U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advancing the Bioeconomy:

From Waste to Conversion-Ready Feedstocks Workshop Summary Report

Arlington, Virginia | February 2020

Preface

The mission of the U.S. Department of Energy's 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. This report summarizes the results of a BETO-sponsored public workshop held at the DoubleTree by Hilton hotel in Arlington, Virginia, on February 19–20, 2020.

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

Acknowledgments

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This report was prepared by the Bioenergy Technologies Office and Idaho National Laboratory.

Executive Summary

On February 19 and 20, 2020, the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) hosted the "Advancing the Bioeconomy: From Waste to Conversion-Ready Feedstocks" workshop at the DoubleTree by Hilton hotel in Arlington, Virginia. The workshop explored the potential of using the various components of the municipal solid waste (MSW) stream (i.e., yard waste, unrecycled paper, food waste, and plastics) to produce feedstock for fuels, chemicals, and products. BETO invited experts in the fields of waste management, solid materials handling, and biofuel and bioproduct development and production to give presentations, as well as a diverse group of stakeholders to develop and share knowledge and establish partnerships. This document provides an overview of the presentations and breakout session discussions.

MSW represents both a disposal challenge and potential resource for feedstock production. Reduced landfill capacity, increasing tipping fees, and loss of valuable materials in MSW to landfills all contribute to the need for diverting MSW to a more productive outcome. However, MSW has multiple challenges associated with its convertibility, including low energy content, high moisture levels, heterogeneous stream composition, and variable distribution. The challenges associated with making MSW a conversion-ready feedstock parallel the challenges observed for terrestrial feedstocks. One objective of this workshop is to identify the gaps in knowledge and capabilities that are critical for enabling MSW-derived feedstock production.

The workshop examined the current state of the art, gaps and challenges, opportunities, and prioritization of the following critical areas: feedstock characterization and technological development for conversion readiness, MSW preprocessing and logistics, and valorization of the MSW streams. Experts from industry, universities and research institutions, national laboratories, and municipalities were invited to present to provide the framework for the three topic areas. The first series of presentations covered Quality by Design, a research approach pioneered by the pharmaceutical industry and being employed by BETO-funded researchers to organize and inform current research and development (R&D) efforts on biofuel feedstock development. The rest of the invited presentations covered the current state of the art for waste management, R&D of MSW preprocessing, and valuing MSW economically, environmentally, and practically. In addition to the plenary sessions, six short "3 × 5" presentations covered MSW handling, challenges with MSW management and utilization, and current R&D on MSW feedstock production.

The workshop participants were divided into four groups to discuss the three critical areas. Groups 1 and 2 were assigned to address characterization of MSW as a material and feedstock, Group 3 worked on MSW preprocessing and logistics, and Group 4 covered assigning value to the MSW stream. Within each of these breakout session topics, the group considered the state of the art in MSW management and utilization, gaps and challenges in knowledge, infrastructure and technology, and potential strategies and solutions to address gaps and challenges. They also discussed the highest priorities within these areas of R&D to enable these technologies and industries.

The information and feedback generated from the workshop will help guide programmatic decisions at DOE to ensure that investments in R&D address the most critical barriers to successful technology development. DOE's Bioenergy Technologies Office would like to thank all of the participants for their valuable input.

List of Acronyms

AD	anaerobic digestion
AI	artificial intelligence
BETO	Bioenergy Technologies Office (DOE)
CMA	critical material attribute
CPP	critical process parameter
CQA	critical quality attribute
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
HDPE	high-density polyethylene
HTP	hydrothermal processing
INL	Idaho National Laboratory
LCA	life cycle analysis
MRF	materials recovery facility
MSW	municipal solid waste
OFMSW	organic fraction of municipal solid waste
QbD	Quality by Design
R&D	research and development
REMADE	Reducing EMbodied-energy And Decreasing Emissions
RIN	renewable identification number

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1 Introduction

1.1 The Challenge and the Opportunity

In the United States, municipal solid waste (MSW) presents both a disposal challenge and potential source of valuable materials. The United States produced more than 292 million tons of MSW in 2018, per the U.S. Environmental Protection Agency (EPA).[1] This equates to roughly 4.91 pounds per day per person. Over 50% of MSW is landfilled, 32% is recycled and composted, and almost 12% is combusted for energy recovery (Figure 1).

