U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advancing Synergistic Waste Utilization as Biofuels Feedstocks:

Preprocessing, Coproducts, and Sustainability

Workshop Summary Report | April 14 – 15, 2021

Disclaimer

Preface

The U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of technologies to ensure domestic energy security, continued economic competitiveness, environmental sustainability, and the availability of cleaner fuels and power. The mission of the Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office (BETO) is to develop transformative and revolutionary sustainable bioenergy technologies for a prosperous nation. BETO develops technologies that convert domestic biomass and waste resources into fuels, products, and power to enable affordable energy, economic growth, and innovation in renewable energy and chemicals production. This report summarizes the results of a BETO-sponsored public virtual workshop held on April 14–15, 2021.

BETO would like to thank those who participated in the workshop.

Acknowledgments

BETO would like to thank all the participants who contributed invaluable experience and insights to making the Advancing Synergistic Waste Utilization as Biofuels Feedstocks: Preprocessing, Coproducts, and Sustainability Workshop a success.

This summary report was prepared by Chenlin Li and Lauren Illing, with contributions from Art Wiselogel, Mark Elless, Brianna Farber, Elizabeth Burrows, and Nichole Fitzgerald. The authors would like to sincerely thank the workshop participants for their contributions, which provided input for this publication. The full list of individuals who registered for the workshop is provided in Appendix B.

Workshop conceptualization and planning was led by Chenlin Li, with contribution and support from Nichole Fitzgerald, Mark Elless, Art Wiselogel, Elizabeth Burrows, Brianna Farber, and Lauren Illing. Lauren Illing led the stakeholder input session facilitation planning, including group discussion process, virtual format, and training the team of session leaders. Stacey Young conducted logistics planning for the initial in-person workshop date, as well as the postponed virtual workshop. Workshop scribes, who recorded workshop presentation and discussion highlights, were Alexander Jansen and Clayton Rohman.

We gratefully acknowledge the keynote speaker—JD Lindeberg, Principal and President at Resource Recycling Systems (RRS)—who discussed the current state of waste recycling for attendees. Additionally, we appreciate the panel participants who provided their expertise and insight to kick off each stakeholder input session (Table 1). Last but not least, we would like to thank the session rapporteurs who created and shared session summary presentations to their peers with quick turnaround (Table 1).

Table 1. Workshop Panelists and Rapporteurs

Stakeholder Input Sessions	Session Moderators	Session Panelists	Session Rapporteurs
Feedstock Preprocessing	Chenlin Li, DOE-BETO Mark Elless, DOE-BETO	Edward J. Wolfrum, National Renewable Energy Laboratory Jeff Lacey, Idaho National Laboratory Junyong Zhu, U.S. Department of Agriculture (USDA), Forest Products Laboratory Perry Toms, Steeper Energy	Jim Dooley, Forest Concepts
Coproduct Development	Art Wiselogel, DOE-BETO Elizabeth Burrows, DOE-BETO	Charles Tremblay, Enerkem William Orts, USDA Soydan Ozcan, Oak Ridge National Laboratory	Lynn Wendt, Idaho National Laboratory
Sustainability and Trade-Off Analysis	Brianna Farber, DOE-BETO Elizabeth Burrows, DOE-BETO	Shakira Hobbs, University of Kentucky Stacy Katz, WSP Jay Fitzgerald, BETO	Abigail Engelberth, Purdue University

List of Acronyms

BETO	Bioenergy Technologies Office
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FCIC	Feedstock-Conversion Interface Consortium
GHG	greenhouse gas
HTL	hydrothermal liquefaction
LCA	life cycle analysis
MRF	material recovery facility
MSW	municipal solid waste
PLA	polylactic acid
RRS	Resource Recycling Systems
USDA	U.S. Department of Agriculture

Executive Summary

On April 14 and 15, 2021, BETO hosted the public virtual workshop "Advancing Synergistic Waste Utilization as Biofuels Feedstocks: Preprocessing, Coproducts, and Sustainability." Recognizing the potential of using various components of municipal solid waste (MSW) streams for biofuels, biochemicals, and bioproducts, this workshop built on previous efforts in the research area by discussing challenges and opportunities to meet cost, quality, and sustainability targets for MSW utilization as a feedstock. This workshop invited stakeholders representing academia, industry, municipalities, and federal agencies involved in waste management, resource and energy recovery, waste utilization, and sustainability. A series of keynote presentations, plenary presentations, and stakeholder input sessions provided opportunities for sharing knowledge and establishing partnerships. This document provides an overview of the content discussed in the presentations, as well as a summary of the stakeholder input received during the session discussions. Key areas for consideration are discussed that may inform future research opportunities.

MSW represents a potential low-cost, abundant feedstock for producing fuels and products. The heterogeneity of MSW characteristics, including chemical composition and physical and biological properties, presents a significant challenge for utilization. BETO recognizes that waste streams are promising resources, but they must meet cost, quality, and sustainability targets for broad utilization.

This virtual workshop solicited input on a variety of topics: identifying technical challenges and opportunities associated with developing advanced preprocessing technologies, defining critical paths toward synergistic use of municipal solid waste streams for both conversion-ready feedstocks and valuable coproducts, and examining the economic viability and sustainability impacts of waste stream valorization. The keynote presentation speaker provided an overview of the current state of recycling; discussed the issues with evolving packaging waste streams, challenges in material recovery, recycling cost, global plastics waste, and sustainability; and provided insights in emergent needs of extended producer responsibility and top recycling trends in the next 10 years. The remaining presentations were arranged in three stakeholder input sessions: Feedstock Preprocessing, Coproduct Development, and Sustainability and Trade-Off Analysis. These panelists' presentations, as well as the diverse stakeholder perspectives, provided workshop participants with a shared understanding of the state of MSW preprocessing, coproduct development, and sustainability evaluation. Group discussion further enabled cross-pollination of ideas.

The preprocessing session addressed preprocessing challenges and opportunities relevant to biochemical and thermochemical conversion pathways. The workshop participants recognized that variability in MSW streams poses challenges on downstream conversion. Efficient and environmentally sound preprocessing technologies such as advanced mechanical/ thermochemical/biological/hybrid fractionation, densification, homogenization, storage, and decontamination need to be developed to improve the MSW purity, stability, and flowability

required for downstream conversion and address the environmental concerns. In addition, MSW preprocessing and conversion systems need to be developed considering the resource and waste management infrastructure at various scales, from small rural communities to mega-metro centers. Large-scale deployment needs to understand the relevance and leverage the existing material recovery facilities, depots, long-haul MSW transportation, and other logistic systems. It is also important to develop community-scale solutions with the involvement of local communities in rural areas in the decision-making process and address environmental injustice.

The coproduct development session recognized that the development of valuable coproducts offers promising opportunity to better utilize all fractions of MSW and improve the economic viability of biofuel conversion pathways. When developing coproducts, the quality attributes of MSW streams and the potential market size of the coproduct need to be considered. Future R&D requires improved efforts in characterizing properties of MSW fractions to identify and develop quality specifications, developing preprocessing strategies and processes to transform the low-quality MSW fractions into valuable coproducts, and evaluation of co-coproduct markets and the process economic and environmental sustainability.

The sustainability session set up a baseline of social, environmental, and economic sustainability indicators and associated impacts of MSW supply and preprocessing technologies; discussed existing data, tools, and capabilities; and, more importantly, identified research gaps and capabilities and tools needed to monitor environmental impacts. Participants recognized that a comprehensive set of sustainability indicators, data, tools, and modeling efforts are required to better understand and quantify the sustainability impacts of utilizing MSW streams.

The information and feedback gathered at this workshop will help DOE address the most critical barriers to using MSW for biofuels and bioproducts production. DOE's Bioenergy Technologies Office would like to thank all the participants for their valuable input.

Table of Contents

List of Figures

List of Tables

Introduction

The Challenge and the Opportunity

Municipal solid waste (MSW) accounts for nearly 40% of the total national biomass waste resource potential (54.8 million dry tons out of a total 142 million dry tons available at $84 or less per dry ton), according to the *2016 Billion-Ton Report*.[1] MSW is a meaningful source of low-cost biomass feedstock that can be potentially utilized for production of bioenergy and bioproducts; however, it also represents significant environmental liabilities in the forms of greenhouse gas (GHG) emissions, air and water quality impacts, and odors. MSW streams are diverse, including mixed commercial and residential garbage such as yard trimmings, paper and paperboard, plastics, rubber, leather, textiles, and food wastes. The generation of MSW has risen dramatically in the past 60 years in the United States, per data from the U.S. Environmental Protection Agency (EPA) (Figure 1).[2]

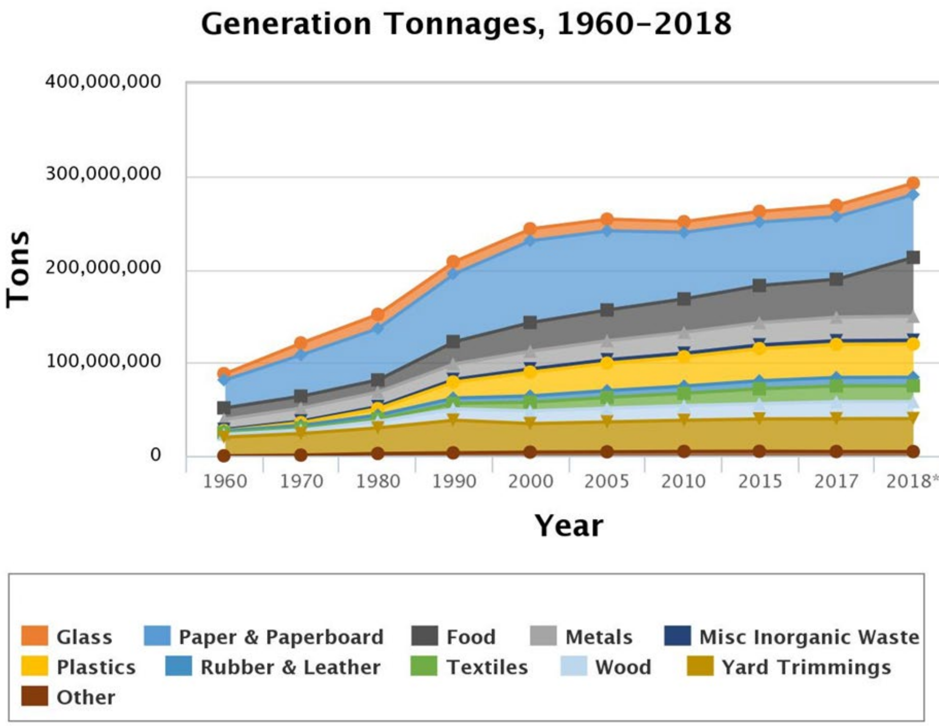

Figure 1. Municipal solid waste generation tonnages from 1960–2018 in the United States

[1] U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN.

[2] EPA. 2020. "National Overview: Facts and Figures on Materials, Wastes and Recycling." Last updated November 10, 2020. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials.

The total generation of MSW in 2018 was 292.4 million tons (U.S. short tons, unless specified), or 4.9 pounds per person per day.[3] Of the MSW generated, only roughly 94 million tons were recycled and composted—equivalent to a 32.1% recycling and composting rate—and only 34.5 million tons, representing 12% of total generated MSW, were combusted with energy recovery. In fact, 146.2 million tons of MSW, equivalent to 50.0% of total generated MSW, were landfilled in 2018, posing significant disposal and environmental challenges such as reduced land use capacity, increased tipping fees, increased GHG emissions, air and groundwater pollution and odor, and uncertainty of long-term landfill stability.

The nonrecycled portion of MSW that was landfilled contains large amounts of biodegradable components, as illustrated in Figure 2. These 2018 EPA data show that of all MSW landfilled, there were 35.3 million tons of food waste, 27.0 million tons of plastics, 17.2 million tons of paper and paperboard, 12.2 million tons of wood, 11.3 million tons of textiles, 10.5 million tons of yard trimmings, and 5.0 million tons of rubber and leather. All of these organic components represent potential sources of valuable materials for valorization.

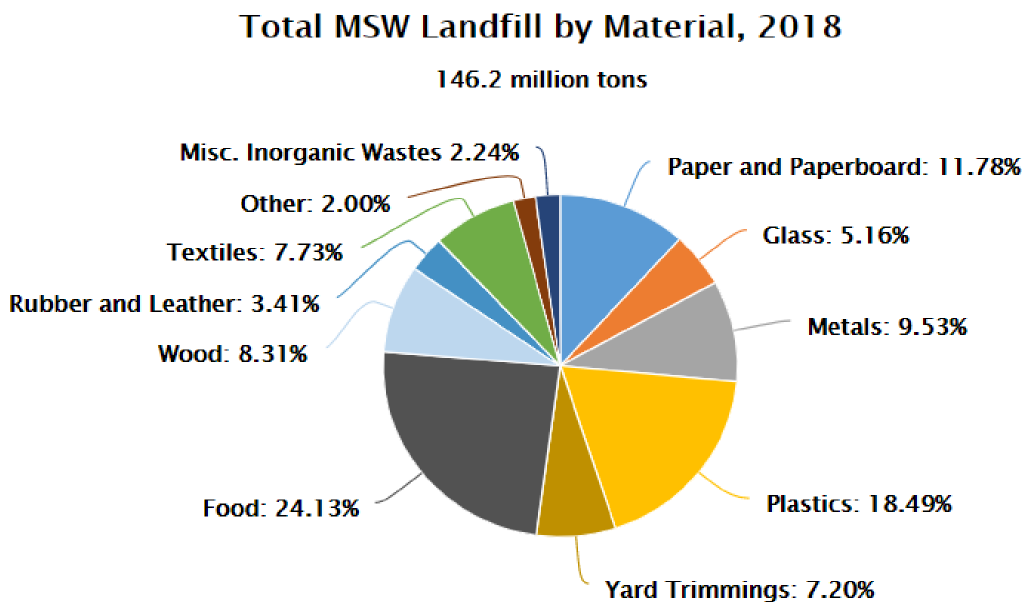

Figure 2. Distribution of material compositions in the landfilled MSW in 2018 in the United States

Source: 2016 Billion-Ton Report

Utilization of nonrecycled waste materials provides one promising pathway to shift the value of MSW from disposal and environmental challenges to a potential resource, both by developing technological advancements that enhance waste management and recycling systems and creating an economically viable and high-quality feedstock to produce bioenergy and bioproducts. Efficiently valorizing MSW is of interest to municipalities, academia, and industry. Increasing

[3] EPA. 2020. "Advancing Sustainable Materials Management: 2018 Fact Sheet – Assessing Trends in Materials Generation and Management in the United States."

waste utilization also aligns with the EPA's four-tiered waste management hierarchy and supports the goal of waste management to reduce the amount of disposable waste and preserve valuable limited landfill space.[4] Although using MSW has advantages in that there is extensive collection, transportation, and handling infrastructure in place—i.e., material recovery facilities (MRFs)—such infrastructure deals primarily with the waste volume and weight. The heterogeneity and variability in MSW streams are not being addressed in MRFs and remain significant technical barriers for using MSW as a bioenergy and bioproducts feedstock. R&D in waste recycling, preprocessing, and conversion is warranted to enable moving difficult components of the MSW streams to more preferred methods in the waste management hierarchy, from treatment and disposal to energy recovery and recycling. The U.S. Department of Energy (DOE) has been devoting efforts in MSW R&D areas, hosted several workshops, and published reports to outline strategies for improving economic viability of waste utilization.[5,6,7,8] Although R&D has started to characterize MSW across scales, develop rapid/real-time analysis techniques, and develop fractionation technologies to better separate MSW streams into distinct components, there are still gaps in MSW utilization for economic and sustainable technology development:

- Variability in MSW streams and influential MSW material attributes pose challenges for various conversion pathways (biochemical conversion vs. thermochemical conversion) and coproduct development.
- MSW decontamination, preprocessing, and formatting are required, and are specific to each conversion pathway.
- Sustainability impacts of MSW stream utilization require data, tools, and modeling efforts for thorough evaluation.

