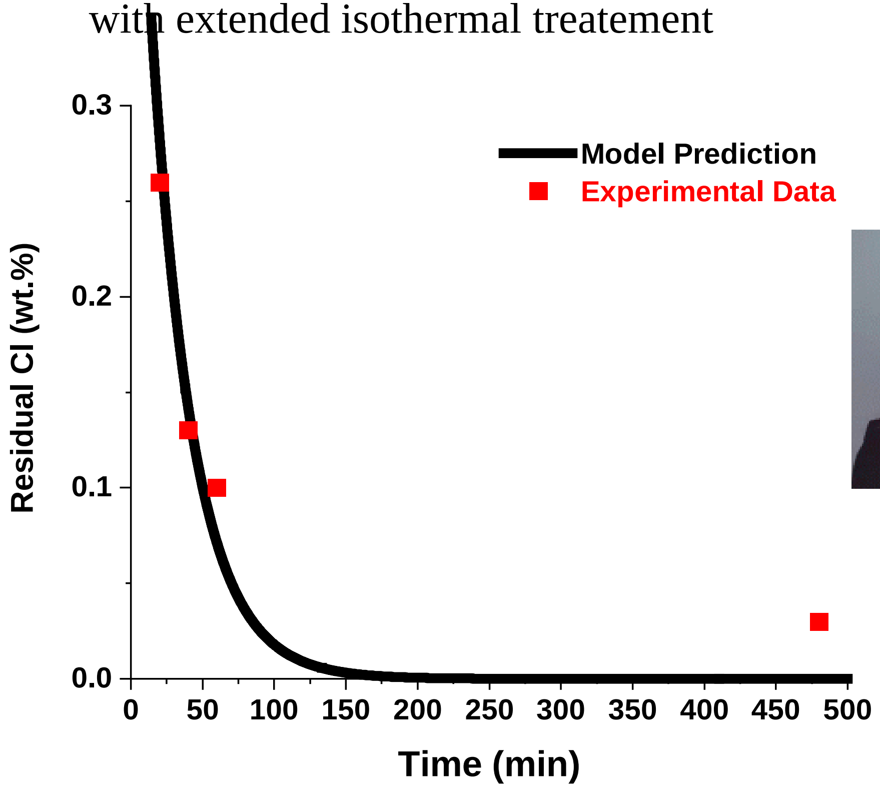
	Ea (kJmol^{-1})	A (S^{-1})
k1	115.72 ± 0.69	$8.63\times10^{6} \pm 1.23\times10^{5}$
k2’	5.98 ± 0.034	$3.6\times10^{-3} \pm 2.08\times10^{-5}$
k2’’	230.60 ± 1.24	$5.8\times10^{12} \pm 3.2\times10^{9}$

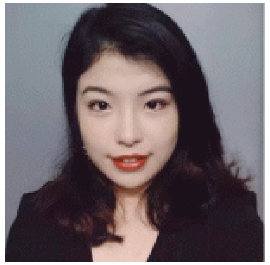
The dehydrochlorination kinetics:

Ea (k1): 116 kJ/mol

Ea (DFT): 135 kJ/mol

The model can predict the Cl removal degrees at 320 ºC with extended isothermal treatement