Workshop Objectives

MSW requires advanced preprocessing technologies to produce homogeneous feedstock streams for conversion into biofuels and bioproducts. Advanced physical, chemical, and biological preprocessing to reduce variability and remove harmful contaminants from MSW and other

[4] EPA. 2022. "Waste Management Hierarchy and Homeland Security Incidents." Last updated April 10, 2022. https://www.epa.gov/homeland-security-waste/waste-management-hierarchy-and-homeland-security-incidents.
[5] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE). 2019. *Waste-to-Energy from Municipal Solid Wastes*. Washington, D.C.: EERE. DOE/EE-1796. https://www.energy.gov/sites/prod/files/2019/08/f66/BETO--Waste-to-Energy-Report-August--2019.pdf.
[6] Bioenergy Technologies Office (BETO). 2020. *Plastics for a Circular Economy Workshop: Summary Report*. Washington, D.C.: BETO. DOE/EE–2074. https://www.energy.gov/sites/prod/files/2020/08/f77/beto-amo-mars-plastics-wksp-rpt-final.pdf.
[7] BETO. 2017. *Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities*. Washington, D.C.: BETO. DOE/EE-1472. https://www.energy.gov/sites/prod/files/2017/09/f36/biofuels_and_bioproducts_from_wet_and_gaseous_waste_streams_full_report.pdf.
[8] BETO. 2021. *Advancing the Bioeconomy: From Waste to Conversion-Ready Feedstocks Workshop Summary Report*. Washington, D.C.: BETO. DOE/EE-2312. https://www.energy.gov/sites/default/files/2021/02/f82/beto-municipal-solid-waste-report.pdf.

waste resources are critical steps to meeting key quality and variability specification necessary to produce conversion-ready feedstocks for conversion into biofuels and high-value coproducts.

For the purposes of the workshop, "MSW" refers to waste that is not considered or used for recycling, and is discharged from MRFs and disposed in landfills (e.g., nonrecycled paper and paperboard, plastics, yard trimmings, wood, food wastes, rubber and leather, textiles, and any relevant containments such as ash inorganic materials that could affect conversion of the MSW into a fuel and coproduct). Figure 3 provides the schematic flowchart of MSW supply, preprocessing, and utilization and outlines the focus of this workshop (as illustrated in light blue boxes) on preprocessing of nonrecycled MSW streams into conversion and coproduct development, as well as sustainability aspects along the MSW supply and utilization chain.

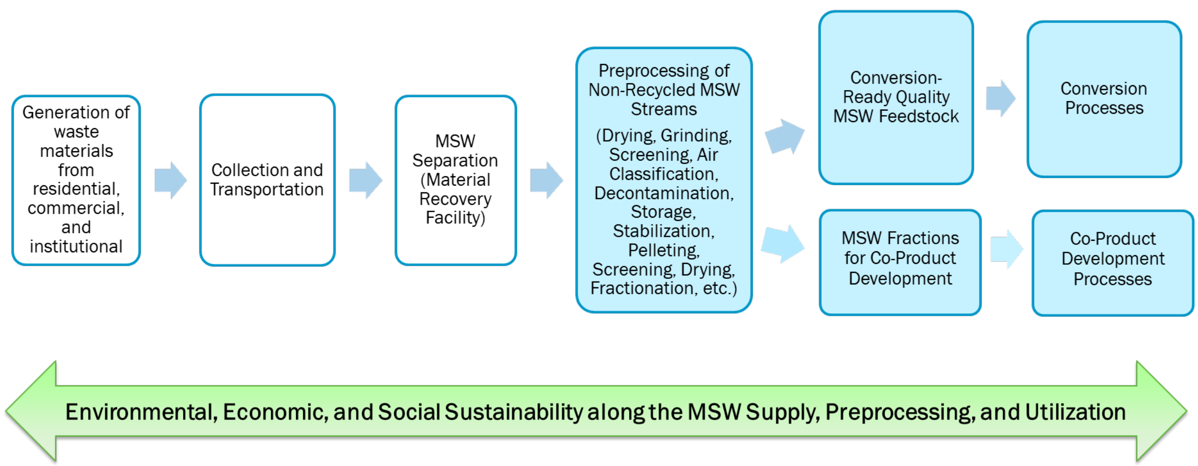

Figure 3. MSW supply, preprocessing, and utilization processes and sustainability aspects considered in the workshop

Specifically, the primary objective of the workshop was to have workshop participants consider and discuss the state of the art, gaps, challenges, and opportunities in the following areas:

- Developing advanced preprocessing technologies:
  - What knowledge can we learn and transfer from herbaceous and woody biomass for converting MSW into biofuels?
  - What are existing and new preprocessing technologies to address heterogeneity of MSW streams?
- Critical paths toward synergistic use of municipal solid waste streams for both conversion-ready feedstocks and valuable coproducts
  - What potential coproducts can be derived from MSW streams to maximize feedstock value?
- Economic and environmental viability and sustainability impacts of waste stream valorization

- What are potential environmental impacts and indicators of utilizing various streams of MSW to produce fuel and products?

Workshop presentations and stakeholder input sessions focused on advanced preprocessing, coproduct development, and economic and environmental viability and sustainability.

BETO Mission

DOE's Bioenergy Technologies Office (BETO) establishes partnerships with key public and private stakeholders to develop technologies for producing cost-competitive advanced biofuels from renewable biomass resources including cellulosic biomass, algae, and wastes. BETO's mission is to develop industrially relevant, transformative, and revolutionary bioenergy technologies to enable economically and environmentally sustainable, domestically produced biofuels for a prosperous nation.

The key activities of BETO are aimed at developing a viable, sustainable domestic biomass industry that produces renewable biofuels, bioproducts, and biopower; enhances U.S. energy security; provides environmental benefits; and creates nationwide economic opportunities. Meeting these goals requires significant and rapid advances in the entire biomass-to-bioenergy supply chain—from the farmer's field to the consumer.

Parallels Between Municipal Solid Waste and Biomass

BETO has developed tools and technologies for optimizing and reducing the variability of lignocellulosic biomass. Because of similar challenges with MSW concerning aspects such as temporal and geological variability, as well as different physical, chemical, and biological properties required by various conversion pathways, these tools and technologies can be applied to MSW. For example, chemical preprocessing and thermal preprocessing can improve energy content and organic contents and reduce moisture and contaminants. Sorting, sensing, and cleaning up diverse elemental composition such as nitrogen, sulfur, and ash speciation can improve the conversion readiness and quality of feedstocks. These technologies can address key feedstock challenges, whether derived from lignocellulosic biomass or MSW. An objective of this workshop was to understand synergies between technology development for biomass and for MSW, leverage existing preprocessing technologies and learnings on biomass, and identify gaps and opportunities for efficient MSW utilization.

Workshop Structure

The purpose of the virtual workshop was to bring together experts and stakeholders to discuss the current state of the art of MSW management and utilization and to explore the gaps, challenges, and opportunities in MSW preprocessing, coproduct development, and economic and environmental sustainability. This workshop builds on previous BETO-sponsored workshops focusing on wastes, such as "Plastics for a Circular Economy,"[9] "Biofuels and Bioproducts from

[9] BETO. 2020. *Plastics for a Circular Economy Workshop*.

Wet and Gaseous Waste Streams,"[10] and "Advancing the Bioeconomy: From Waste to Conversion-Ready Feedstocks."[11]

The workshop had 211 registrants, representing a wide range of stakeholders and experts (Figure 4).

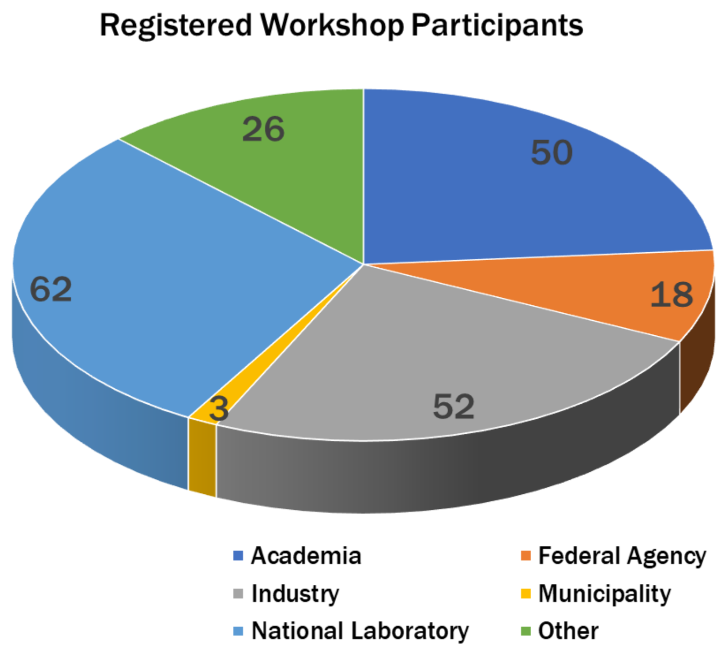

Figure 4. Workshop participants by sector

The workshop consisted of keynote presentations reviewing the current state of recycling, introducing BETO mission and Feedstock Technologies Program areas, as well as panel presentations discussing the state of the art, challenges, and opportunities in MSW preprocessing, coproduct development, and sustainability and trade-off analysis at the beginning of each stakeholder input sessions to inform the facilitated group discussion.

The structure and logistics of the workshop is summarized below:

Wednesday, April 14

- Morning: Introduction and Keynote Presentations
- Afternoon: Stakeholder Input Session #1 – Feedstock Preprocessing

Thursday, April 15

- Stakeholder Input Session #2 – Coproduct Development
- Stakeholder Input Session #3 – Sustainability and Trade-off Analysis

[10] BETO. 2017. *Biofuels and Bioproducts from Wet and Gaseous Waste Streams*.
[11] BETO. 2021. *Advancing the Bioeconomy*.

Each session included:

- Presentations from invited panelists.
- Moderated panel Q&A.
- Facilitated group discussion with opportunity for direct input via a web-based collaboration software X-LEAP.
- Discussion summary provided by rapporteur.

These presentations provided valuable framing and knowledge to inform stakeholder input session discussions focusing on the three critical areas and discussing the state of the art, gaps and challenges, and opportunities and prioritization of R&D.

Keynote Presentation: JD Lindeberg, Principal and President, Resource Recycling Systems (RRS)

State of Recycling – Q1 2021

The keynote presentation speaker, Mr. Lindeberg, provided an overview of the current state of recycling, market pressures, emerging policy changes, and opportunities for new technological innovations. He discussed the changes of recycling rates and evolving packaging waste stream from 1990 to 2015. Traditional recyclables (e.g., newspaper, glass containers, steel containers, aluminum containers) are declining, whereas plastics packaging (e.g., high-density polyethylene bottles, plastic containers, plastic bags, polyethylene terephthalate bottles and jars, plastic packaging corrugated cardboard) is increasing. The lightweight nature, large volume, and heterogenous properties of these materials have posed significant technical and economic challenges in material recovery. For example, the RRS data showed that the reduction of the feeding and separation throughput from 35 tons per hour in 2010 to 26 tons per hour in 2018 was caused by the plastics material property, requiring careful equipment design such as screen openings, air flow, and conveyor speeds. The material residue cost has tripled due to single-stream recycling, and almost 22% of material is not recyclable, leading to an increase in processing costs. The cost of well-run MRFs kept rising for a decade and began to stabilize to $82–$91 per ton in 2015–2020. The commodity revenue is critical to support processing costs, although the China policy on banning the import of recycled materials caused a significant drop in commodity revenue in late 2019 and early 2020. The single-stream recycling service remains popular, as evidenced by program numbers tripling in 15 years, more than doubling MRF capacity, and fast-growing new municipal services in the United States.

Mr. Lindeberg also provided his perspectives on top recycling trends over the next 10 years, including the regulatory strategies pushing packaging in North America, MRF automation and advanced sorting techniques in combination with artificial intelligence, increase of recyclables consumption worldwide, pressure on plastic grows, chemical recycling chimera, reuse coming back into focus, China fiber needs still dominating the market, and co-location of industrial-scale production and recycling facilities. He brought up the circular economy, as shown in Figure 5,[12] a vision shared across industries, nongovernmental organizations, and governments. The waste material supply, products and system design, and business model in the concept applies to a plastic economy. He commented that a plastic economy with a heavy focus on plastics results in global commitment and pacts, and that these commitments need to be translated into goals and actions across various stakeholders. Plastics have a long way to go to achieve circularity and are widely mismanaged, but fortunately regulatory responses and policies are catching up in many countries. In addition, the emergence of extended producer responsibility and policies and practice in which producers take responsibility for management of the products and/or packaging they produce at the end of their useful life become very important, and many states are adopting such policies. He envisioned that we would start seeing big companies come together to operate uniformly across the country.

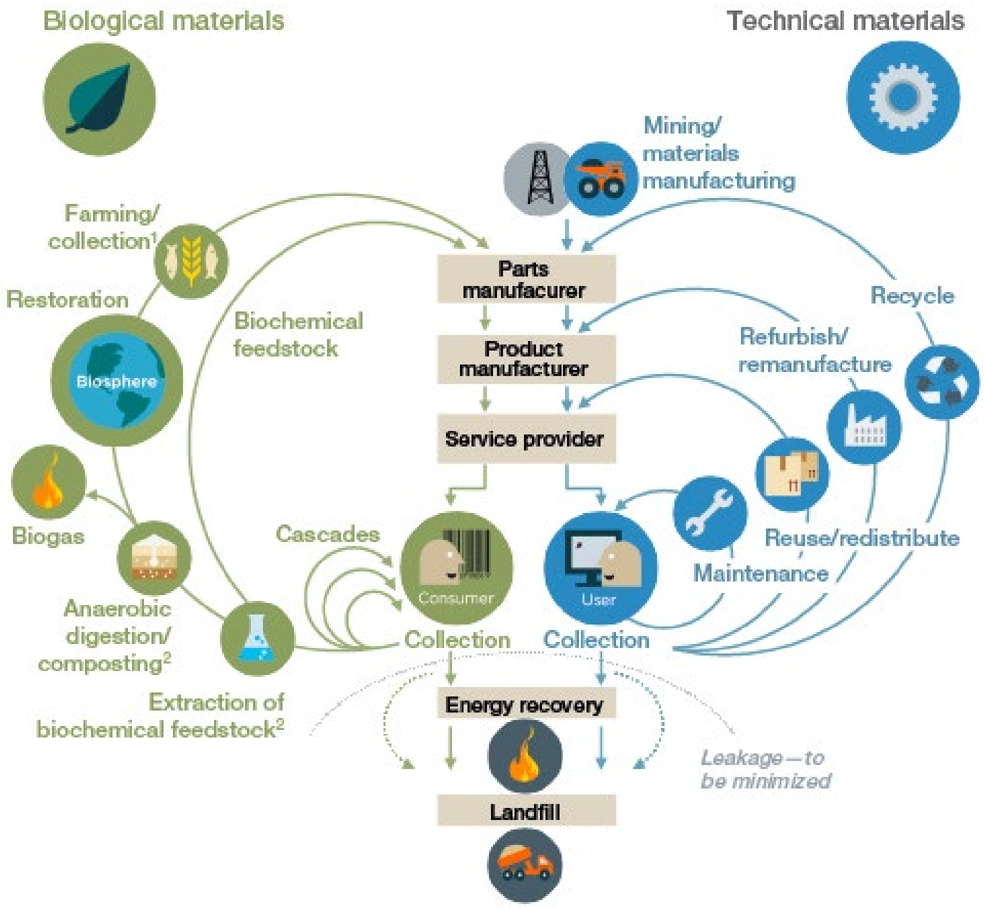

Figure 5. The circular economy

Source: Ellen MacArthur Foundation

[12] Ellen MacArthur Foundation. 2013. *Towards the Circular Economy: Economic and business rationale for an accelerated transition*. Cowes, UK: Ellen MacArthur Foundation. https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Session #1: Feedstock Preprocessing

Topic Overview

Feedstock preprocessing is the operation that transform raw, field-run lignocellulosic biomass into stable, standardized-format feedstocks with physical and chemical characteristics that meet the required quality specs of conversion facilities and that can be moved with existing high-volume transportation systems. Similar to lignocellulosic biomass such as corn stover and logging residues, MSW streams also have highly heterogenous characteristics that could pose significant challenges to downstream conversion, requiring preprocessing to produce conversion-ready feedstocks and ensure compatibility with conversion and utilization prior to delivery at the biorefinery.