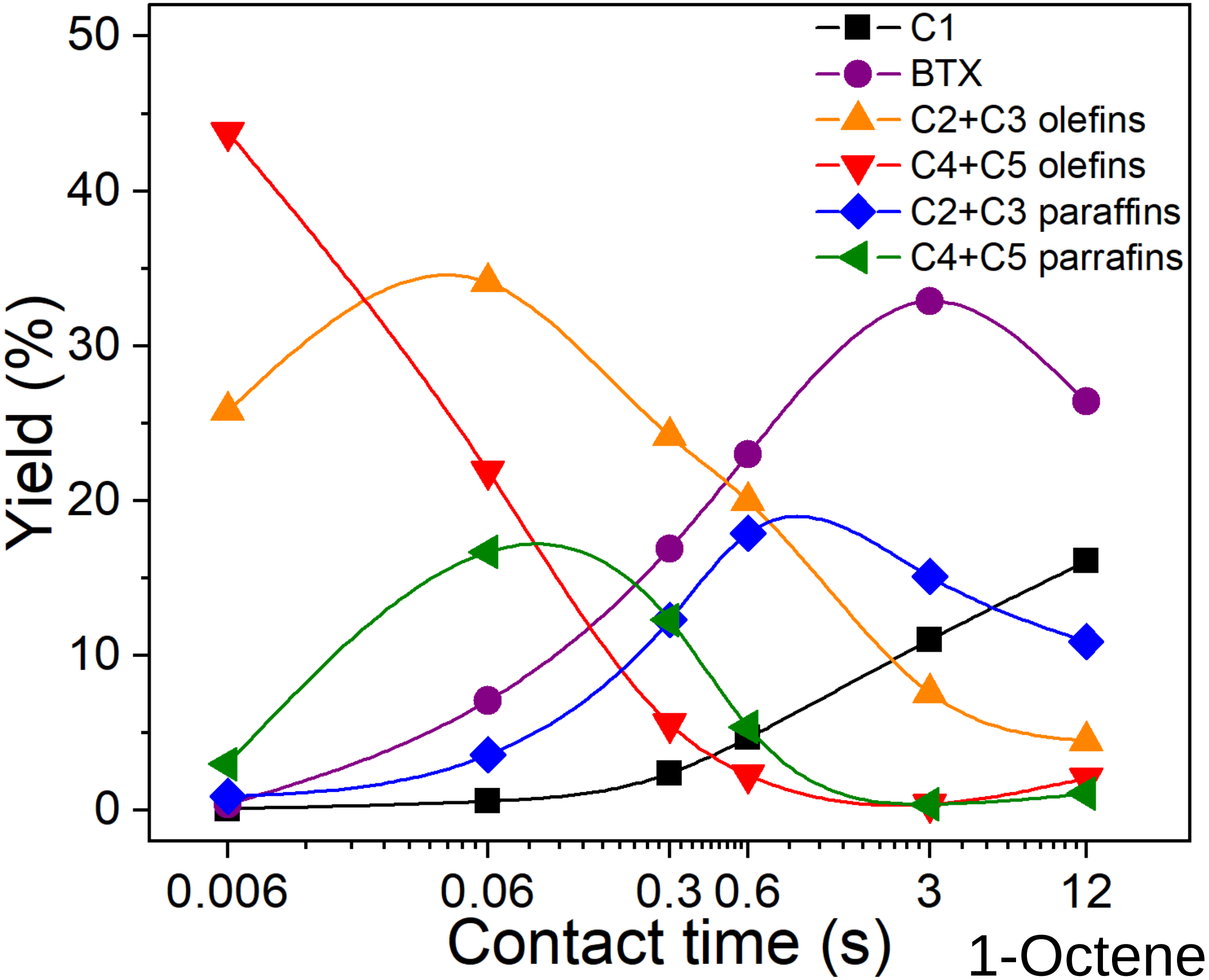


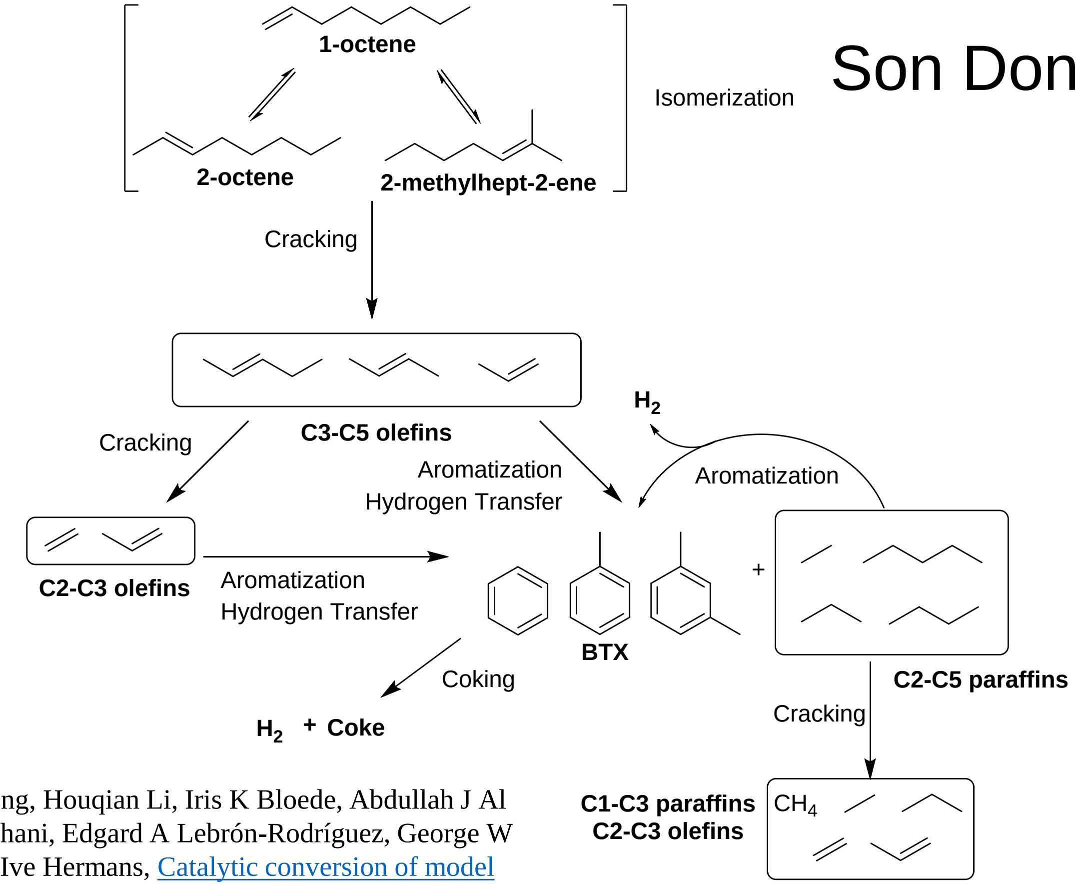


Isothermal period at 320 ºC (min)	Residual Cl (wt %)
PVC without pretreatment	56.8%
20	0.26%
40	0.13%
60	0.10%
480	0.03%

2 Progress and Outcomes: Zeolites can be used to produce aromatics/olefins from Pyrolysis Oils

Son Dong





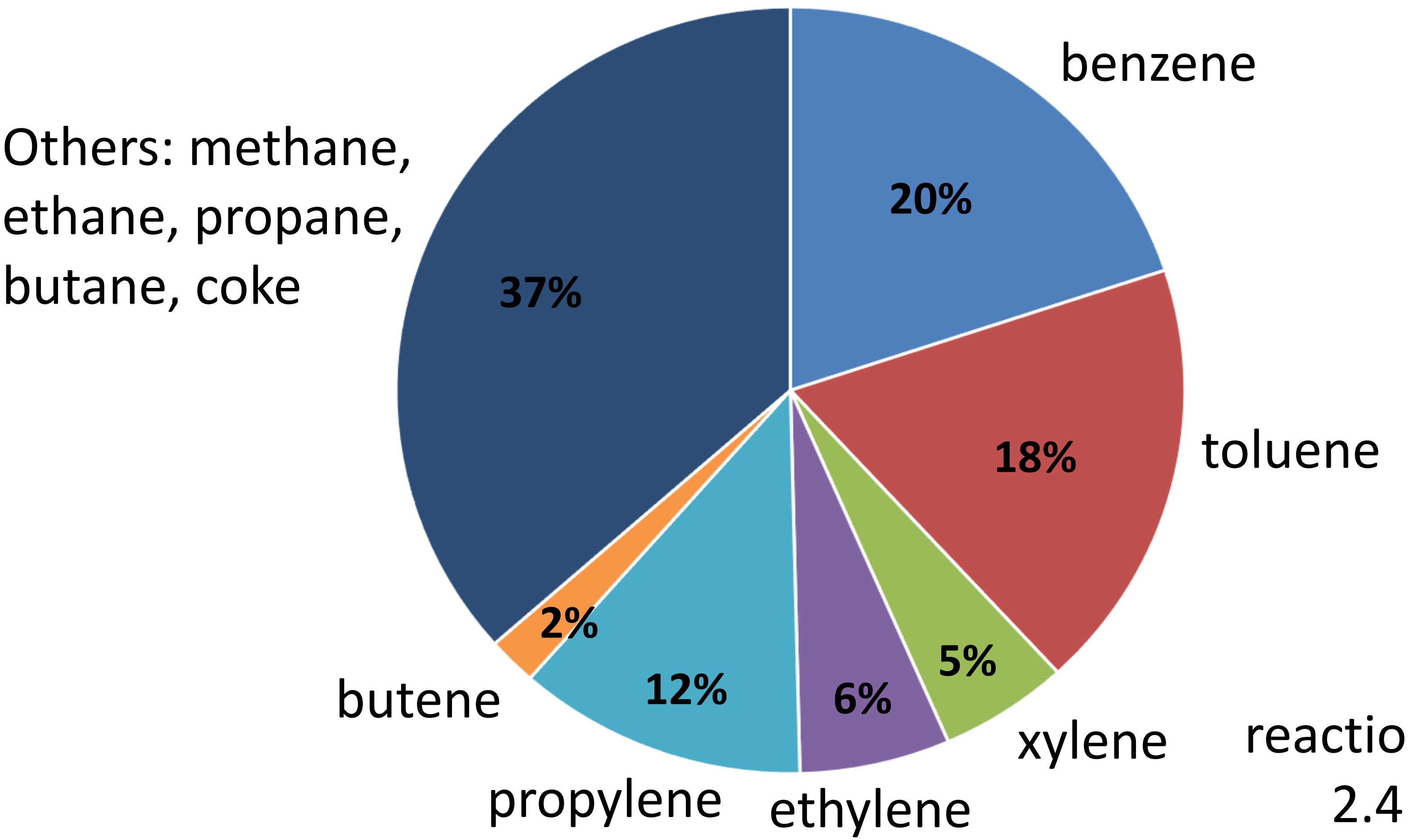
Son Dong, Houqian Li, Iris K Bloede, Abdullah J Al Abdulghani, Edgard A Lebrón-Rodríguez, George W Huber, Ive Hermans, Catalytic conversion of model compounds of plastic pyrolysis oil over ZSM-5, Applied Catalysis B: Environmental, (2023) 324, 122219.

1-Octene conversion over ZSM-5 at 500 C

1-Octene →C4/C5 olefins →C2 /C3 Olefins → BTX + Paraffins →BTX

2 Progress and Outcomes: Making aromatics and olefins from HDPE plastic pyrolysis oil

Son Dong



43% BTX yield

63% monomer yield

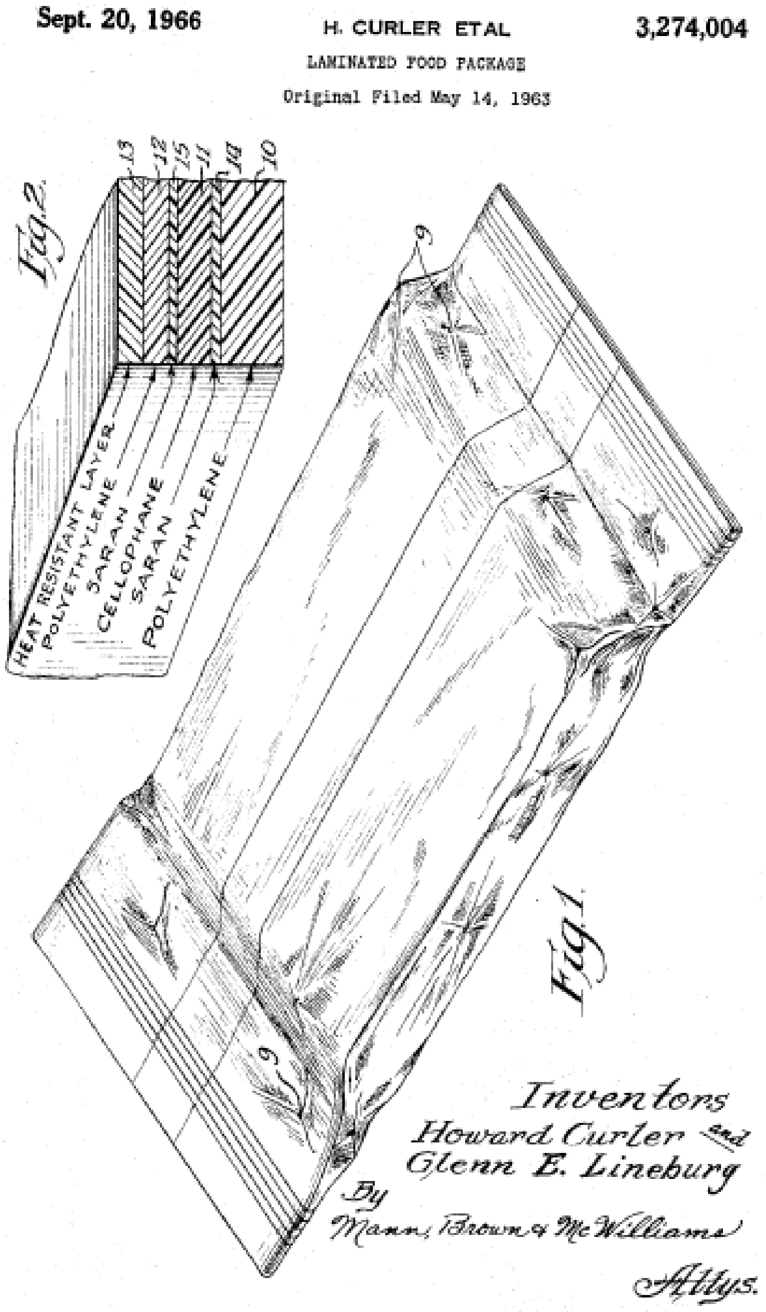
reaction conditions: $m_{\text{ZSM-5}}$ = 5g, 500 ^{o}C, 2.4 cc oil /hour, N_2 = 140 mL/min