The objective of the Feedstock Preprocessing session was to collect valuable input from panelists and stakeholders to identify known MSW fractions' starting quality attributes and compositions and what preprocessing technologies and associated performance parameters are needed to convert them into a feedstock. The preprocessing session had four invited panelists to discuss MSW quality attributes, lessoned learned from traditional lignocellulosic biomass, and opportunities for waste stream preprocessing technologies.

During the stakeholder group discussion session, valuable input was taken to understand feedstock quality targets, gaps, and opportunities in current preprocessing technologies. Building on information gathered at the fiscal year 2020 workshop, MSW material attributes were discussed to draw the link to different conversion pathways of interest, including gasification, fast pyrolysis, and alcohol-to-jet. The focus was on nonrecyclable organic fractions of MSW. Recyclable materials such as glass, metals, and paper were not included in the discussions.

Panelist 1: Edward J. Wolfrum, National Renewable Energy Laboratory

Lessons Learned in the Feedstock-Conversion Interface Consortium (FCIC)

Dr. Wolfrum is the principal investigator for the FCIC, a multi-lab consortium funded by DOE-BETO that is developing first-principles-based knowledge and tools to understand and mitigate the effects of biomass feedstock and process variability on biorefineries.[13] Dr. Wolfrum discussed key learnings from the FCIC on agriculture residues (e.g., corn stover) and pine logging residues:

- A quality-by-design approach enables the fundamental understanding of feedstock attributes, input and output streams, and unit operation.
- Critical material and quality attributes manifest differently at different scales, can skip unit operations, and can influence and be influenced by multiple unit operations.

[13] For more information about the FCIC, please visit https://www.energy.gov/eere/bioenergy/feedstock-conversion-interface-consortium.

- Investment in preprocessing, such as low-cost fractionation of various anatomical fractions and tissues, can yield dividends in downstream conversion.
- First-principles-based modeling tools and molecular dynamics simulation can predict material attributes and process parameters of preprocessing unit operations for performance optimization.
- Material wear in preprocessing equipment can be predicted and mitigated by advanced material characterization and experimentally validated mathematical models.

Figure 6. Molecular dynamics simulation (left) can predict material behavior and process parameters of and inform strategies for performance optimization of preprocessing unit operations. Corn stover anatomical fractions (middle and right) require advanced fractionation for downstream conversion.

Source: Dr. Edward Wolfrum and FCIC

The quality-by-design principles, understanding of material attributes, and knowledge and data generated on preprocessing unit operations and equipment wear within the FCIC can be leveraged into diverse MSW preprocessing steps to obtain quality feedstocks for downstream conversion.

Panelist 2: Jeff Lacey, Idaho National Laboratory

Development of a Deployable Plastic Sorting and Decontamination System

Dr. Lacey from Idaho National Laboratory presented a project funded by the Defense Advanced Research Projects Agency (DARPA) ReSource program on plastics sorting and decontamination. He first introduced the program, which aims to revolutionize how the military procures critical supplies on the battlefield by engineering self-contained, integrated systems that rapidly produce large quantities of supplies from feedstock collected on-site. The military applications include an expeditionary scenario that delivers new supplies out of wastes and a disaster recovery/stabilization scenario to respond to a natural disaster and manage supply and generated waste. Recognizing that current waste management strategies are to landfill and/or incinerate—with significant economic, environmental, and social challenges—Dr. Lacey's team is developing novel technologies and building systems to support stabilization/expeditionary scenarios by sorting waste into compatible bins and decontaminating and purifying waste into usable feedstocks for upcycling. Near-infrared sensors, in combination with predictive models and automated sorting, were developed and used to identify different types of plastics and paper wastes with high accuracy. They also developed a one-pot pretreatment and decontamination process that uses solvent (dimethyl ether) extraction to remove contaminants, inks, and plasticizers to obtain clean materials from the wastes.

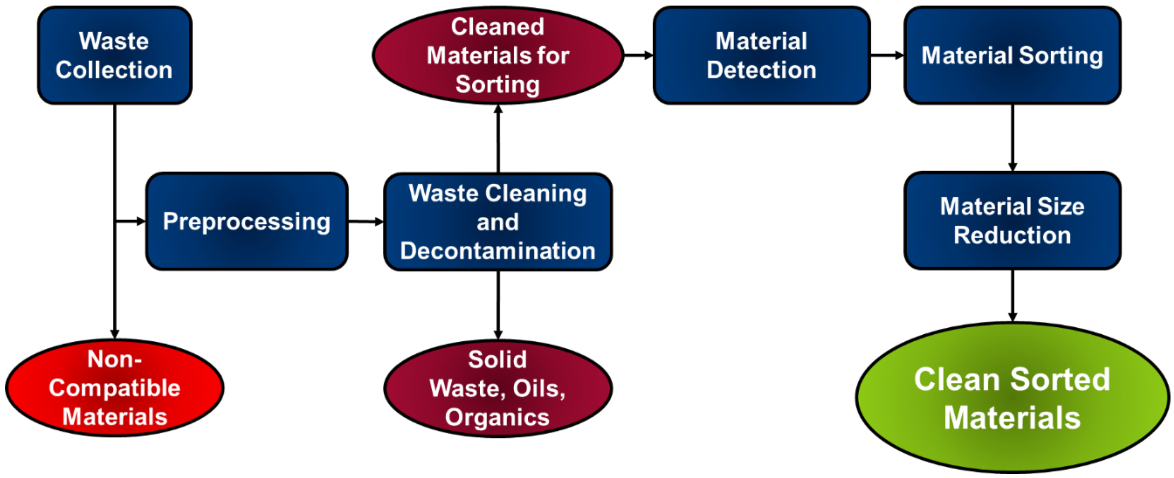

Figure 7. Sorting and decontamination system process flow for MSW

Source: Dr. Jeff Lacey

In addition to the ReSource project, Dr. Lacey also briefly talked about their collaborations with two BETO-funded projects:

1. With AMP Robotics on artificial neural network for MSW characterization by developing vision-based artificial neural network, X-ray fluorescence, 3D/depth imaging, and Raman spectrometer that can identify MSW material categories at 95% classification accuracy.
2. With UHV Technologies on advanced sensing for characterization and sorting of nonrecyclable plastics using sensor fusion with artificial intelligence. The extensive work demonstrated the importance of sensing technologies for MSW characterization and preprocessing technologies for separation to obtain clean, sorted fractions/materials.

Panelist 3: Junyong Zhu, U.S. Department of Agriculture (USDA), Forest Products Laboratory

Fractionation of MSW: What Can We Learn from Plant Biomass Biorefinery?

Dr. Junyong Zhu, a research general engineer from the Forest Products Lab at USDA, shared his knowledge and experiences with lignocellulose biorefineries that can be leveraged into MSW utilization. He stated that over 50% of MSW such as yard trimming, paper wastes, and food wastes are cellulose-rich materials and can be converted into sugars. Assuming most municipality areas generate 150–750 tons/day lignocellulosic MSW, determining the synergistic benefit by coprocessing MSW with local plant-biomass sources to address biomass logistics for a biorefinery should be considered.

MSW utilization has similar challenges as cellulosic biomass in materials. These challenges include heterogeneity, cellulosic accessibility, fractionation, and pretreatment impacts on downstream processing and conversion performance. Dr. Zhu used several case studies to demonstrate (1) the impact of materials drying time and temperature on enzymatic saccharification; (2) the effect of pelletizing pressure, temperature, and duration time on enzymatic accessibility and sugar yields; (3) hornification of cellulosic fibers in MSW could cause pore collapse and make the materials more recalcitrant to enzyme processing; (4) sorting and separation of cellulosic-rich materials from plastics is the key strategy for efficient MSW utilization; and (5) steam and physical size reduction may offer the most economical treatment for MSW bioconversion.

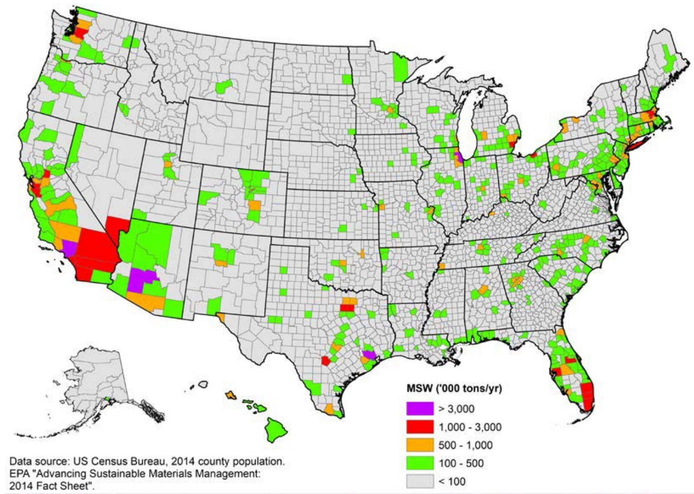

Figure 8. Quantities of MSW in the United States

Data Source: U.S. Census Bureau

Panelist 4: Perry Toms, Steeper Energy

Hydrofaction: Transforming Organic Waste into Advanced Biofuels and Other Valuable Resources

Mr. Perry Toms, CEO of Steeper Energy, talked about their proprietary Hydrofaction® technology that uses high temperature and high pressure to convert bio-organic waste residues to advanced fuels. This technology is a unique implementation of hydrothermal liquefaction, which applies supercritical water as a reaction medium for the conversion of biomass and organic wastes into high-energy-density renewable crude oil. The product from this technology is targeted at the heavy transport sector. The Hydrofaction Oil not only provides base input for renewable lubricants and fine chemicals, but also could be upgradable to on-road diesel, marine diesel, gasoline, and jet fuel. Steeper Energy is developing this technology to produce products like renewable bio-oil and fertilizers from forestry residues, sewage sludge, and biogenic MSW.

Mr. Toms discussed the evolving and tightening regulatory standards and the need to open opportunities for disruptive technologies concerning urban waste bio-organics, digestate disposal/management, nutrients recovery (e.g., N or P), and landfill controls. He also brought up public concerns on contaminants entering farming systems, air and water, incineration air emissions, endocrine disruptors from pharmaceuticals, microplastics, and heavy metals.

High contamination in the waste materials (such as protein and sulfur) can lead to specialized fuel upgrading that raises cost for target end markets, and sorting waste streams to create homogenous feedstock will help address quality and cost issues. Growing population and waste resources require new infrastructure. Steeper Energy is commercializing its technology for lignocellulosic biomass and bio-organic wastes for broad market acceptance of Hydrofaction-derived advanced biofuels.

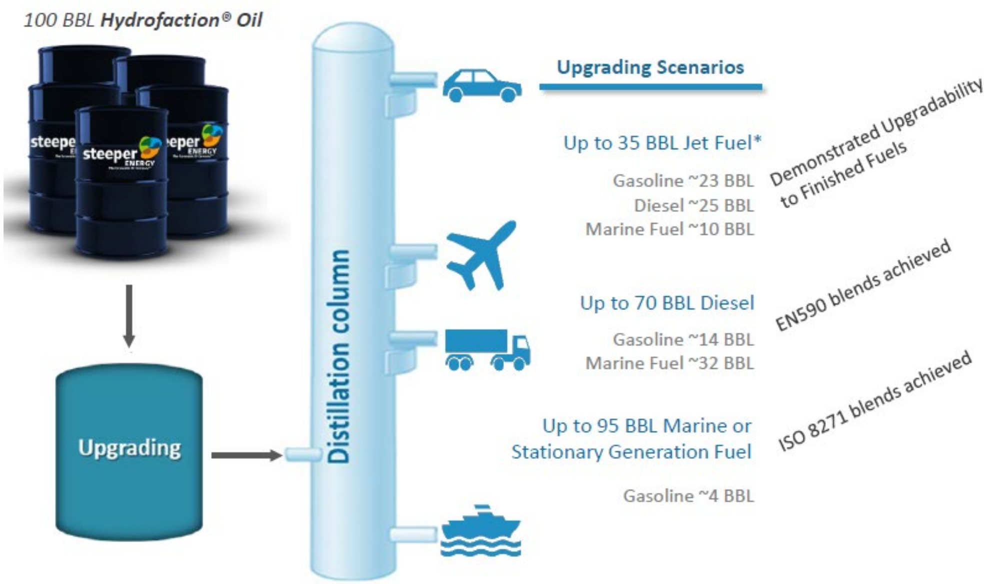

Figure 9. Steeper Energy's Hydrofaction Oil product and upgrading scenarios

Stakeholder Input Session #1: Feedstock Preprocessing Group Discussions

Objective

The objective of this stakeholder input discussion was to:

- Identify material quality attributes relevant to conversion technologies, including biochemical processes, gasification, fast pyrolysis, and hydrothermal liquefaction.
- Identify gaps, opportunities, and R&D priorities in preprocessing technologies to improve MSW quality to meet specifications for individual conversion pathways.

MSW Quality Attributes

The group discussed and recognized that many of the quality attributes, such as particle size and distribution, particle shape, moisture, chemical composition, and morphology, are important across conversion technologies, but each conversion technology will require different optimal ranges for quality attributes. Most of the preprocessing methods developed for biomass feedstocks could potentially apply to MSW and its fractions. Some MSW fractions (i.e., high-carbon-density plastics) are of sufficient value to justify methods such as advanced sensing, sorting and separation, and mechanical fractionation to get pure streams for valorization.

However, additional attributes and process parameters come into play for very heterogenous MSW that are different from traditional herbaceous and woody biomass. Unique MSW feedstock quality attributes associated with conversion pathways identified from the group discussion include:

- Contaminants and biohazards in MSW are critical issues for its conversion and utilization.
    - Materials highly contaminated by potassium, chlorine, sulfur, and proteins limit the efficacy of thermochemical conversion.
    - There is a lack of understanding on what contaminants may be toxic to enzymes and microbes in biological conversion processes.
    - Concerns of environmental problems caused by biohazardous materials and microplastics need to be addressed.
- Abrasives, glass fines, and fine metals in the MSW streams can differ significantly from soil environmental ash components of other traditional lignocellulosic biomass types.
- Bulk density of MSW is low when compared to other types of woody and herbaceous biomass, which can complicate feeding, storage, handling, and transportation processes and pose more challenges.
- Size uniformity, structural properties, flowability, feeding, and handling of heterogeneous MSW streams need to be carefully evaluated.
- Melting and volatilization temperature are different for the various MSW streams; for example, plastics in MSW may need to be separated from paper wastes and other cellulosic materials due to difference in response to temperatures, and plastics may get melted and cause plugging problems depending on the preprocessing technologies and conversion pathways.
- MSW variability could drastically change yield and quality of biofuels products, and critical quality attributes need to be explored to understand first principles around each fraction of MSW.
    - Fractions such as plastics that are not biologically convertible need to be separated and removed for thermochemical conversion.
    - High-moisture fractions such as food waste can be easily used in biochemical conversion and require separation at point source of generation to leave other suitable fractions for thermochemical conversion.

Gaps and Challenges of MSW Preprocessing Technologies

The group discussed specific conversion technologies applicable to post-sorting MSW utilization and agreed that all that apply to lignocellulosic biomass also apply to MSW fractions but will require preprocessing to improve the material quality and meet the conversion specifications. The discussion also focused on identifying the functions, benefits, and limitations of these preprocessing technologies for nonrecycled MSW, as well as the opportunities for novel and improved preprocessing technologies.

Table 2 represents a compiled list of preprocessing technologies and their detailed impacts on several conversion pathways including biochemical conversion, gasification, pyrolysis, and hydrothermal liquefaction (HTL) discussed at the stakeholder input session.

Table 2. Impacts of Preprocessing Technologies on Feedstock Quality and Conversion Pathways

Preprocessing Technologies	Conversion Technologies			
	Biochemical Conversion	**Gasification**	**Fast Pyrolysis**	**Hydrothermal Liquefaction**
Sorting and separation	Functions and benefits: Sorting and separating commingled MSW materials by methods including visual inspection, screens, eddy currents, shakers, magnetic Removing the problematic constituents such as chlorine, potassium, sulfur, proteins, and plastic to improve downstream conversion Separating food waste at the point of generation would add logistic complexity but could provide a benefit to HTL and biochemical conversion Existing sorting and separation technologies lack capacity to produce high-purity material streams to meet downstream conversion Feedstock specifications need to be explored to understand first principles around each fraction of MSW for optimization of sorting and separation process for specific conversion technology.			
Mechanical fractionation and size reduction	Functions and benefits: Unit operations include shredder, hammer mill, rotary shear grinder, knife mills, etc. Milling and shearing of MSW materials to obtain desired particle size and distribution. Size reduction may reduce moisture content. Size reduction helps some separation technologies. Limits: R&D has mainly focused on reduction and fractionation to obtain particle size. The impacts on other physical properties such as particle morphology, aspect ratio, cut surface structure, etc., needs investigations. Equipment wear is influenced by MSW properties and needs investigation on wear mechanisms and materials of construction. Impact of size reduction on properties at micro and molecular level needs investigation. Size reduction methods need to take into consideration MSW's unique qualities, high variability, and fibrous nature.			

Preprocessing Technologies	Conversion Technologies			
	Biochemical Conversion	**Gasification**	**Fast Pyrolysis**	**Hydrothermal Liquefaction**
	Functions unique to individual pathway: Increased surface-to-volume ratio improves the enzymatic digestibility and microbial fermentation performance. Requires mechanical fractionation and removal of non-convertible MSW fraction such as plastics.	Functions unique to individual pathway: Size reduction of MSW to uniformly sized particles is required for feeding and thermochemical conversion (heat and mass transfer, interaction with catalyst). Melting and volatilization temperature are different for the MSW components and can cause feeding issues. Further understanding of these differences needs to be obtained to develop separation methods. MSW variability could drastically change quality of bio-oil. Feedstock specifications need to be explored to understand first principles around each fraction.		Functions unique to individual pathway: Optimization of size reduction to obtain the desired particle size distribution and particle morphology depends on fluid flow considerations such as slurry dewatering, line size, pump type, etc. Fine particles can fill in the void spaces between large particles, thus improving solid loadings and impact handling. Limited knowledge about softer deformable solids during HTL process. Extrusion to produce long fibers may aid pumpability and require further investigation.
Thermochemical fractionation and preprocessing	Functions and benefits: Steam treatment and/or chemical treatment can sterilize the contaminated materials and swell cellulosic materials in MSW for better enzyme and microbial accessibility. Using high-pressure steam to fractionate plastics (based on different melting points) from paper could help the downstream conversion. Limits: Costly process using chemical at high temperature. Solvent recovery is needed to reduce cost.	Functions and benefits: Staged heating to melt and volatilize different MSW components at different temperature and pressure. There is a need for further R&D and cost evaluation of plasma technology in conjunction with thermochemical conversion process for process and environmental benefits of MSW utilization.		Functions and benefits: Low-temperature hydrothermal carbonization can homogenize heterogenous materials, increase energy density, and convert MSW into sterilized, value-added biochar. Multistage thermochemical preprocessing can target solubilizing a specific MSW fraction with an appropriate solvent/temperature and improve the yields of liquid intermediates for catalytic upgrading. Limits: Catalytic effects of MSW inorganics species on the HTL process are very limited and warrant more research.

<table>
<tr><th rowspan="2">Preprocessing Technologies</th><th colspan="4">Conversion Technologies</th></tr>
<tr><th>Biochemical Conversion</th><th>Gasification</th><th>Fast Pyrolysis</th><th>Hydrothermal Liquefaction</th></tr>
<tr><td>Biological fractionation</td><td colspan="4">Enzymatic or microbial approach could serve as a biological fractionation process to separate the heterogenous MSW streams, as enzymes and microbes are very selective and will digest what they can and leave the rest for downstream processing—e.g., separating plastics, metals, and glass from easily digestible carbohydrates. Plastics could be separated and enriched to use as gasification and pyrolysis feedstocks.
Could reduce mechanical sorting and separation cost.</td></tr>
<tr><td>Water or chemical washing</td><td>Functions and benefits:
Remove contaminants.
Separate high-moisture food wastes.
Could fit well with biological conversion that uses water.
Limits:
Water usage and energy consumption.
Hard to define the impact of washing on extent of nitrogen, sulfur, and alkali and alkaline earth metals removal in feedstock to meet the critical quality specifications for conversion.</td><td colspan="2">Limits:
Using washing will require energy-intensive dewatering/drying to reduce feedstock moisture content for pyrolysis or gasification.
Not a cost-feasible method for thermochemical conversion.</td><td>Functions and benefits:
Remove contaminants.
Separate high-moisture food wastes.
Could fit with hydrothermal liquefaction process.
Municipal wastewater can be additional water source for HTL process.
Limits:
HTL of MSW could require significant water addition.
Hard to define the impact of washing on extent of nitrogen, sulfur, and alkali and alkaline earth metals removal in feedstock to meet the critical quality attribute for conversion.</td></tr>
<tr><td>Dewatering and drying</td><td colspan="4">Functions and benefits:
Remove water and reduce biological, chemical, and mechanical deterioration.
Improve materials stability and reduce storage need.
Emerging method such as solvent-based drying with easily recoverable chemical like dimethyl ether may have good potential to reduce drying costs and lower process GHG emissions.
Limits:
Impact on the particle characteristics and morphology for downstream conversion performance.
High energy consumption.
Loss of volatile organic compounds and GHG emissions during high-temperature drying.</td></tr>
</table>

Preprocessing Technologies	Conversion Technologies			
	Biochemical Conversion	**Gasification**	**Fast Pyrolysis**	**Hydrothermal Liquefaction**
	High-moisture materials such as food waste can be used in biochemical conversion, and drying is not a strict requirement.	Requires a pre-drying step to ensure the material water content is less than 10%.	Requires a pre-drying step to ensure the material water content is less than 10%.	High-moisture materials such as food waste can be used in HTL process, and drying is not a strict requirement.
Densification	Functions and benefits: Unit operations include pellet mill, briquette press, cuber. Densify materials at elevated pressure and temperature to remove excess water and compress the biomass. Reduce transportation cost. Improve feeding and flowability. Increase bulk density and energy density. Highly controlled pellet size/density allow the easy design and optimization of the reactor system. Limits: Different compression characteristics of various MSW fractions need to be investigated to identify the optimal conditions. Densification is impacted by water content. Require mechanical fractionation and separation to reduce ash content and abrasion for densification and downstream process. High grinding and pelleting energy consumption. The structural characteristics of materials are altered and may increase required conversion time and impact mass and heat transfer.			
	Act as a mild thermochemical pretreatment that can alter the structural characteristics of materials. Densified biomass materials can fall apart easily in liquid streams and show slight increase in pretreatment and enzymatic hydrolysis performance, but very limited information on densified MSW materials flowability and conversion performance.	Densified MSW is used in gasification to improve the flowability and reduce abrasive wear in gasifier. Need to understand the densification impact on reaction chemistries of various components of MSW, and mass/heat transfer properties of densified pellets.	Need to understand the densification impact on reaction chemistries of various components of MSW, and mass/heat transfer properties of densified pellets. Pellets typically need to be crushed before feeding into reactors such as fluidized bed reactors or entrained flow reactors.	Very limited information on densification impact on material flowability and conversion performance of HTL process.

<table>
<tr><th rowspan="2">Preprocessing Technologies</th><th colspan="4">Conversion Technologies</th></tr>
<tr><th>Biochemical Conversion</th><th>Gasification</th><th>Fast Pyrolysis</th><th>Hydrothermal Liquefaction</th></tr>
<tr><td>Torrefaction</td><td>Not applicable</td><td colspan="2">Functions and benefits:
A mild form of pyrolysis at mild temperature (200°C–300°C).
Reduce moisture content, improve grindability and flowability, increase energy density.
Change biomass properties, remove chlorine, increase O/C ratio, and provide better fuel quality for gasification or combustion.
Torrefaction combined with densification creates energy-dense and stable feedstocks.
Limits:
Torrefaction off-gassing could require a significant air permit process for large scales.</td><td>Limited information, not an applicable preprocessing method.</td></tr>
<tr><td>Blending and homogenization</td><td colspan="4">Functions and benefits:
Blending of MSW with lignocellulosic materials could offer advantages in handling and processing and provide a path to greater consistency, regardless of conversion technologies.
Allow for achieving the required in-feed specifications for conversion and offer the potential for feedstock quality upgrades and reduced variability.
Limits:
Add more complexity to the heterogenous nature of MSW streams.
Rheology profiles at feedstock blend ratios and various temperatures needs to be investigated.</td></tr>
<tr><td>Storage and quality preservation</td><td colspan="4">Function and benefits:
Storage allows the year-round supply of sufficient quantities of quality feedstock.
Quality preservation and moisture management during storage are critical to avoid dry matter loss and biological degradation.
Limits:
MSW materials long-term storage and quality preservation strategies are limited and warrant detailed investigation.
Storage conditions alter physical, chemical, and biological properties of materials and downstream flowability, so holistic process study is essential.
Safe and efficient operations and processes need to be developed.
Environmental problems need to be taken into serious considerations for storage operations.</td></tr>
</table>

As summarized in Table 2, some existing preprocessing technologies can be used to improve MSW materials but are limited in addressing unique quality characteristics. In addition, advanced preprocessing R&D is required to meet quality specifications for specific pathways. These major advanced preprocessing methods include:

- Advanced mechanical, thermochemical, and biological fractionation technologies to separate high-purity stream from heterogenous MSW materials to meet quality specifications for a desired conversion pathway.
- Material handling of heterogenous MSW and its fraction in both dry and wet streams needs to be improved via characterization of materials properties and flow behavior in conjunction with predictive modeling tools.
- Densification offers benefit of improved flowability and reduced transportation cost but requires fundamental understanding of materials property alteration and reaction chemistry related to downstream conversion conditions.
- MSW decontamination requires the development of efficient sorting, separation, advanced dewatering/drying, fractionation, homogenization, and storage to preserve feedstock quality for downstream conversion and environmental concerns.
- Instead of presorting and separation, biological or chemical preprocessing or hybrid technologies may be adapted for use at different stages on the whole input of MSW—for example, digestion of carbohydrate components into soluble fraction, remove, and then continue with removal/sorting/processing of other fractions. These approaches can take advantage of staged conversion process products (i.e., soluble sugars) to enable easier separation.
- MSW temporal variability over days, events, seasons, years, and decades needs to be taken into consideration when developing the advanced preprocessing methods.

The stakeholder input session also discussed the path forward to scale-up and technology deployment. They noted that MSW preprocessing and conversion systems need to be developed considering the resource and waste management infrastructure at various scales from small rural communities to mega-metro centers. It was noted that the industry cannot afford to aggregate from all communities, which can contribute to environmental injustice, in that not all communities receive the same waste management services or are overburdened with waste and waste management infrastructure. The group identified priority gaps and research questions related to MSW infrastructure to be addressed in future R&D, including:

- Relevance of local existing infrastructure such as MRFs, depots, MSW transportation systems, and other techniques for MSW utilization from multiple MSW sources.
- Role/opportunity for mining existing landfills to capture carbon and recyclables and to extend landfill life.

- Development of community-scale solutions for community-scale resources will need to involve local communities in the decision-making process more than a typical biorefinery because waste movement and aggregation introduces different environmental concerns.
- Regional depots for preprocessing could be an important strategy to capture MSW in rural areas that generate small volumes of MSW.
- Develop MSW databases and standardized protocols that support reproducibility in unit operations R&D, piloting, and feedstock characterization to enable more reliable biorefinery scale-up.
- Develop approaches to integrate renewable fuels and bioproducts from MSW with sectors of the waste industry

Session Summary

The key takeaway from this stakeholder session is that some existing preprocessing technologies could be used to improve the MSW materials but are limited in addressing some unique quality characteristics to meet specific conversion pathway requirements. More efficient methods of preprocessing such as advanced mechanical/thermochemical/biological/hybrid fractionation technologies, densification, homogenization, storage, and decontamination need to be identified and developed to improve the MSW purity, stability, and flowability required for downstream conversion and address the environmental concerns. In addition, MSW preprocessing and conversion systems need to be developed considering the resource and waste management infrastructure at various scales from small rural communities to mega-metro centers. Large-scale deployment needs to understand the relevance and leverage the existing MRFs, depots, and long-haul MSW transport to utilize large quantities of MSW resource in the United States. It is also important to develop community-scale solutions with the involvement of local communities in rural areas in the decision-making process and address environmental injustice in MSW utilization.

Session #2: Coproduct Development Panel Presentations

Topic Overview

MSW materials and low-quality MSW fractions that do not meet biofuel conversion feedstock specifications could be a potential resource for coproduct development. Feedstock is typically the costliest component of a conversion facility’s operational cost. Using all the feedstock coming into a facility for its highest value is key to economic success. Coproduct development is a strategy to increase feedstock value and advance the viability of biofuels from these waste resources. BETO’s Feedstock Technologies Program is working to verify coproduct technologies that utilize fractions of biomass derived from preprocessing to produce a 10% increase in total feedstock value by 2025. The objective of this Coproduct Development session was to collect input from panelists and stakeholders to identify promising potential coproducts and the associated R&D needs that could ultimately increase the viability of biofuels from MSW.