unpublished

Package Design: Natural Cheese—1966

1966

- 1.5 billion lb
  - 45% cans, boxes and rigid plastic containers
  - 35% packaged in paper and foil
  - 20% plastic film
- PVDC-coated cellophane + PE
- Polyester (PET)-PVDC-PE



Sept. 20, 1966

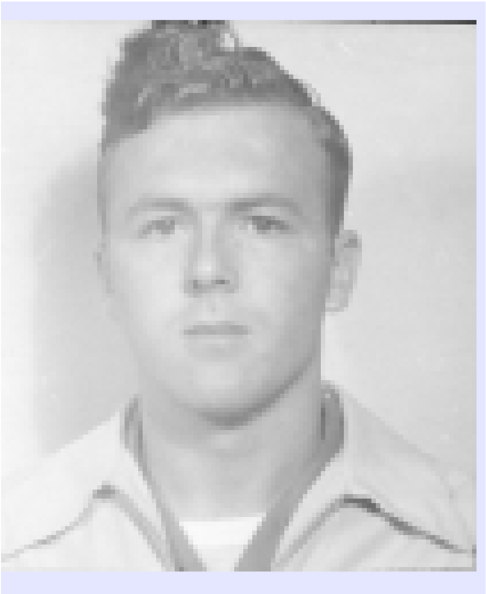
H. CURLER ETAL

3,274,004

LAMINATED FOOD PACKAGE

Original Filed May 14, 1963

Inventors
Howard Curler and
Glenn E. Lineburg
By
Mann, Brown & McWilliams
Attys.

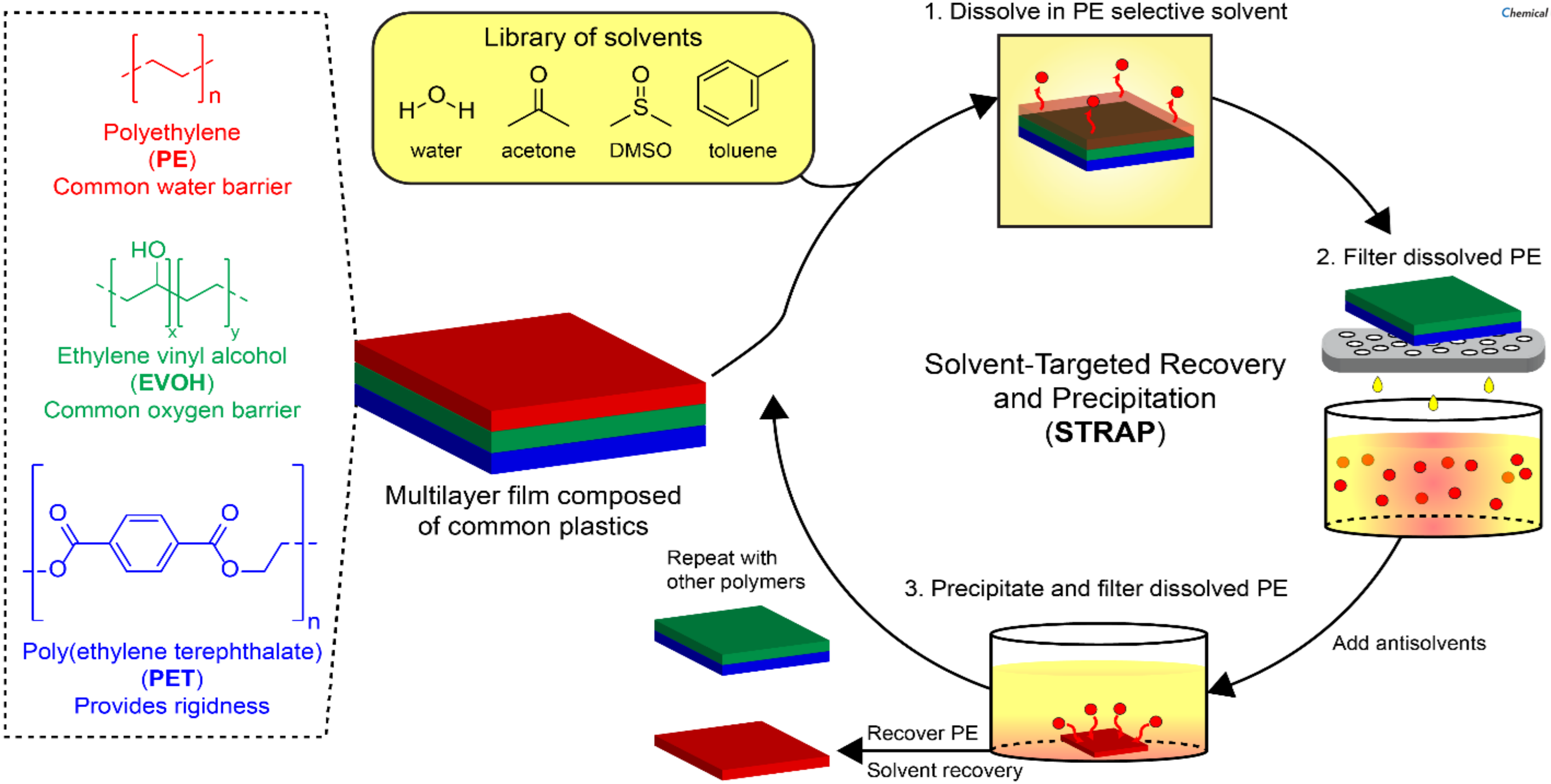


Howard Curler
UW-Madison
(1948)

Howard Curler
CBE
Distinguished
Chair (1997)

Sacharow, Stanley, and Roger C. Griffin. Food Packaging; a Guide for the Supplier, Processor, and Distributor. Westport, CT: AVI Pub., 1970.

2 Progress and Outcomes: Solvent-Targeted Recovery and Precipitation (STRAP) of multilayer plastic packaging



TW Walker, N Frelka, Z Shen, AK Chew, J Banick, S Grey, MS Kim, JA Dumesic, RC Van Lehn, GW Huber, Recycling of multilayer plastic packaging materials by solvent - targeted recovery and precipitation, ScienceAdvances (2020), 6, eaba7599.

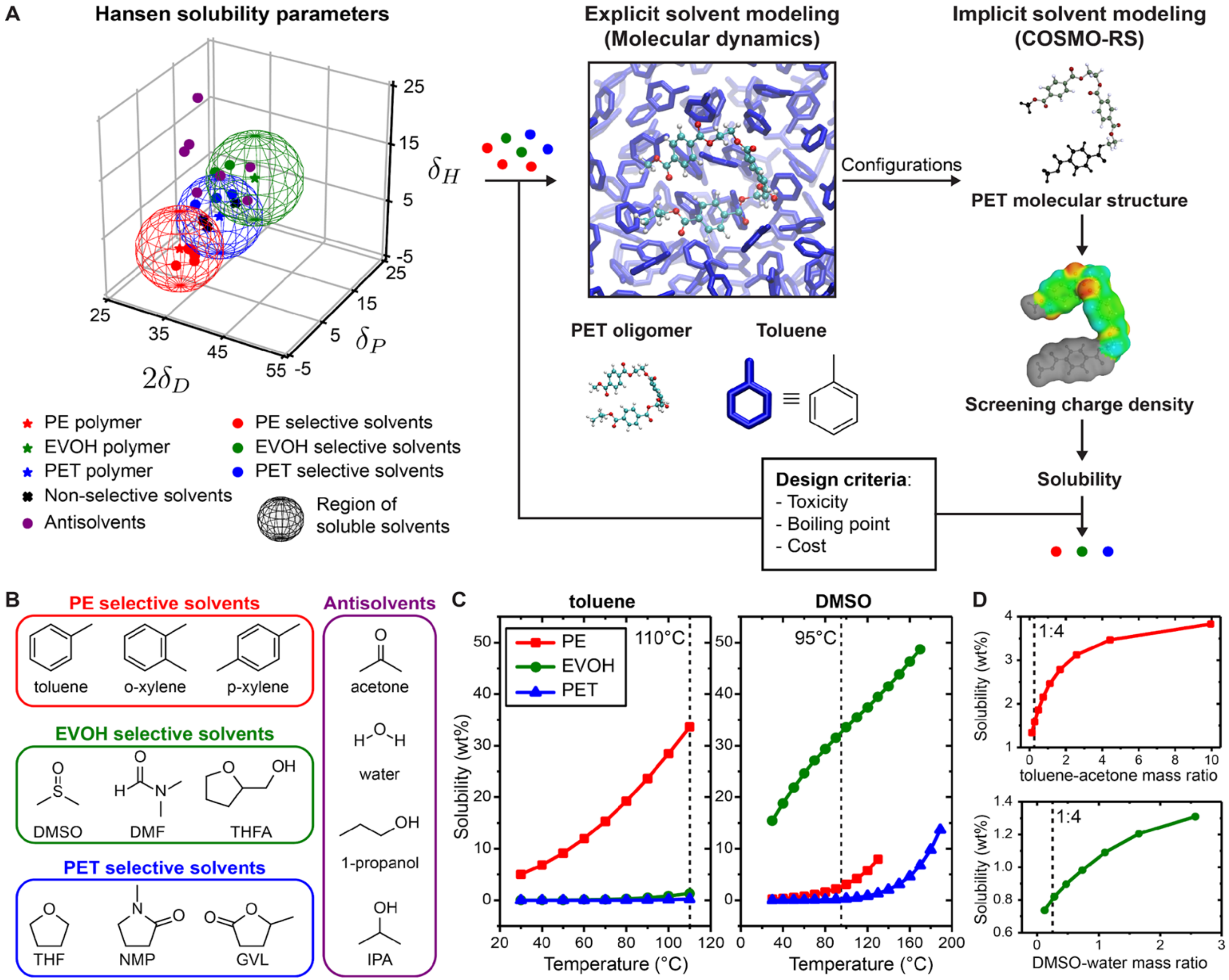
CUWP

Chemical Upcycling of Waste Plastics

Panzheng Zhou

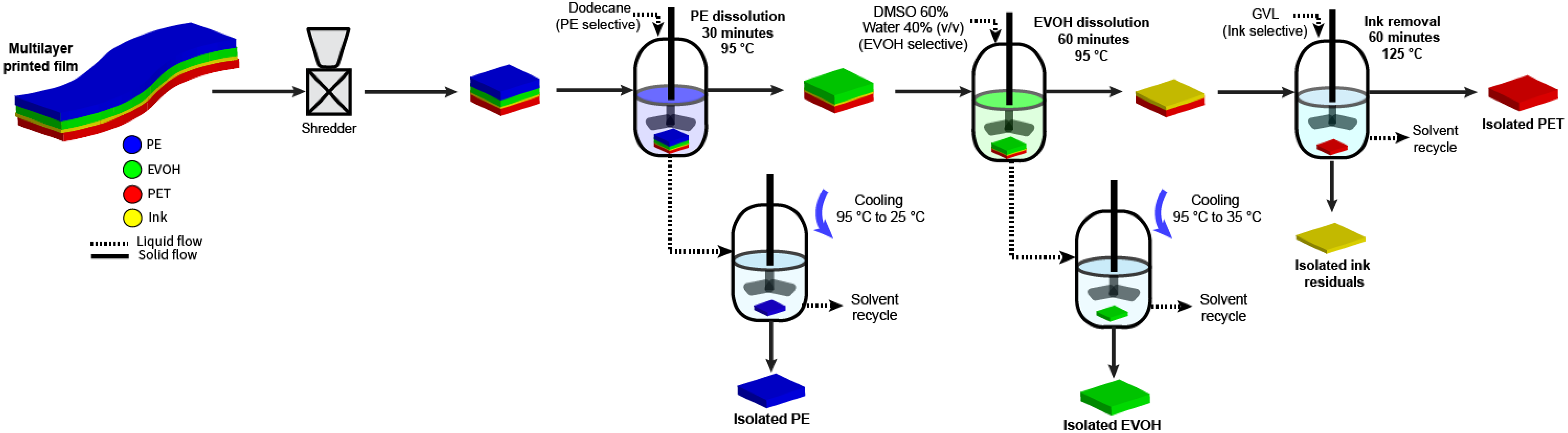
2 Progress and Outcomes: Thermodynamic computational tools are used to guide solvent selection

Database of 8 polymers in more than 1000 solvents



Panzheng Zhou, Kevin L Sánchez-Rivera, George W Huber, Reid C Van Lehn, Computational Approach for Rapidly Predicting Temperature-Dependent Polymer. Solubilities Using Molecular-Scale Models, (2021) ChemSusChem 14 (19), 4307-4316.

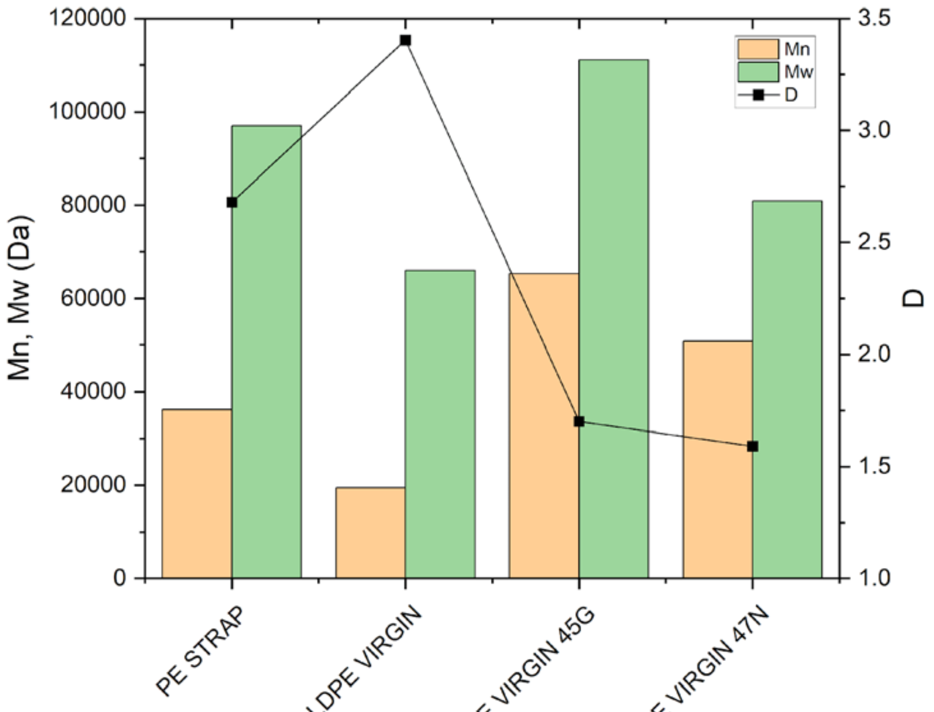
2 Progress and Outcomes: Food Grade Resins from Reverse Laminated Printed Flexible Films



Kevin Sánchez-Rivera

KI Sanchez-Rivera, Zhuo Xu, Ezra Bar-Ziv, et al. Recycling of printed multilayer plastic packaging films via solvent-targeted recovery and precipitation (STRAP). (submitted)