Panelist 1: Charles Tremblay, VP, Enerkem

Feedstock Coproduct Development Opportunity

The first presentation in Session 2 came from Charles Tremblay, VP of Project Delivery at Enerkem. The presentation focused on the feedstock coproduct development opportunity at Enerkem's gasification facilities. The company views gasification as a complement to mechanical recycling because the technology is capable of producing near-virgin-grade polymers from after-use plastics, a resource with large availability. It is estimated that the global plastics recycling rate is only 12%. Enerkem's Edmonton facility was able to demonstrate the ability to produce stable, clean syngas from a wide range of feedstocks including mixed solid waste, biomass, and mixed plastics. In the process, they learned how certain feedstocks react in the gasification system and what treatment downstream was required. Key feedstock requirement drivers are caloric value, inert percentage, moisture content, density, and biogenicity. The syngas produced can then be used to create methanol, ethanol, or other products following a Fisher-Tropsch platform. The biofuel market targeted by Enerkem is driven by the carbon economy that is continuing to grow through carbon recycling and product incentives. Companies today are under immense pressure to reduce their carbon footprint. Those that are unable to mechanically recycle their product are often looking for byproducts to improve the recovery of carbon in their product. Enerkem has partnered with Shell and Suncor, among others, to build the world's largest waste-to-methanol-and-ethanol facility in Montreal, Canada. This plant will be able to convert over 200,000 tonnes/year of nonrecyclable waste and residual biomass into biofuels, resulting in over 125 million liters of fuel. The greenhouse gas reduction will be equivalent to taking 50,000 vehicles off the road annually.

Panelist 2: William Orts, USDA

Optimizing Biorefinery Infrastructure Toward "Zero-Waste" Agriculture

The second presentation in Session 2 came from William Orts of the USDA Western Regional Research Center. The presentation focused on the optimization of biorefinery infrastructure toward "zero-waste" agriculture. Dr. Orts explained that, as it currently stands, there is a disconnect getting the feedstock to the conversion technology. We have good knowledge in infrastructure and collection and in conversion technology individually but are currently lacking in connecting the two. One of the causes of this disconnect lies with the locations of existing biorefineries. Unlike traditional oil refineries that are located in population-dense areas, U.S. ethanol plants are located in more rural areas, where the corn is. Utilizing MSW as a feedstock in these biorefineries would require transportation over large distances from the population-dense, waste-generating areas. A proposed solution to help solve this issue is to turn landfills into biorefineries, or as the USDA team refers to it, "energy parks." Their research utilized an autoclave system to steam clean the MSW at 125°C for 20 minutes. The material is then screened, resulting in 75% cellulosic fraction in material less than 2 cm in size—a very cheap source of cellulose when the landfills in California are paid $50–$75/ton to take the waste. This cellulosic material can easily be converted into paper and packaging products.

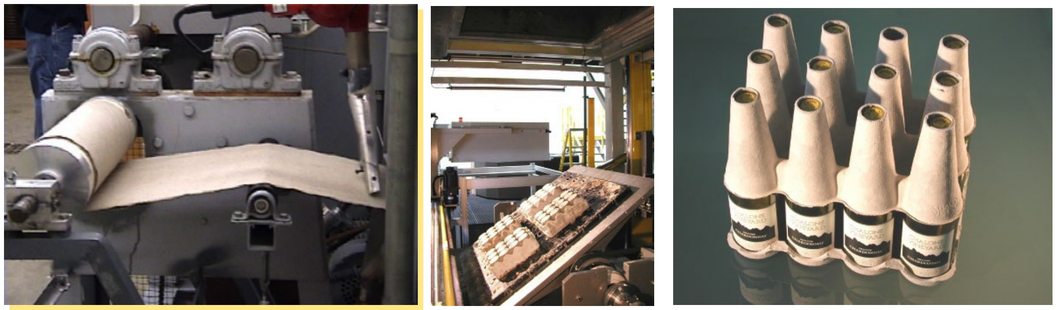

Figure 10. Processed paper and packaging products from MSW-derived fiber materials

Photos from Williams Orts, USDA

In terms of ethanol production, the team was able to produce 70 gallons per metric dry ton of autoclave pulp. Alternatively, the team investigated an anaerobic digestion route to create biomethane. The method resulted in 155 ethanol-equivalent gallons of methane per metric dry ton, or 99 diesel-equivalent gallons per metric dry ton. Most recently, the team has partnered with Mango Materials to biologically create polyhydroxyalkanoates from the biomethane. Polyhydroxyalkanoates have very similar properties to polypropylene and can be used to create fibers for many biodegradable products, creating a circular economy with the landfills. The presentation was concluded with a few takeaways. Biorefineries do not need to be built from scratch—they can be created at locations like landfills, wastewater treatment facilities, and large food processing plants. There will be no single answer to optimizing the biorefinery. Solutions will be regional and based on the resources available. Lastly, multi-institutional collaboration across industries, agencies, and regulators will be essential to move the technology forward.

Panelist 3: Soydan Ozcan, Oak Ridge National Laboratory

Maximizing the Value of Biofuel Feedstock Through Diverse Applications

The third and final presentation in Session 2 came from Soydan Ozcan, Thrust Lead at Oak Ridge National Laboratory's Manufacturing Demonstration Facility. The presentation focused on maximizing the value of biofuel feedstock through diverse applications. One of these applications is creating polymer composite feedstocks. Composite materials that have reached the end of their useful life, like wind power blades and automotive and aircraft parts, can be recycled for future use through the development of next-generation composites recovery technology, such as gasification or pyrolysis, enabling a circular economy. Specifically, carbon fiber waste scrap could amount to up to $2 billion in carbon composites by 2040, and recycling this could save 3.8 trillion Btu of energy from normal production. The team has been able to create Class A finish automotive parts with similar strength characteristics compared to those made from virgin carbon composites. The team has also shown the advantages of using carbon fiber to reinforce polymers used in large-scale 3D-printing applications. Using this method, molds can be printed for use in concrete casting. Similarly, the team has shown that biomass, such as poplar and bamboo, can be used to replace carbon fiber in composites that do not have as high of a tensile strength requirement. Using these materials can significantly decrease production energy requirements, carbon footprint, and cost.

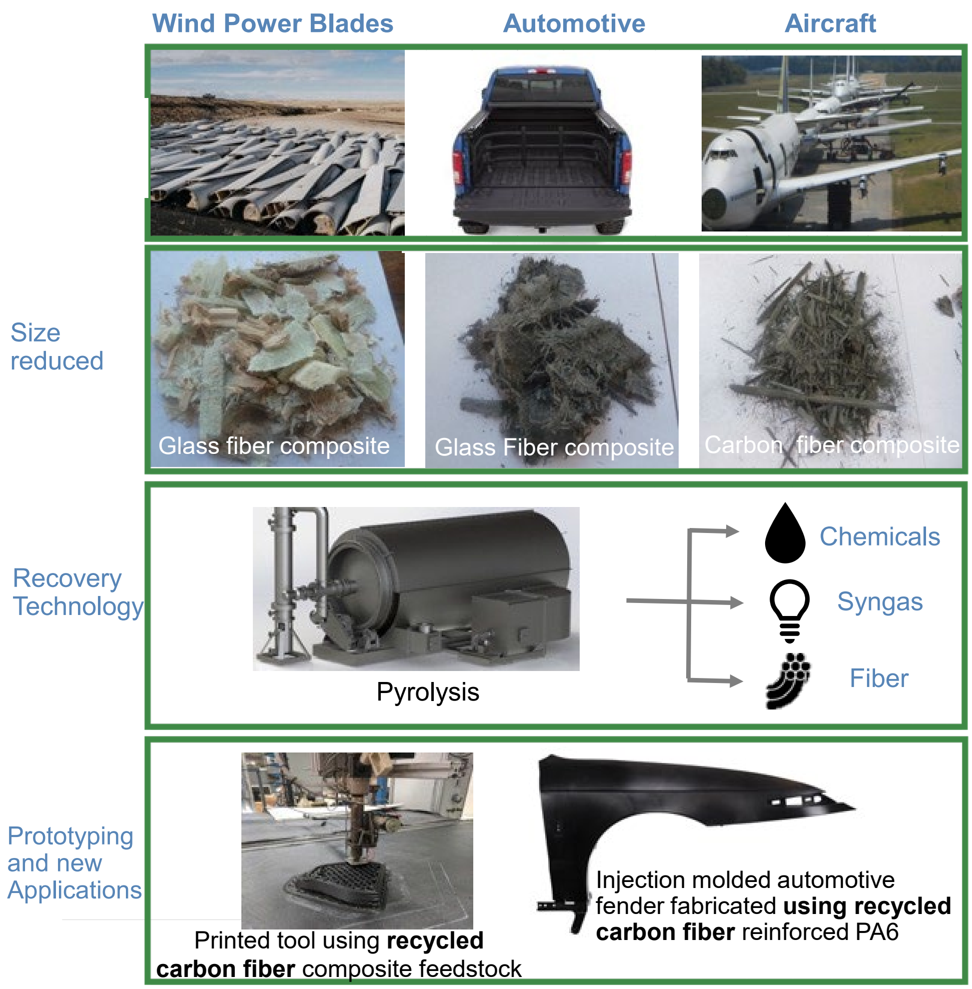

Figure 11. Value-added recycled feedstocks from waste composites for diverse applications

Photos from Ozcan Soydan, Oak Ridge National Lab

Stakeholder Input Session #2: Coproduct Development

Objective

The objectives of this stakeholder input discussion were to:

- Identify viable opportunities for coproduct developments from MSW low-quality fractions.
- Identify the next-step R&D that can advance viability of biofuels from MSW through coproduct development.

Opportunities of Low-Quality MSW Fractions for Coproduct Development

For a conversion facility to be economically viable, it is necessary to ensure that feedstock components that cannot be used for biofuel production could be used to make valuable coproducts. Coproduct development is a strategy to increase feedstock value and advance the viability of biofuels from the MSW resources. Feedstock is typically the costliest component of a conversion facility's operational cost. Finding uses for all portions of the feedstock coming into a facility is key to economic success. Developing high-value, non-fuel coproducts from low-quality MSW fractions (e.g., fractions separated prior to the conversion reactor throat that do not meet the quality specifications for biofuels production) will improve the economic viability of biofuel conversion pathways.

This stakeholder group discussed potential coproducts that could be recovered from preprocessing of the raw low-quality MSW materials. Table 3 is a compiled list of the potential coproducts, required preprocessing technologies, and market evaluation. Their potential annual market size in the United States is discussed in three categories: large (i.e., billion tons), medium (i.e., million tons), and small (i.e., hundreds of thousands of tons).

Table 3. Potential Coproducts of Interest, Technologies, and Market Evaluation.

Coproduct Types	Technologies	Market Size	Market Application
Fibers from paper and paperboard waste	Sorting and separation	Medium	Nondurable goods and packaging materials
High ash fractions, dirt, rocks from MSW contaminants	Sorting and separation, gasification, pyrolysis	Large	Cement, building materials, paving materials
Composites	Sorting and separation, mechanical and chemical fabrication, molding, compression, extrusion, injection	Large	Building materials, adhesive industry, automotive industry, manufacturing industry
Extractives from yard wastes and cellulosic materials of MSW—i.e., sugars, oils, terpenes, polyphenols, tannins, flavonoids, essential oils	Mechanical and chemical fractionation	Small	Chemical commodities
Plastics, packaging materials	Sorting and separation, mechanical, chemical, and biological fractionation	Medium	New and useful plastic commodity products
Protein and nutrients from food waste	Sorting and separation, mechanical, chemical, and biological fractionation	Large	Animal feed
Biochar	Thermochemical processes—i.e., pyrolysis, torrefaction, hydrothermal carbonization, gasification	Medium	Soil amendments and carbon sequestration

Several emerging coproduct opportunities were also brought up—including high-surface-area carbon materials to use as water absorbents, macronutrients, plastics resin, medical composites, and green hydrogen—but knowledge and information is relatively limited to develop these coproducts from MSW, and further R&D is needed.

In addition, this group also discussed technology readiness levels of various coproduct technologies. They recognized the animal feed derived from food waste is at high technology readiness level, and there is a need to hand off to the private sector for large-scale demonstration and market deployment. Mechanical compression and molding of waste materials to make valuable composites are also being developed by the manufacturing industry.

Coproducts derived from cellulosic fibers, extractives, plastics, packaging materials, and biochar coproducts require significant R&D to develop efficient processes and improve the material properties to meet specifications for their applications. It is important to establish collaboration between academic professionals/scientists and industry experts/corporations in these research areas.

Opportunities to Adopt Coproduct Development along with Biofuel Feedstocks

This group also recognized the importance of environmental and economic considerations to adopt coproduct development technologies and improve the economic viability of biofuel conversion pathways. Some key drivers and roadblocks discussed during the session are summarized below:

Environmental Drivers

- Reuse of carbon and other materials rather than obtaining most products from virgin resources.
- Creation of a market for waste plastics and paper, which could reduce leakage into the environment.
- The acute need to reduce material going to the landfill in some regions of the United States.
- The need to differentiate fossil vs. biogenic carbon sources for accounting purposes.

Environmental Roadblocks

- The desire for the perfect solution, versus an improvement over the current business-as-usual.
- Any technology that further increases the entropy of plastic particles and microparticles is a non-starter.
- Require energy- and material-efficient technologies and operations for collection, sorting, and preprocessing of nonrecyclable, biogenic MSW streams at commercial scale.

- Reintroducing MSW-derived products into the biosphere (chicken feed, soil amendments) may have higher concerns regarding the bioaccumulation of contaminants than for MSW-derived fuels and chemicals, which will require a holistic analysis.
- In many regions of the United States, land is cheap/available and there is no incentive to reduce the amount of material going into landfills.

Economic Drivers

- For the coproduct from the waste upstream handling process, we will need to start somewhere; if there is not much data available, it is challenging to evaluate the economic drivers/roadblocks.
- Policy can provide an economic driver.
- Extended producer responsibility would greatly drive this field.

Economic Roadblocks

- MSW handling is controlled by a relatively small number of large companies. This may not be a roadblock, but the big players need to be involved.

Policy Considerations

- Getting sustainability credits for MSW utilization is harder than for biomass utilization.
- Policies that do not accept MSW as a feedstock (e.g., EPA Renewable Fuel Standard), or rather, the approval process is onerous and requires very expensive, not necessarily scientific-based requirements to prove that only the cellulosic portions are being used. This is an example of perfect requirements hindering the good.
- Require incentivization for companies to change from the status quo to better utilize MSW.

Major R&D Priorities

Major R&D priorities and key takeaway message discussed at this session include:

- Develop sorting, separation, and preprocessing strategies to isolate low-quality fractions upstream for coproducts development.
- Advanced materials characterization method to identify and develop quality specifications for all coproducts.
- Develop mechanical, thermal, chemical, electrochemical, or biological processes to transform the low-quality MSW fractions and enhance their formulation to produce the valuable coproducts.
- Coproduct development must accompany reasonable market analysis and life cycle analysis (LCA) to evaluate the market application potential and economic and environmental sustainability impacts.

Session Summary

In summary, participants emphasized that development of valuable coproducts offers promising opportunity to better utilize all fractions of MSW and improve the economic viability of biofuel conversion pathways. Future R&D requires improving efforts in characterizing properties of MSW fractions to identify and develop quality specifications, developing preprocessing strategies and processes to transform the low-quality MSW fractions into valuable coproducts and evaluating both the co-coproducts market and the process economic and environmental sustainability.

Session #3: Sustainability Trade-Off Analysis Panel Presentations

Topic Overview

The objectives of this sustainability session were to seek input from panelists and stakeholders to (1) identify environmental impacts associated with various MSW fractions (supply), (2) identify environmental impacts of various preprocessing technologies (logistics), (3) identify metrics/tools for measuring and tracking environmental sustainability impacts of MSW utilization, and (4) identify needed R&D to improve the sustainability of MSW utilization.