2 Progress and Outcomes: MW and Thermal Properties of STRAP polymers are similar to virgin materials

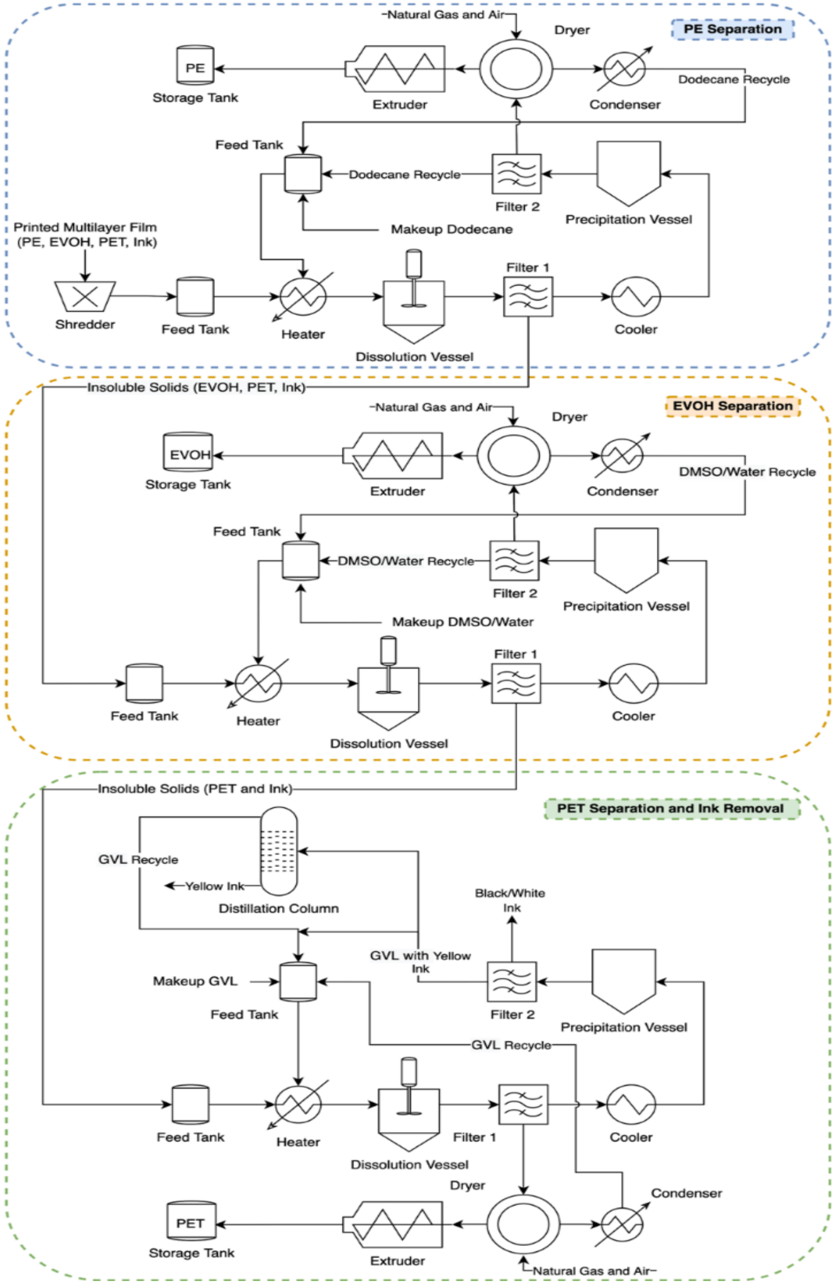


Resin	T_c (°C)	$T_{m,2}$ (°C)	ΔH_c (J/g)	$\Delta H_{m,2}$ (J/g)	Crystallinity
PE STRAP	**105.0**	**119.7**	**76.0**	**82.3**	**28.38%**
LDPE Virgin	98.3	112.0	84.8	86.1	29.69%
LLDPE Virgin 45G	106.1	122.4	83.3	85.5	29.48%
LLDPE Virgin 47N	107.0	122.2	70.2	73.3	25.28%
EVOH STRAP	**150.4**	**175.7**	**41.8**	**37.4**	**17.17%**
EVOH Virgin	147.8	176.4	54.2	54.3	24.93%
PET STRAP	**209.6**	**246.0**	**41.7**	**22.7**	**16.21%**
PET Virgin	169.2	244.6	30.0	38.5	27.50%

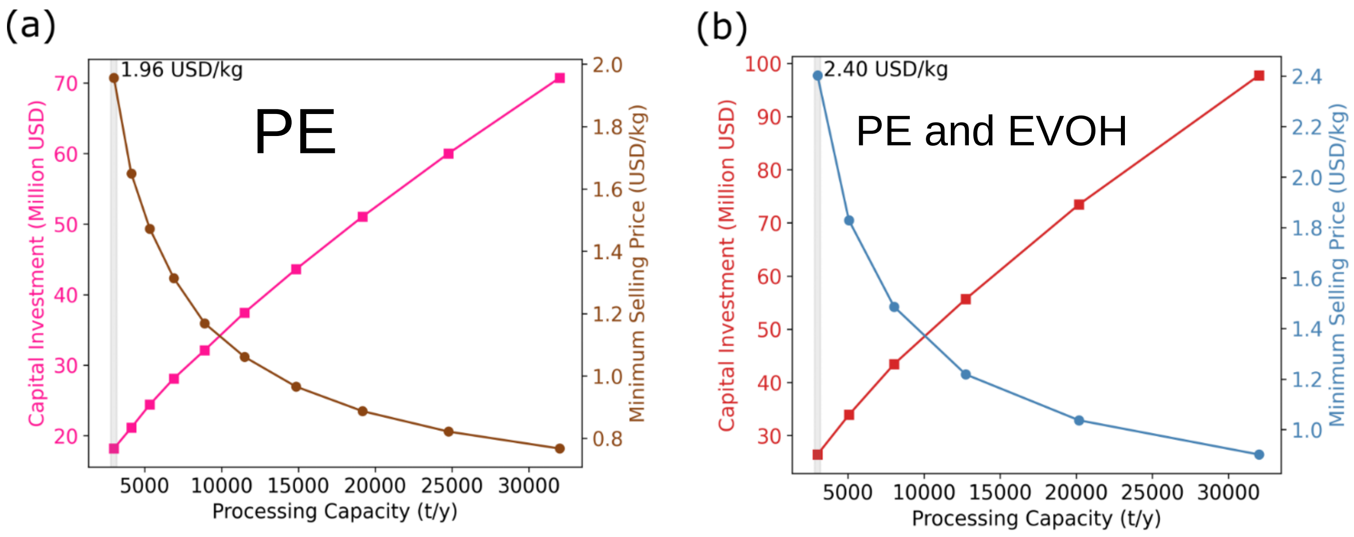


Victor Cecone Greg Curtzwiler Keith Vorst

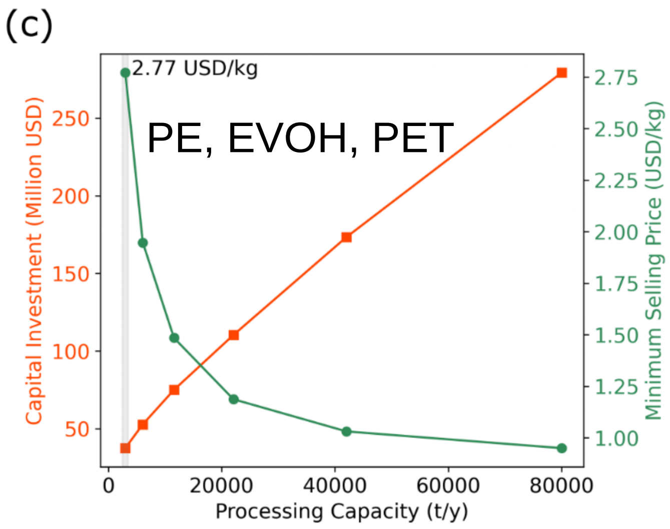
Sanchez-Rivera, et al. Recycling of printed multilayer plastic packaging films via solvent-targeted recovery and precipitation (STRAP). (submitted)



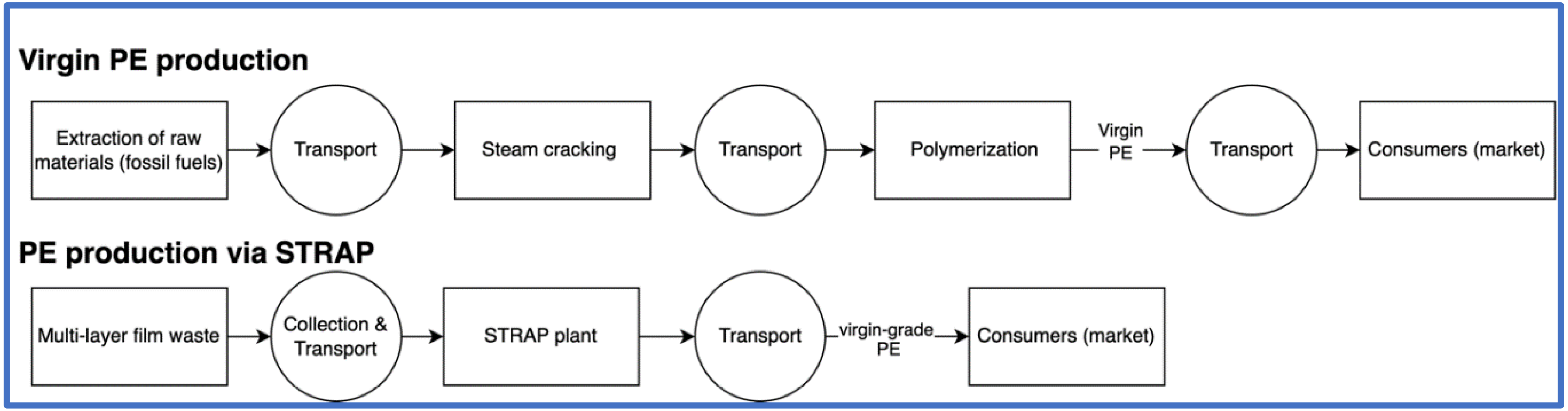
2 Progress and Outcomes: Process model from laboratory Data for STRAP films