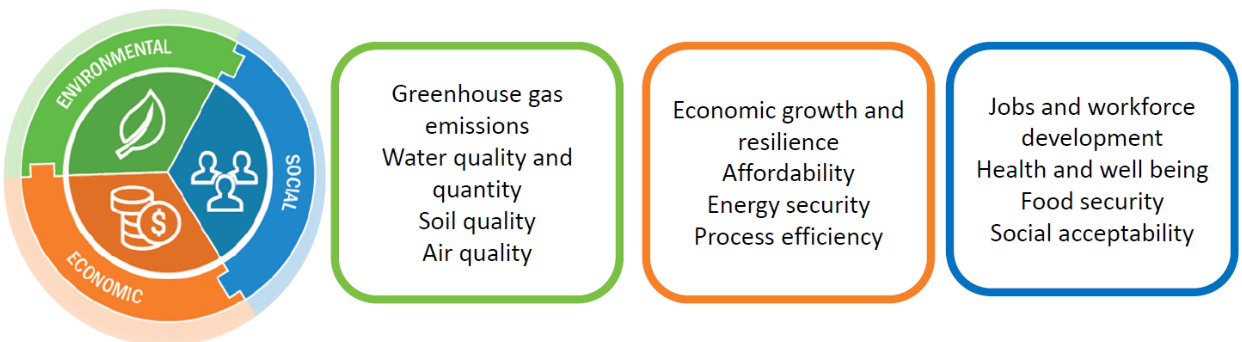

Figure 12. Representative parameters of environmental, economic, and social sustainability

Figure 12 illustrates the representative parameters of environmental, economic, and social sustainability generally used for the bioenergy supply chain. However, MSW utilization is more complicated when considering a variety of economic, environmental, and social sustainability challenges. Significant costs are associated with MSW treatment, handling, and management infrastructure, and MSW streams also represent major sources of greenhouse gas emissions and contribute to water, air, and land pollution and health issues. Careful and detailed evaluation of the environmental impacts (benefits and risks) and associated economic and social factors of MSW supply, preprocessing, and conversion are required.

This session sought to collect input from panelists on infrastructure of MSW utilization and the economics and environmental and social sustainability considerations of MSW conversion into biofuels and viable products.

Panelist 1: Shakira Hobbs, University of Kentucky

Utilization of Waste Polylactic Acid and Assessment of its Environmental Sustainability

Dr. Shakira Hobbs from the University of Kentucky presented on the utilization of polylactic acid (PLA), a bioplastic waste, and its environmental impacts. Waste management for handling bioplastics is complicated by food waste contamination. Bioplastics such as PLA are often discarded with food waste, which contaminates bioplastics and makes them difficult to recycle without separation, adding another complexity to waste management of bioplastic handling. In addition, PLA degradation is slow, and conventional waste management methods (e.g., composting, landfill) do not meet zero-waste goals.

Dr. Hobbs's research group has performed laboratory experiments and demonstrated the potential for an alkaline pretreatment process followed by anaerobic co-digestion of food waste and PLA to accelerate the degradation of bioplastics. She discussed and compared five waste management scenarios—anaerobic digestion, anaerobic digestion with pretreatment, compost, compost with pretreatment, and landfill—for their environmental advantages/offsets. Her results suggest that sending food waste and pretreated bioplastics to anaerobic digesters offers life cycle-based environmental and social benefits for the following impact categories: cumulative energy demand, ecotoxicity, eutrophication, global warming potential, and human health non-carcinogenic impacts due to landfill avoidance (Figure 13). Anaerobic digestion of food waste and pretreated bioplastic may provide the greatest benefit due to the relative importance of these impact categories. Implications from this study can lead to nutrient and energy recovery from an anaerobic digester that can diversify the types of fertilizers and decrease landfill waste while decreasing dependency on nonrenewable technologies. Thus, using anaerobic digestion to manage bioplastics and food waste should be further explored as a viable and sustainable solution for waste management, depending on desired environmental impact outcomes.

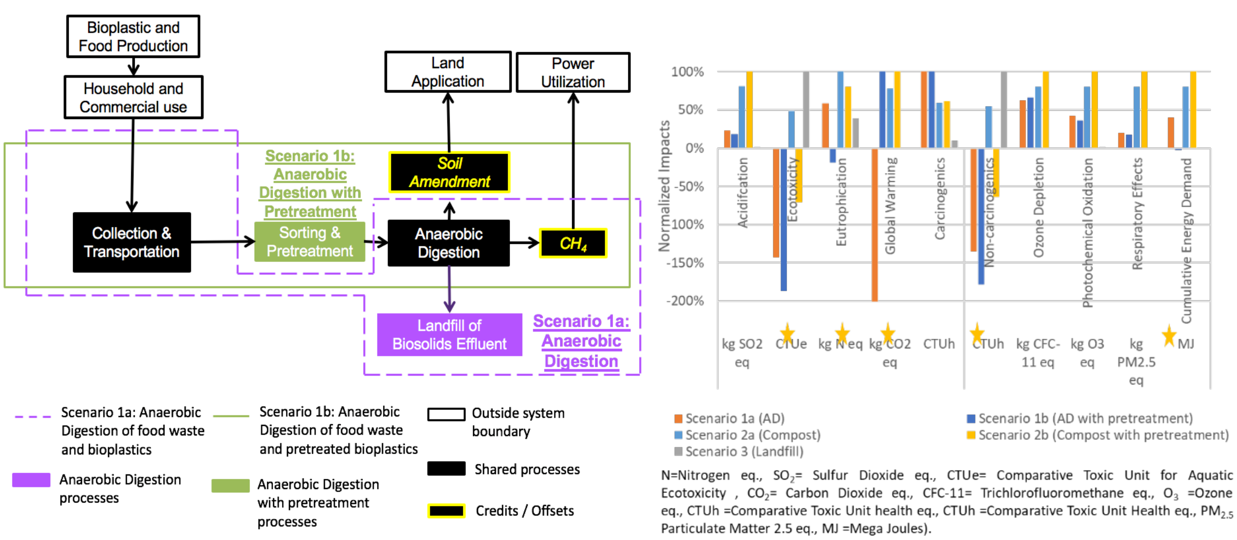

Figure 13. Life cycle assessment assists in quantifying environmental impacts of anaerobic digestion of food and PLA waste scenarios.

Panelist 2: Stacy Katz, WSP

Infrastructure, Economics & Sustainability Considerations for MSW into Viable Products

Stacy Katz, project director of WSP, shared her perspectives about the critical considerations in terms of infrastructure requirements, economics, and environmental sustainability for converting MSW into viable products. The sources of MSW, including curbside pickup residues, residues from MRFs, and single-category residues from source-separated waste, greatly impact collection and recovery. The variability of MSW can increase maintenance of heavy equipment in the preprocessing facilities, and different sources and compositions of waste residues require different infrastructure and preprocessing steps for recycling and utilization. Cost considerations include feedstock acquisition cost and transportation to the preprocessing facility, facility build and ongoing maintenance ($8–$70 million to build a complex preprocessing facility), and residue transport and disposal, which could cost $40–$100+/ton, depending on location. She discussed several important environmental and social factors, including energy and water consumption, chemicals and emissions, end of product life, and environmental justice, and brought up important questions under each category, as shown in Figure 14. These important questions need to be considered and addressed when evaluating waste management sustainability.

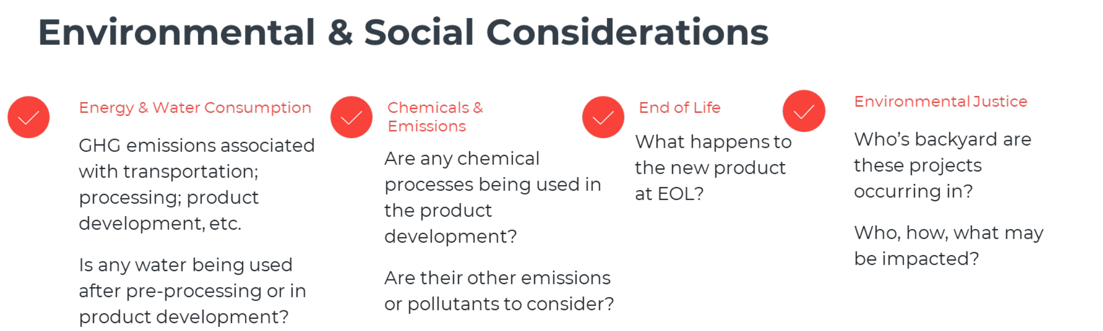

Figure 14. Critical environmental and social considerations for converting MSW into viable products

Panelist 3: Jay Fitzgerald, DOE-BETO

Bioenergy, Sustainability, and Waste Resources

Dr. Jay Fitzgerald, Chief Scientist of DOE-BETO, gave the final presentation, describing how sustainability is a key focus area within BETO and covers environmental, economic, and social aspects. Waste resources offer potential economically advantaged feedstocks as well as sustainability challenges in these three areas. Some examples include:

- Economic sustainability—the cost of managing wastes is increasing, organics bans in landfills have increased distances for transportation, and sludge management costs have increased by 37% since 2018.
- Environmental sustainability—landfills are the third largest source of methane emissions nationwide. The number of landfills will decrease by 69% over the next 40 years (Figure 15). Organic waste landfill bans have been implemented in more than seven states.

- Social sustainability—siting of waste handling infrastructure is disproportionately in disadvantaged communities. Impacts can include increases in odor, noise, litter, particulate emissions, and exposure to infectious disease vectors.

Dr. Fitzgerald also used a case study to show that plastic waste is an economic, environmental, and social sustainability challenge, and the increase in plastics production and disposal could pose significant concerns. However, sustainability of plastic waste is complicated, and use of plastics still offers benefits. For example, plastic bags and bottles have much lower global warming potential compared to cotton bags and aluminum containers, and plastics have large benefits in preventing food spoilage and other positive climate effects. As such, new technologies for recycling and upcycling plastic wastes will need to be developed to reduce GHG impacts and improve energy benefits. In addition, he commented on the environmental justice issues with plastic waste, referencing, as an example, the United Nations' Comtrade Program and World Bank data show that richer countries disproportionately exported plastic waste to poorer countries. Environmental justice—the fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies—is a critical element that must be taken into consideration for waste management.

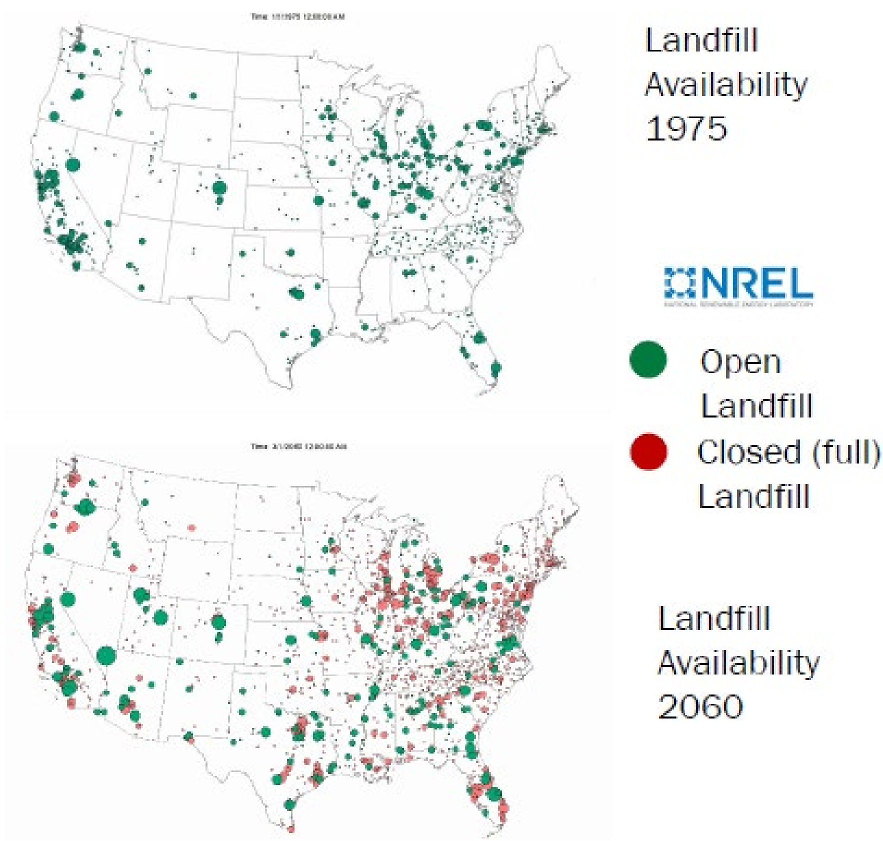

Figure 15. Predicted decrease of landfill availability from 1975 to 2060 to meet zero-waste goals

Source: National Renewable Energy Laboratory

Stakeholder Input Session #3: Sustainability Trade-Off Analysis Group Discussions

Objective

The objectives of this sustainability session were to identify:

- Environmental impacts associated with various MSW fractions' supply and preprocessing technologies.
- Available data/tools/capabilities and gaps for measuring and tracking environmental sustainability impacts of MSW utilization.
- Future R&D needs to improve the sustainability of MSW utilization.

The following critical terms were defined for group discussion to provide common language and understanding:

- Environmental impacts (benefits and risks): Any change to the environment, whether adverse or beneficial, resulting from a facility's activities, products, or services.
- Environmental/social/economic factors: Variables that can be influenced based upon technology or policy and ultimately yield the environmental impact. The impacts can be considered the outcomes of the interventions made to the factors.
- Environmental indicators: Metrics that can be monitored to assess performance over time; for example, rate of MSW degradation or measures of biodiversity.

Environmental Impacts

This stakeholder input session focused on establishing a baseline for sustainability factors and indicators (as shown in Table 4) and associated impacts of MSW supply and preprocessing technologies. This group further discussed about potential environmental impacts of utilizing these various streams of MSW to develop fuel and products.

Table 4. Baseline Sustainability Factors and Indicators

	Factors (variables that can be influenced based upon technology or policy)	Indicators (metrics that can be monitored to assess performance over time)
Social Sustainability	Job creation Workforce development Social acceptance Energy literacy	Quantity of jobs Quality of Jobs Public health Energy security Social benefit/social harm
Environmental Sustainability	Ecosystem services Land use Carbon cycle	Soil/air/water quality aspect GHG emissions Environmental health/biodiversity
Economic Sustainability	Biofuel production Coproduct development Market demand and supply Commercial viability	Market/industry growth

A theme from this conversation was finding opportunity where typically waste is seen. For example, plastics were not necessarily designed for the purposes they serve. We have the opportunity to better design plastics or materials for an intended purpose, and we can also design plastics (and other materials) for the end of life, which may include being used as a fuel/coproduct feedstock.

Another common theme was around education and communication, especially related to single-use flexible plastics, which are a significant challenge in MSW management generally. Consumers are told they are easily recycled, so they don't feel bad about using them. In reality, it is not easy to recycle these plastics, and the burden is shifted from the consumer to the MRF and/or the environment. This could potentially be avoided by focusing on the full life cycle of the plastic and not simply on plastics separation and recycling.

The remainder of this section lists the group's input on the environmental impacts of utilizing various MSW streams to develop fuels and products.

Stakeholders had a wide ranging, multifaceted discussion regarding the environmental sustainability considerations of MSW utilization and overall management.

For example, in addition to environmental impacts, they discussed trade-off scenarios, circular economy and whole life cycle analysis, and supply chain considerations. For trade-off scenarios, the group agreed that the most advanced solutions may tackle environmental impact needs while impacting other parts of the process negatively. A positive impact could be reduction of materials sent to a landfill and supporting a transition from a linear to more circular economy. However, emissions and contamination impacting air, land, and water quality could occur at landfills and MRFs, or other facilities where MSW preprocessing occurs.