Aurora del Carmen Munguía-López



2 Progress and Outcomes: STRAP has 60-70% lower greenhouse gas emissions than the Virgin Resins production process.

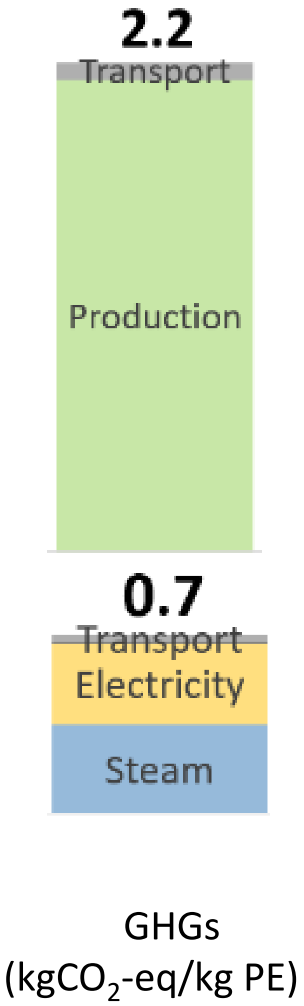


Virgin PE production

Extraction of raw materials (fossil fuels) → Transport → Steam cracking → Transport → Polymerization → Virgin PE → Transport → Consumers (market)

PE production via STRAP

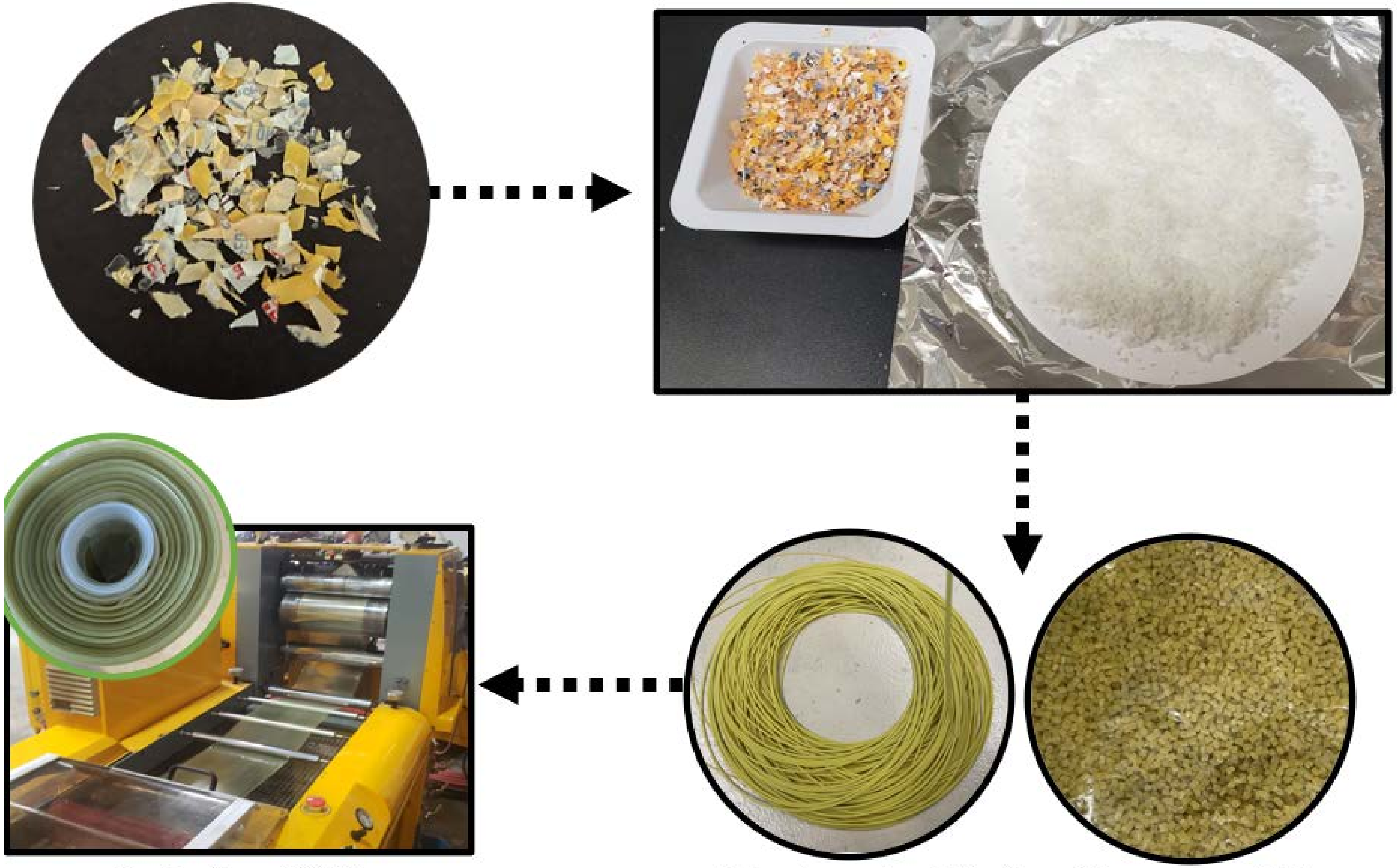
Multi-layer film waste → Collection & Transport → STRAP plant → Transport → virgin-grade PE → Consumers (market)



Aurora del Carmen
Munguía-López

Sanchez-Rivera, et al. Recycling of printed multilayer plastic packaging films via solvent-targeted recovery and precipitation (STRAP). (submitted)

2 Progress and Outcomes: Extrusion of LLDPE from STRAP



Shredded post-industrial multilayer printed plastic film

Recovery of PE component from printed film via STRAP

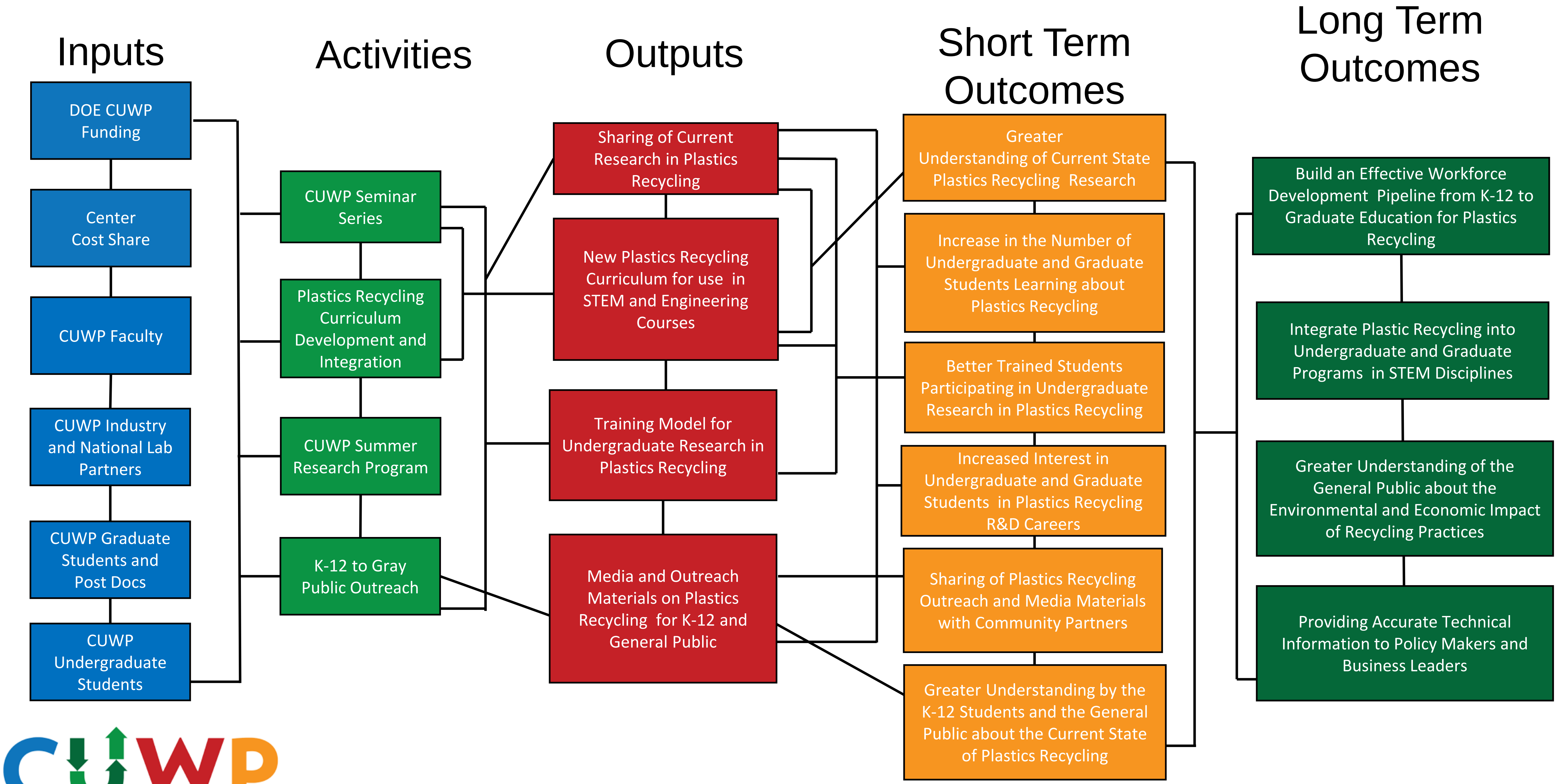
Extrusion and pelletization of the recovered PE