They also discussed the whole life cycle of materials that make up MSW, and that utilization must consider non-carbon-based benefits and/or impacts—i.e., not solely focusing on GHG emissions impacts. Stakeholders considered what factors affect environmental sustainability of production of materials that eventually become MSW. Factors included point sources for MSW, such as residential and commercial, as well as value propositions and their associated policies that impact MSW life cycles, such as extended producer responsibility laws or bottle deposits (pay-as-you-throw policies). As stakeholders discussed preprocessing, they mainly focused on both materials separation and contamination removal and the potential benefits of those types of steps for environmental impacts, while also considering water and energy usage and environmental impacts of the chemical and thermal requirements of these steps. When considering conversion processes for MSW utilization, stakeholders discussed that the energy requirements for converting MSW could be greater than virgin materials. They also discussed how conversion processes could be matched to what kinds of MSW are produced and regional needs that MSW-derived products and fuels could fulfill. They also considered the transportation requirements for such regional solutions, between both consumers and MRFs and MSW management facilities themselves. In general, the group noted that there were unknowns about the material composition and steps of handling, preprocessing, and converting MSW into fuels and products.

The group ranked various environmental impacts as the highest priority to understand and track for overall MSW management and potential utilization, as shown in Figure 16.

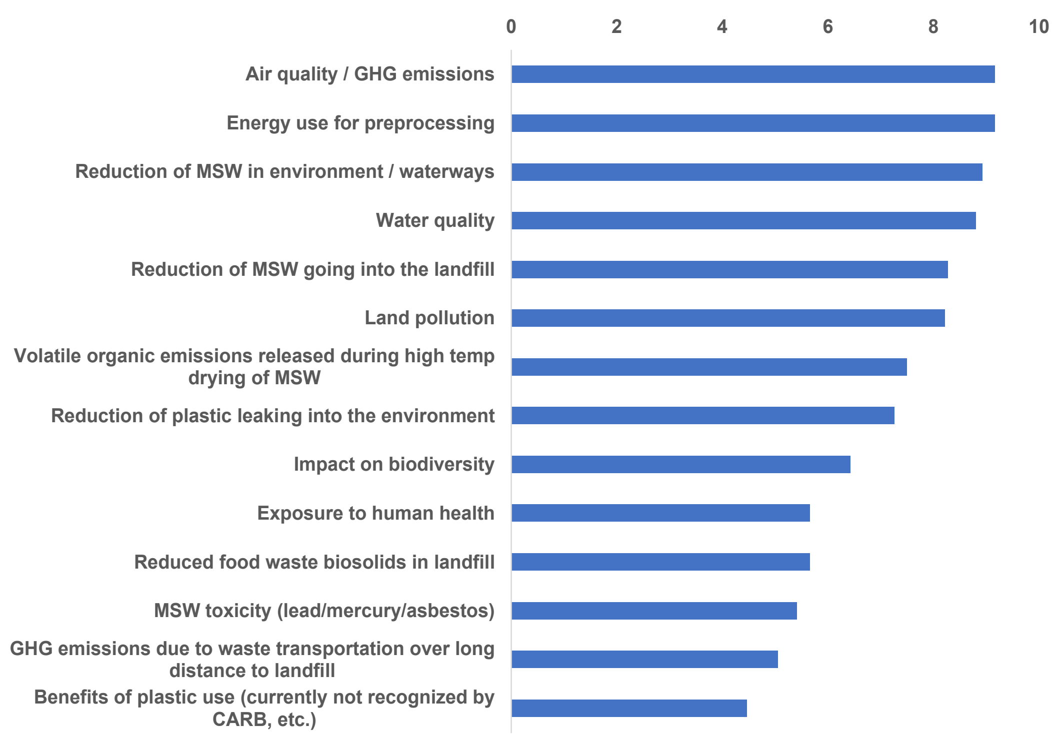

Figure 16. Highest-priority environmental impacts to understand and track for MSW management and utilization, ranked by stakeholder group

Data Availability and Gaps to Monitor Environmental Impacts

The stakeholder group also discussed data needs to track the impact over time for each priority environmental impact. They also provided reference and comments about available databases, reports, etc., and discussed data gaps and opportunities to potential feasibility of data collection.

Table 5. Available Data and Resources on Environmental Impacts

Impact	Data Available
Energy use for preprocessing	Idaho National Laboratory state-of-technology reports and industry-proprietary information
Benefits of plastic use	Impact of Plastics Packaging on Life Cycle Energy Consumption & Greenhouse Gas Emissions in the United States and Canada: Substitution Analysis; Plastics and Environmental Health: The Road Ahead
Volatile organic compound emissions at high-temperature MSW drying	Refinery Products Volatile Organic Compounds Emissions Estimator (RP-VOC): User Manual and Technical Documentation
Impact on biodiversity	Governing Transboundary Waters: Canada, the United States, and Indigenous Communities
Land pollution	Waste-to-Energy, Chapter 8 - Life cycle analysis of waste-to-energy pathways
Water quality	Waste-to-Energy, Chapter 8 - Life cycle analysis of waste-to-energy pathways
Reduction of MSW into environment	Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways
Reduction of MSW entering landfill	Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways
Reduction of plastics	Waste-to-Energy, Chapter 8 - Life cycle analysis of waste-to-energy pathways
Air quality/GHG emissions	EPA tools: Waste Reduction Model (WARM); Municipal Solid Waste Decision Support Tool (MSW DST)
Exposure to human health	EPA tool: Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI)
Reduced food waste to landfills	EPA Excess Food Opportunities Map
Environmental impact data of landfill of nonrecycled, organic MSW streams	EPA Waste Reduction Model (WARM); National Renewable Energy Laboratory database – documented in the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model

However, many data gaps still exist, and future efforts are required to collect data and information to evaluate more environmental impacts, as summarized below:

- Energy consumption for MSW sorting and preprocessing.
- Volatile organic compound emissions at high-temperature MSW drying.
- Impact on biodiversity; data are limited to track loss of biodiversity due to MSW making its way into the environment.

- Reduction of MSW entering landfill—need robust mass balances at the gate of landfills.
- GHG emissions due to transportation of MSW.
- Impact of MSW on human health—difficult for trace amounts and difficult to get reliable data to assess the impact.
- Data associated with MSW management infrastructure systems.

Tools and Capabilities Needed to Monitor Environmental Impacts

In this discussion, participants provided valuable reference and suggestions about tools or capabilities needed to monitor sustainability impacts related to synergistic waste utilization.

Table 6. Tools and Capabilities for Monitoring Environmental Impacts

Tool	Tools/Capabilities Exist	Tools/Capabilities Needed
GHG emissions, energy use, and carbon intensity of energy technologies	Argonne National Laboratory Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) LCA model Feedstock Carbon Intensity Calculator (FD-CIC)	
Waste reduction evaluation	EPA Waste Reduction Model (WARM)	
Biodiversity in soils	Oxford Nanopore genetic sequencing for measuring impacts on biodiversity in soils	
MSW management strategies with respect to GHGs, cost, energy, and environmental impacts	EPA MSW Decision Support Tool (DST)	
Water and land use	GaBi LCA database with water and land use data	
Energy requirement of emerging sorting/preprocessing technologies		X
Database of key material quality attributes for emerging sorting/preprocessing technologies		X
Cost-effective MSW washing/leaching drying		X
Machine-learning artificial intelligence for sorting and extraction		X
Access to infrastructure and manufacturing of plastics		X

Tool	Tools/Capabilities Exist	Tools/Capabilities Needed
Consolidated, searchable interagency databases on historical environmental data		X
Social impact data quantification		X
Cost-benefit analysis pathways		X
Co-location site assessment tools		X

Participants also provided commentary regarding the key MSW quality attributes and how meeting different specification requirements affects sustainability. The LCA community, including Argonne National Laboratory, has developed some data and modeling capabilities to address sustainability of MSW-derived fuels, such as ethanol and jet fuels. However, there is still a great data gap regarding the energy requirements of emerging sorting/preprocessing technologies and how such technologies help improve key attributes required to be conversion-ready. The LCA community needs to work with technology developers to gather such information to evaluate the environmental performance of specific technology solutions.

Session Summary

The sustainability session set up a baseline of social, environmental, and economic sustainability indicators and associated environmental impacts of MSW supply and preprocessing technologies; discussed existing data, tools, and capabilities; and, more importantly, identified gaps and tools needed to monitor environmental impacts. Participants recognized that a comprehensive set of sustainability indicators, data, tools, and modeling efforts are required to better understand and quantify the sustainability impacts of utilizing MSW streams.

Conclusion

In this virtual workshop, participants discussed a variety of topics, including (1) identifying technical challenges and opportunities associated with developing advanced preprocessing technologies for MSW, (2) defining critical paths toward synergistic use of municipal solid waste streams for both conversion-ready feedstocks and valuable coproducts, and (3) examining the economic viability and sustainability impacts of waste stream valorization.

The preprocessing session addressed preprocessing challenges relevant to biochemical and thermochemical conversion pathways. The workshop participants recognized that variability in MSW streams poses challenges on downstream conversion. Developing solutions for MSW decontamination, advanced sorting and fractionation, homogenization, stability, feeding, and handling were identified as critical challenges in preprocessing R&D. Participants noted that it is imperative to leverage existing infrastructure such as MRFs, depots, long-haul raw MSW transportation systems, and other logistics systems. The participants also described the importance of developing MSW preprocessing and conversion systems considering variable scales from small rural communities to mega-metro centers. It is important to develop community-scale solutions with the involvement of local communities in rural areas in the decision-making process and address environmental injustice in MSW utilization.

The coproduct development session considered the potential coproducts that can be derived from low-quality MSW fractions and discussed their baseline market size, viable preprocessing and coproduct development R&D opportunities, and technology readiness levels. When developing coproducts, the quality attributes of coproducts, as well as the potential market size and process economic and environmental suitability of the coproduct, need to be considered.

The sustainability session set up a baseline of sustainability indicators and associated environmental impacts of MSW supply and preprocessing technologies; discussed available data, tools, and capabilities; and, more importantly, identified gaps and R&D efforts needed to monitor environmental impacts. Participants recognized that a comprehensive set of sustainability indicators, data, tools, and modeling efforts are required to better understand and quantify the sustainability impacts of utilizing MSW streams. The LCA community needs to work with technology developers to gather such information to evaluate the environmental performance of specific technology solutions.

The information and feedback generated from the workshop will help DOE address the most critical barriers to using MSW for biofuels and bioproducts production. DOE’s Bioenergy Technologies Office would like to thank all the participants for their valuable input on these topics.

Appendix A: Workshop Agenda

Advancing Synergistic Waste Utilization as Biofuels Feedstocks: Preprocessing, Coproducts, and Sustainability Workshop
U.S. Department of Energy (DOE), Bioenergy Technologies Office (BETO)
April 14–15, 2021
(Agenda subject to change)

Wednesday, April 14

Time (EDT)	Agenda Item	Speaker
9:30 a.m. – 10:00 a.m.	*Login and Optional Networking Activities*	
10:00 a.m. – 10:10 a.m.	Welcome and Opening Remarks	Chenlin Li – Technology Manager, DOE-BETO
10:10 a.m. – 10:20 a.m.	BETO Mission and Vision	Valerie Sarisky-Reed – Acting Director, DOE-BETO
10:20 a.m. – 10:30 a.m.	BETO Feedstock Technologies Research and Development Program Overview	Nichole Fitzgerald – Program Manager, Feedstock Technologies R&D Program, DOE-BETO
10:30 a.m. – 11:00 a.m.	Keynote Presentation – Waste Preprocessing and Sustainability	JD Lindeberg – Principal and President, RRS
11:00 a.m. – 11:15 a.m.	Breakout Session Introduction – Structure and Software Overview	Lauren Illing – Lead Facilitator, BCS LLC
11:15 a.m. – 12:00 p.m.	*Lunch Break – Optional Networking Activities*	
12:00 p.m. – 3:45 p.m.	Stakeholder Input Session #1 – Feedstock Preprocessing	Panel and Group Discussions
12:00 p.m. – 1:30 p.m.	*Presentations and Q&A*	*Moderators: Mark Elless and Chenlin Li* *Panelists:* • *Edward J. Wolfrum, Ph.D., National Renewable Energy Laboratory* • *Jeff Lacey, Idaho National Laboratory* • *Junyong Zhu, U.S. Department of Agriculture (USDA), Forest Products Laboratory* • *Perry Toms, Steeper Energy*
1:30 p.m. – 1:45 p.m.	*Break*	
1:45 p.m. – 3:15 p.m.	*Group Discussions*	*All Participants*
3:15 p.m. – 3:45 p.m.	*Group Report Out*	*Rapporteurs*
3:45 p.m. – 3:50 p.m.	Day 1 Closing Remarks	Chenlin Li

Thursday, April 15

Time (EDT)	Agenda Item	Speaker
9:30 a.m. – 10:00 a.m.	*Login and Optional Networking Activities*	

Advancing Synergistic Waste Utilization as Biofuels Feedstocks: Preprocessing, Coproducts, and Sustainability Workshop U.S. Department of Energy (DOE), Bioenergy Technologies Office (BETO) April 14–15, 2021 *(Agenda subject to change)*		
10:00 a.m. – 1:00 p.m.	Stakeholder Input Session #2 – Coproduct Development	Panel and Group Discussions
10:00 a.m. – 11:00 a.m.	*Presentations and Q&A*	*Moderators: Art Wiselogel and Elizabeth Burrows* *Panelists:* • *William Orts, USDA* • *Soydan Ozcan, Oak Ridge National Laboratory* • *Charles Tremblay, Enerkem (invited)*
11:00 am. – 12:30 p.m.	*Group Discussions*	*All Participants*
12:30 p.m. – 1:00 p.m.	*Group Report Out*	*Rapporteurs*
1:00 p.m. – 1:45 p.m.	*Lunch Break – Optional Networking Activities*	
1:45 p.m.– 4:45 p.m.	Stakeholder Input Session #3 – Sustainability and Trade-Off Analysis	Panel and Breakout Group Discussions
1:45 p.m.– 2:45 p.m.	*Presentations and Q&A*	*Moderators: Brianna Farber and Elizabeth Burrows* *Panelists:* • *Shakira Hobbs, University of Kentucky* • *Stacy Katz, WSP* • *Jay Fitzgerald, BETO*
2:45 p.m. – 4:15 p.m.	*Group Discussions*	*All Participants*
4:15 p.m. – 4:45 p.m.	*Report Out*	*Rapporteurs*
4:45 p.m. – 5:00 p.m.	Closing Remarks	Chenlin Li – Technology Manager, DOE-BETO

Appendix B: Workshop Attendees

First Name	Last Name	Email	Organization
Zia	Abdullah	zia.abdullah@nrel.gov	National Renewable Energy Laboratory
Sushil	Adhikari	sza0016@auburn.edu	Auburn University
Bruce	Adkins	adkinsbd@ornl.gov	Oak Ridge National Laboratory
Andrew	Alden	aalden@vtti.vt.edu	Virginia Polytechnic Institute and State University
Richard	Altman	rcbaltman@gmail.com	CAAFI (Commercial Aviation Alternative Fuel Initiative)
Adeyemi	Ayodeji	aoayodeji@futa.edu.ng	Federal University of Technology, Akure
Andrea	Bailey	andrea.bailey@ee.doe.gov	DOE – BETO
Alexandra	Ban	alexandraban@yahoo.com	Termoline
Mark	Blenner	blenner@udel.edu	University of Delaware
Hannah	Brigham	hbrigham@villanova.edu	Villanova University
Craig	Brown	craig.brown@nrel.gov	National Renewable Energy Laboratory
Elizabeth	Burrows	elizabeth.burrows@ee.doe.gov	U.S. Department of Energy
Hao	Cai	hcai@anl.gov	Argonne National Laboratory
Daniel	Carpenter	daniel.carpenter@nrel.gov	National Renewable Energy Laboratory
Herb	Case	hcase@parracombe.com	Parracombe Consulting LLC
Qiushi	Chen	qiushi@clemson.edu	Clemson University
Sot	Chimonas	chimonas@katzen.com	KATZEN International
Amira	Chowyuk	amira@buildmomentum.io	Momentum
Peter	Ciesielski	peter.ciesielski@nrel.gov	National Renewable Energy Laboratory
Luísa	Clemente Magalhães Gomes	luisacmgomes@gmail.com	Universidade Estadual de Campinas
Richard	Coaxum	richard.coaxum@thebuildingpeople.com	DOE – BETO
Vinícius	Concentino	vini.concentino@gmail.com	Not provided
LJ	Conrad	ljconrad@ix.netcom.com	Not provided
Katie	Copenhaver	copenhaverke@ornl.gov	Oak Ridge National Laboratory
Christine	Costello	chriscostello@psu.edu	Penn State University
Benjamin	Cross	NuSynergyEnergy@gmail.com	NuSynergy Energy, LLC