Production of 100% recycled PE film

2 Progress and Outcomes: STRAP is moving towards commercialization

- Successfully demonstrated STRAP technology with a range of post-industrial and post-consumer plastic materials
- Generated laboratory scale high quality resins for food packaging applications
- Designed (and are building) a 25 kg/hr STRAP system at Michigan Tech University (with Ezra Bar-Ziv)
- Identified location to build first commercial STRAP system at Convergen Energy in Green Bay, WI
- Have industrial partners who want to help us commercialize or implement STRAP technology

2 Progress and Outcomes: Education and Outreach Logic Model



Inputs

- DOE CUWP Funding
- Center Cost Share
- CUWP Faculty
- CUWP Industry and National Lab Partners
- CUWP Graduate Students and Post Docs
- CUWP Undergraduate Students

Activities

- CUWP Seminar Series
- Plastics Recycling Curriculum Development and Integration
- CUWP Summer Research Program
- K-12 to Gray Public Outreach

Outputs

- Sharing of Current Research in Plastics Recycling
- New Plastics Recycling Curriculum for use in STEM and Engineering Courses
- Training Model for Undergraduate Research in Plastics Recycling
- Media and Outreach Materials on Plastics Recycling for K-12 and General Public

Short Term Outcomes

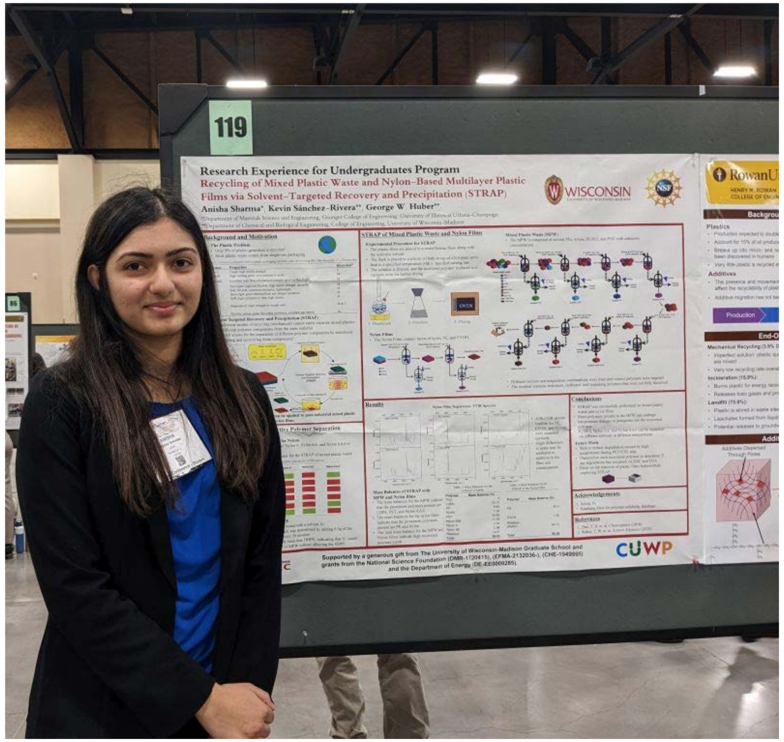
- Greater Understanding of Current State Plastics Recycling Research
- Increase in the Number of Undergraduate and Graduate Students Learning about Plastics Recycling
- Better Trained Students Participating in Undergraduate Research in Plastics Recycling
- Increased Interest in Undergraduate and Graduate Students in Plastics Recycling R&D Careers
- Sharing of Plastics Recycling Outreach and Media Materials with Community Partners
- Greater Understanding by the K-12 Students and the General Public about the Current State of Plastics Recycling

Long Term Outcomes

- Build an Effective Workforce Development Pipeline from K-12 to Graduate Education for Plastics Recycling
- Integrate Plastic Recycling into Undergraduate and Graduate Programs in STEM Disciplines
- Greater Understanding of the General Public about the Environmental and Economic Impact of Recycling Practices
- Providing Accurate Technical Information to Policy Makers and Business Leaders

Chemical Upcycling of Waste Plastics

2 Progress and Outcomes: 2022 CUWP REU Program Outcomes



Anisha Sharma Presenting her CUWP Summer REU Project at the AIChE Meeting

- Two CUWP REU students presented the outcomes of their REU projects at the Fall 2022 AIChE Student Conference.
- Anisha Sharma (Huber Group) won 3rd place in the Environmental Category for her poster on the STRAP
-

Question	Mean (Out of 5)
How much did you engage in real-world research?	4.8
How much did you feel part of a scientific community?	4.8
Gain in understanding what everyday research is like.	4.3
Gain in preparing a scientific poster.	4.7

> “The ability to travel to Madison and conduct research somewhere besides my home institution, as well as connecting with other undergraduates who are pursuing research careers.”

> “My mentor. She was so welcoming and made my experience great. She even went out of her way to include me in non-lab events since I did not have the same REU event/activities at ISU.”

3 – Impact

- Have completed all BP1 and BP2 milestones and verified them with verification team.
- Have had 23 industrial CUWP partners
- Published a comprehensive review on plastic recycling
- Seven published peer reviewed papers, five publications under review, three patent applications
- Understanding the sorting and characterization of plastic waste streams
- Understand the fundamental chemistry and reaction engineering for plastic thermal depolymerization
- Studied the catalytic chemistry of plastic pyrolysis oils over ZSM5
- Demonstrated STRAP with rigid film, printed flexible film, facemasks (moving towards commercialization)
- Estimated the economics of STRAP and pyrolysis technologies
- Integrated plastic recycling into curriculum at CUWP schools

3 – Impact Beyond the SOPO: Long term Goals for CUWP

- To become the global leader in plastic recycling technology research and development
- Bring in international partners
- Understand limitations and advantages of mechanical recycling
- Understand opportunities and limitations for improving MRFs and waste pickers
- Commercialize STRAP technology
- Develop fundamentals of plastic thermal depolymerization technologies
- Design new catalytic approaches to more easily convert plastic pyrolysis oils
- Develop educational materials for plastic recycling

Additional Slides

Responses to Previous Reviewers' Comments

- *Recommenations from BP2 Verification Visit Report: It is recommended to have more synergy between tasks and project teams. As mentioned above, it is critical to have more coordination between tasks 2, 3, 4, and 5 regarding critical properties of plastic feedstock and plastic oils impacting their conversion, especially around the catalyst stability for plastic oil conversion and solvent recovery for STRAP. It is also recommended to have more synergy between UW-Madison and ISU teams and more rigorous comparison between the two technologies. Selection should be made based on operation conditions, feedstock properties, and product requirement.*

- ➢ Some of the recommendations is based on work that will be accomplished next BP in the SOPO but has not been done yet.
- ➢ We have monthly Pyrolysis and STRAP meetings to coordinate our research. We also have other meetings as needed o better coordinate this effort. We have an annual CUWP meeting with entire team.
- ➢ Task 2 team addresses questions about the plastic feedstock and understands the performance/needs of the feedstock during the decomposition process. Task 3 team progress by UW, ISU and NREL is regularly updated to compare the results, coordinate the research plans, and discuss the challenges. Task 4 team presentations are included to help Task 3 to understand the pyrolysis oil performance during the catalytic upgrading process and product quality, and Task 2 team to better understand the impacts of the feedstock impurities on the products.
- ➢ The pyrolysis oils produced from ISU are sent to NREL and UW for the product characterizations and catalytic upgrading

CUWP has 8 Publications to date with several under review

1. Son Dong, Houqian Li, Iris K Bloede, Abdullah J Al Abdulghani, Edgard A Lebrón-Rodríguez, George W Huber, Ive Hermans, Catalytic conversion of model compounds of plastic pyrolysis oil over ZSM-5, Applied Catalysis B: Environmental, (2023) 324, 122219.
2. Konstantinos G Papanikolaou, Jiayang Wu, George W Huber, Manos Mavrikakis, Mechanistic Insights into the Pyrolysis of Poly(Vinyl Chloride), Journal of Polymer Research, (2023) 30, 1-16.
3. Cecon, Victor S., Greg W. Curtzwiler, and Keith L. Vorst. "A Study on Recycled Polymers Recovered from Multilayer Plastic Packaging Films by Solvent-Targeted Recovery and Precipitation (STRAP)." *Macromolecular Materials and Engineering 307.11 (2022): 2200346.*
4. Aurora del Carmen Munguía-López, Dilara Göreke, Kevin L Sánchez-Rivera, Horacio A Aguirre-Villegas, Styliani Avraamidou, George Huber, Victor M Zavala, Quantifying the Environmental Benefits of a Solvent-Based Separation Process for Multilayer Plastic Films, Green Chemistry, (2022)
5. Jiaze Ma, Philip Tominac, Olumide Olafasakin, Horacio Aguirre-Villegas, Mark Mba Wright, Craig H Benson, George W Huber, Victor M Zavala, Economic Evaluation of Infrastructures for Thermochemical Upcycling of Post-Consumer Plastic Waste, Green Chemistry, in-press.
6. Houqian Li, Horacio A Aguirre-Villegas, Robert D Allen, Xianglan Bai, Craig H Benson, Gregg T Beckham, Sabrina L Bradshaw, Jessica L Brown, Robert C Brown, Marco Antonio Sanchez Castillo, Victor S Cecon, Julia B Curley, Greg W Curtzwiler, Son Dong, Soumika Gaddameedi, John E Garcia, Ive Hermans, Min Soo Kim, Jiaze Ma, Lesli O Mark, Manos Mavrikakis, Olumide O Olafasakin, Tim A Osswald, Kostas G Papanikolaou, Harish Radhakrishnan, Kevin L Sánchez-Rivera, Khairun N Tumu, Reid C Van Lehn, Keith L Vorst, Mark M Wright, Jiayang Wu, Victor M Zavala, Panzheng Zhou, George W Huber, Expanding Plastics Recycling Technologies: Chemical Aspects, Technology Status and Challenges, Green Chemistry (2022) 24, 8899-9002 .
7. Kevin L Sánchez-Rivera, Panzheng Zhou, Min Soo Kim, Leonardo D González Chávez, Steve Grey, Kevin Nelson, Shao-Chun Wang, Ive Hermans, Victor M Zavala, Reid C Van Lehn, George W Huber, Reducing Antisolvent Use in the STRAP Process by Enabling a Temperature-Controlled Polymer Dissolution and Precipitation for the Recycling of Multilayer Plastic Films, ChemSusChem (2021) 14 (19), 4317-4329.
8. Panzheng Zhou, Kevin L Sánchez-Rivera, George W Huber, Reid C Van Lehn, Computational Approach for Rapidly Predicting Temperature-Dependent Polymer. Solubilities Using Molecular-Scale Models, (2021) ChemSusChem 14 (19), 4307-4316.

5 other publications are currently under review.

25+ Presentations at Companies, National and International Conferences. 3 Patent applications

Presentations

1. Greenebrg, Andrew; Barta Cheri; Design and implementation of a virtual undergraduate summer research program in the chemical sciences, San Diego, CA; March 22nd -24th ; 2022.
2. Ive Hermans, Pyro conference in Ghent (May 15, 2022).
3. Konstantinos Papanikolaou, ACS Spring 2022 National Meeting in San Diego, CA
4. H ouqian Li, The 27th North American Catalysis Society Meeting in New York (May 23, 2022).
5. Jiayang Wu, Konstantinos Papanikolaou, Feng Cheng, Bennett Addison, Amy Cuthbertson, Manos Mavrikakis, George Huber, Gregg T. Beckham. “The Chemistry and Kinetics of Polyvinyl Chloride (PVC) Pyrolysis” American Institute for Chemical Engineers Annual Meeting, Phoenix, AZ, November 14-18, 2022.
6. GW Huber, Disruptive Technologies to Improve the Sustainability of the Plastics Industry, University of British Columbia (January 20, 2023).
7. GW Huber, Solvent Targeted Recovery and Precipitation (STRAP): Recycling Multilayer and Mixed Plastics to Food Grade Resins, Invista, virtual talk (January 6, 2023).
8. GW Huber, Center for Chemical Upcycling of Waste Plastics, Green Bay Innovation Group , Amcor, Neenah, WI (October 25, 2022).
9. GW Huber, Disruptive Technologies to Improve the Sustainability of the Plastics Industry, Cornell (October 17, 2022).
10. Huber, G.W., Van Lehn, Reid., Center for Chemical Upcycling of Waste Plastics, Hoya Vision, Minneapolis, MN, March 26, 2022.
11. GW Huber, Center for Chemical Upcycling of Waste Plastics, Wisconsin Industry Printing Council Meeting (January 25, 2022).
12. GW Huber, Chemical Upcycling of Waste Plastics, BASF, New Jersey (December 3, 2022)
13. GW Huber, Disruptive Chemical Technologies for the Polymer Industry, University of Pittsburgh (October 1, 2021).
14. GW Huber, Disruptive Chemical Technologies for the Polymer Industry, Lahore University of Management Sciences, Punjab Pakistan (September 29, 2021).
15. GW Huber, Chemical Upcycling of Waste Plastics, Braskem, multiple international locations (May 11, 2021).
16. GW Huber, Chemical Upcycling of Waste Plastics, University of Oklahoma (April 14, 2021).
17. GW Huber, Chemical Upcycling of Waste Plastics, Mid-Michigan Chapter of American Institute of Chemical Engineers (March 10, 2021).
18. GW Huber, Chemical Upcycling of Waste Plastics, 3M, Minneapolis, MN (February 17, 2021).
19. GW Huber, Chemical Upcycling of Waste Plastics, DOW Chemical, Midland MI (January 21, 2021).
20. GW Huber, Pioneer Chemical Technologies to Improve the Sustainability of the Polymer Industry, 9th Bioenergy and Catalysis Research Unit Seminar, Thammasat University, Thailand (February 8, 2021).
21. GW Huber, Pioneer Chemical Technologies to Improve the Sustainability of the Polymer Industry, Advanced Materials Industry Consortium (AMIC), Madison, WI (January 21, 2021).
22. GW Huber, Chemical Upcycling of Waste Plastics, 48th Science and Technology for Advancing Technology Based Innovation, Walailak University, Thailand November 30, 2022.
23. GW Huber, Chemical Upcycling of Waste Plastics,World Plastic Summit, Monaco, March 24, 2022.
24. GW Huber, Chemical Upcycling of Waste Plastics, SPC Advance 2021, Sustainable Packaging Coalition, October 5, 2021.
25. GW Huber, Chemical Upcycling of Waste Plastics, 25th Annual Green Chemistry and Engineering Conference, June 16, 2021.

Patent Applications

- Three submitted patent applications related to CUWP activites.

Have finished Budget Period 2 (BP2) of contract

Current Contract	**Original Contract**
BP1: 10/1/2020 – 8/31/2021 (3.5 Qs)	BP1: Q1 (10/2020-1/2021)
BP2: 09/1/2021 – 3/31/2023 (7 Qs)	BP2: Q2-Q8 (1/2021-10/2022)
BP3: 03/31/2023-3/31/2024 (4 Qs)	BP3: Q9-Q12 (10/2022 – 10/2023)
BP4: 03/31/2024 – 09/30/2025 (6 Qs)	BP4: Q13-Q20 (10/2023-10/2025)

We are waiting for DOE to send us contract for BP3.