First Name	Last Name	Email	Organization
Steve	Csonka	steve.csonka@caafi.org	CAAFI
Maha	Dakar	dakar@katzen.com	KATZEN International, Inc
Gerard	Damiani	gdamiani@rocklandgreen.com	Rockland Green
Ryan	Davis	rwdavis@sandia.gov	Sandia National Laboratories
Don	Diei	dieidon@yahoo.com	Eko Electricity Distribution Company Plc
Bryon	Donohoe	bryon.donohoe@nrel.gov	National Renewable Energy Laboratory
Jim	Dooley	jdooley@forestconcepts.com	Forest Concepts
Mark	Elless	mark.elless@ee.doe.gov	DOE – BETO
Khalid	Elsheikh	khalid51@siswa.um.edu.my	University of Malaya
Rachel	Emerson	rachel.emerson@inl.gov	Idaho National Laboratory
Abigail	Engelberth	aengelbe@purdue.edu	Purdue University
Joe	English	jenglish@adelanteconsulting.com	Adelante Consulting
Karl	Englund	englund@wsu.edu	WSU
Amanda	Evans	acevans@lanl.gov	Los Alamos National Laboratory
Brianna	Farber	brianna.farber@ee.doe.gov	DOE – BETO
Ignacio	Figoli	ignacio.figoli@miem.gub.uy	Secretary of Energy
Nichole	Fitzgerald	nichole.fitzgerald@ee.doe.gov	DOE – BETO
Eloy	Flores	eloy.flores@swri.org	Southwest Research Institute
Allan	Gao	allan.gao@lanzatech.com	LanzaTech
Daniel	Gaspar	daniel.gaspar@pnnl.gov	Pacific Northwest National Laboratory
Islam	Genina	genina@mit.edu	MIT
Anthe	George	angeorg@sandia.gov	Sandia National Laboratories
Roland	Gleisner	roland.gleisner@usda.gov	U.S. Department of Agriculture
David	Goodloe	david.goodloe@branchtechnology.com	Branch Technology
Raj	Gopal	rgopalmrm@yahoo.com	Not provided
Angelica	Gyllen	agyllen@ways2h.com	Ways2H
Ethan	Hanohano	ethan@buildmomentum.io	Momentum
Troy	Hawkins	thawkins@anl.gov	Argonne National Laboratory
Chad	Haynes	chad.haynes@lanzatech.com	LanzaTech
James	Hays	jim.hays@powereng.com	POWER Engineers
Shakira	Hobbs	shakirahobbs@uky.edu	University of Kentucky
Beau	Hoffman	Beau.Hoffman@ee.doe.gov	U.S. Department of Energy

First Name	Last Name	Email	Organization
Amber	Hoover	amber.hoover@inl.gov	Idaho National Laboratory
Lauren	Illing	lilling@bcs-hq.com	BCS LLC
Sanjay	Jagtap	ABHIRUTU@GMAIL.COM	ABHIRUTU CONSULTANTS
Deepakkumar	Jani	janideepak17@yahoo.in	The M S University of Baroda
Alexander	Jansen	alexander.jansen@ee.doe.gov	DOE – BETO
Yun	Ji	yun.ji@und.edu	University of North Dakota
Wencheng	Jin	wencheng.jin@inl.gov	Idaho National Laboratory
Robin	Johnston	rjohnston@lbl.gov	Lawrence Berkeley National Laboratory
Eugene	Jones	gene@swixusa.org	Southern Waste Information eXchange, Inc.
Ankush	Karemore	Ankush1Karemore@gmail.com	Not provided
Stacy	Katz	stacy.katz@wsp.com	WSP
Timothy	Kim	timothy.kim@a1gtinc.com	A-1 Green Tech Inc
Jean-Louis	Kindler	jlkindler@ways2h.com	Ways2H Inc.
Brandon	Knott	brandon.knott@nrel.gov	National Renewable Energy Laboratory
Deepak	Kumar	dkumar02@esf.edu	SUNY ESF
Ben	Kumfer	kumferb@wustl.edu	Washington University in St. Louis
Jeffrey	Lacey	jeffrey.lacey@inl.gov	Idaho National Laboratory
Philip	Laible	laible@anl.gov	Argonne National Laboratory
David	Lanning	dlanning@forestconcepts.com	Forest Concepts
Connie	Lausten	connie@cLaustenllc.com	C Lausten LLC
Uisung	Lee	ulee@anl.gov	Argonne National Laboratory
Chenlin	Li	Chenlin.Li@ee.doe.gov	DOE – BETO
Zhenglong	Li	liz3@ornl.gov	Oak Ridge National Laboratory
Hui	Li	lihui@wsu.edu	Washington State University
Yupo	Lin	yplin@anl.gov	Argonne National Laboratory
Hongfei	Lin	hongfei.lin@wsu.edu	Washington State University
JD	Lindeberg	jdl@recycle.com	RRS
Jeffrey	Linger	jeffrey.linger@nrel.gov	National Renewable Energy Laboratory
Belinda	Little-Wood	belinda@10thCapital.com	10th Capital
Terre	Logsdon	terre.logsdon@sv-nsn.gov	Scotts Valley Band of Pomo Indians

First Name	Last Name	Email	Organization
Rob	Long	publishernynp@gmail.com	Citron Energy
Tony	Long	tony.long@agraenergy.com	Agra Energy
Shailesh	Lopes	shailesh.lopes@gm.com	General Motors
Gary	Luce	gary.luce@hamiltonclark.com	HamiltonClark Sustainable Capital
Warren	Lyman	warren.lyman@powereng.com	POWER Engineers, Inc.
Emily	Marthaler	emily.marthaler@usda.gov	U.S. Department of Agriculture
Gregory	McDonald	greg.mcdonald@agraenergy.com	Agra Energy
Christopher	McKiernan	cmckiernan@forestconcepts.com	Forest Concepts
Jamie	Meadows	jamie.meadows@ee.doe.gov	DOE – BETO
Gamini	Mendis	gmendis@psu.edu	Plastic Engineering Technology
Anelia	Milbrandt	anelia.milbrandt@nrel.gov	National Renewable Energy Laboratory
Bruno	Miller	bmiller@fulcrum-bioenergy.com	Fulcrum BioEnergy
Mitchell	Minarick	minarick@gmail.com	FarmAfield Labs
Joanne	Morello	joanne.morello@ngc.com	Northrop Grumman
Steven	Moss	smoss@nas.edu	National Academies of Sciences, Engineering, and Medicine
Sheebu	Nair	nair.sheebu@gmail.com	Not provided
Quang	Nguyen	quang.nguyen@inl.gov	Idaho National Laboratory
Olayinka	Oderinde	yinkaoderinde@yahoo.com	Not provided
Oluwatosin	Oginni	oluwatosin.oginni@inl.gov	Idaho National Laboratory
Mari Cruz	Ortega Teruel	maricruz@iberiabiomass.es	IBERIA BIOENERGY
William	Orts	bill.orts@usda.gov	USDA – ARS
Longwen	Ou	oul@anl.gov	Argonne National Laboratory
Oluwafemi	Oyedeji	oyedejia@ornl.gov	Oak Ridge National Laboratory
Soydan	Ozcan	ozcans@ornl.gov	Oak Ridge National Laboratory
Asanga	Padmaperuma	asanga.padmaperuma@pnnl.gov	Pacific Northwest National Laboratory
Sunkyu	Park	sunkyu_park@ncsu.edu	North Carolina State University
Celio	Pasquini	pasquini@unicamp.br	Chemistry Institute - UNICAMP

First Name	Last Name	Email	Organization
Brennan	Pecha	brennan.pecha@nrel.gov	National Renewable Energy Laboratory
Hemant	Pendse	pendse@maine.edu	University of Maine
Adolfo	Perez Henao	alephe57@gmail.com	I+A Ingenieria Aplicada
Mike	Perry	mperry@forestconcepts.com	Forest Concepts, LLC
Sally	Peterson	SunFace110@gmail.com	Middletown Rancheria
Steven	Phillips	steven.phillips@pnnl.gov	Pacific Northwest National Laboratory
Karthikeyan	Ramasamy	Karthi@pnnl.gov	Pacific Northwest National Laboratory
Allison	Ray	allison.ray@inl.gov	Idaho National Laboratory
John	Reardon	Jreardon@tpgengineers.com	The Process Group LLC
Walter	Renz	walter.renz@linde.com	Linde
Michael	Resch	Michael.resch@nrel.gov	National Renewable Energy Laboratory
Alfonso	Reyna	areyna@socalgas.com	SoCalGas
Toufiq	Reza	treza@fit.edu	Florida Institute of Technology
Tim	Rials	trials@utk.edu	University of Tennessee
George	Roe	george.roe@hq.doe.gov	DOE Arctic Energy Office
Clayton	Rohman	clayton.rohman@ee.doe.gov	DOE – BETO
Prafulla	Sabbanwar	prafulsabbanwar@gmail.com	Not provided
Varghese	Saju	Varghese.saju@kuleuven.be	VIB
Joel	Sarapas	joel.sarapas@ee.doe.gov	DOE – BETO
Oral	Saulters	osaulters@lanl.gov	Los Alamos National Laboratory
Brian	Sefton	brian@briansefton.com	novonutrients
Diane	Sellers	dgsellers@energetics.com	Energetics
Priya	Sengupta	priyasengupta5@gmail.com	University of California Riverside
Reyhaneh	Shenassa	reyhaneh.shenassa@ee.doe.gov	DOE – EERE – BETO
Jian	Shi	j.shi@uky.edu	University of Kentucky
Kola	Shonubi	kolashonubi@gmail.com	Not provided
Nicholas	Siefert	nicholas.siefert@netl.doe.gov	DOE – National Energy Technology Laboratory
David	Sievers	david.sievers@nrel.gov	National Renewable Energy Laboratory
Sandip	Singh	loginsandeep86@gmail.com	Montana State University

First Name	Last Name	Email	Organization
Amie	Sluiter	amie.sluiter@nrel.gov	National Renewable Energy Laboratory
Sarah	Smith	sjsmith@lbl.gov	Lawrence Berkeley National Laboratory
William	Smith	william.smith@inl.gov	Idaho National Laboratory
Trevor	Smith	trevor.smith@ee.doe.gov	DOE
Lesley	Snowden-Swan	lesley.snowden-swan@pnnl.gov	Pacific Northwest National Laboratory
Seth	Snyder	seth.snyder@inl.gov	Idaho National Laboratory
Jeff	Spangenberger	Jspangenberger@anl.gov	Argonne National Laboratory
Frederick	Stewart	frederick.stewart@inl.gov	Idaho National Laboratory
Jaxon	Stuhr	jstuhr@anl.gov	Argonne National Laboratory
Lawrence	Sullivan	Larry.Sullivan@forest2market.com	Forest2Market, Inc.
Brett	Swain	brettswain9@gmail.com	Civilian Aeronautic Space Agency
Carl	Swanson	Cswanson@wm.com	Waste Management
Thomas	Swarr	swarrte@comcast.net	Hartford Solid Waste Task Force
Eric	Tan	eric.tan@nrel.gov	National Renewable National Laboratory
Matthew	Taylor	matthew.k.taylor@tn.gov	Tennessee Department of Environment and Conservation
Jeremy	Taylor	jeremy@graybrothersinc.com	SoMax Circular Solutions
Vicki	Thompson	Vicki.Thompson@inl.gov	Idaho National Laboratory
James	Thornsberry	james_thornsberry@aol.com	Sustainable Insulation Technologies, LLC
Colleen	Tomaino	colleen.tomaino@ee.doe.gov	BCS, LLC
Perry	Toms	pt@steeperenergy.com	Steeper Energy Canada Ltd.
Hilal Ezgi	Toraman	hzt5148@psu.edu	Pennsylvania State University
Takehiro	Tsutsumi	tsutsumi.takehiro@kao.co.jp	Kao Corporation
Jaya Shankar	Tumuluru	jayashankar.tumuluru@inl.gov	Idaho National Laboratory
Kim	Tutin	kim@captisaire.com	Captis Aire
Meltem	Urgun-Demirtas	demirtasmu@anl.gov	Argonne National Laboratory
Sheila	Van Cuyk	svancuyk@lanl.gov	Los Alamos National Laboratory

First Name	Last Name	Email	Organization
Juliana	Vasco-Correa	julianavasco@psu.edu	Penn State University
Richard	Venditti	richardv@ncsu.edu	NCSU
Dionisios	Vlachos	vlachos@udel.edu	University of Delaware
Bradley	Wahlen	bradley.wahlen@inl.gov	Idaho National Laboratory
Yi	Wang	yiwang3@auburn.edu	Auburn University
Jingxin	Wang	jxwang@wvu.edu	West Virginia University
Lynn	Wendt	lynn.wendt@inl.gov	Idaho National Laboratory
Carl	White	carl@skyvuewireless.com	Skyvue Wireless, LLC
Matt	Wiatrowski	matthew.wiatrowski@nrel.gov	National Renewable Energy Laboratory
Luke	Williams	luke.williams@inl.gov	Idaho National Laboratory
Aaron	Wilson	aaron.wilson@inl.gov	Idaho National Laboratory
Arthur	Wiselogel	art.wiselogel@ee.doe.gov	BETO
Ed	Wolfrum	ed.wolfrum@nrel.gov	National Renewable Energy Laboratory
Jingjie	Wu	jingjie.wu@uc.edu	University of Cincinnati Main Campus
Yidong	Xia	yidong.xia@inl.gov	Idaho National Laboratory
Bin	Yang	bin.yang@wsu.edu	Washington State University
Winston	Yau	winston.yau@duke.edu	Duke University
Eunji	Yoo	eyoo@anl.gov	Argonne National Lab
Joshua	Yuan	syuan@tamu.edu	Texas A&M University
Yimin	Zhang	yimin.zhang@nrel.gov	National Renewable Energy Laboratory
Yan	Zhang	yzhang@ethanolresearch.com	National Corn to Ethanol Research Center
Junyong	Zhu	junyong.zhu@usda.gov	USDA Forest Products Lab
Hongli (Julie)	Zhu	h.zhu@neu.edu	Northeastern University
Luca	Zullo	luca.zullo@verdenero.com	VerdeNero LLC

U.S. DEPARTMENT OF ENERGY | *Office of* ENERGY EFFICIENCY & RENEWABLE ENERGY

BIOENERGY TECHNOLOGIES OFFICE

For more information, visit: energy.gov/eere/bioenergy

DOE/EE-2610 · June 2022

Cover photos from Forest Concepts and iStock 1301687542, 1174784882, 1352400789, and 865297750.