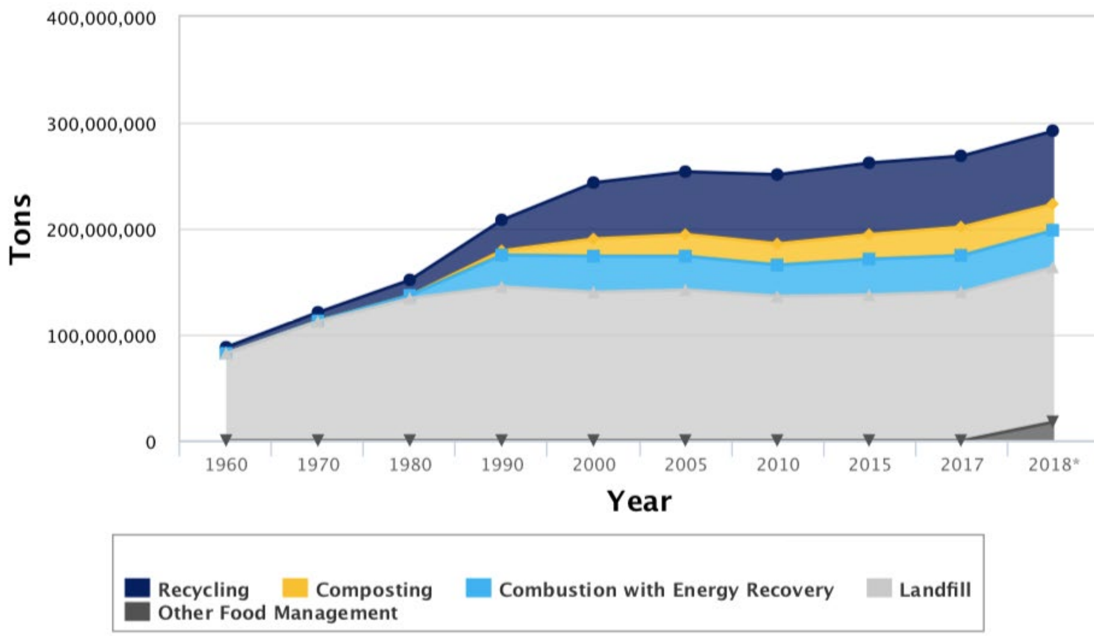

Figure 1. Municipal solid waste management from 1960–2018[2]

For local and state governments, landfills pose several challenges. Land use capacity is reducing, tipping fees are increasing, emissions such as methane negatively impact the environment, and the long-term stability of landfills remains uncertain, despite improvements in leachate containment and removal systems. Reducing MSW going to landfills has positive implications for the environment and society. Utilization of non-recycled waste materials provides one pathway to shift the value of MSW from a disposal challenge to a potential resource, both by developing technological advancements that enhance waste management and recycling systems and creating an economically viable feedstock. Research and development (R&D) in waste utilization can enable moving difficult components of the MSW stream to more preferred methods in the waste management hierarchy, from treatment and disposal to energy recovery and recycling, per the EPA (Figure 2).

[1] EPA. 2020. "Advancing Sustainable Materials Management: 2018 Fact Sheet – Assessing Trends in Materials Generation and Management in the United States." Washington, D.C.: EPA. EPA 530-F-20-007. https://www.epa.gov/sites/production/files/2020-11/documents/2018_ff_fact_sheet.pdf.

[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.

Figure 2. Waste management hierarchy[3]

Despite its abundance, waste has not always been considered a viable feedstock due to its compositional complexity and regional and temporal variability, as well as lack of economic impetus to deal with that complexity. However, industry and researchers have become increasingly interested in enabling MSW as a feedstock for the production of fuels and products. For example, the U.S. Department of Energy (DOE) published the "Waste-to-Energy from Municipal Solid Wastes" report in 2019,[4] which outlines strategies for improving economic viability of waste utilization, particularly for the production of liquid fuels, biochemicals, and other bioproducts. Chief among these is leveraging R&D around the production of biofuels and co-products from cellulosic materials and algae, as well as improving and developing preprocessing technologies and infrastructure to manage MSW variability.

Using MSW to produce a conversion-ready feedstock has significant challenges. This includes features of the waste stream such as low energy content, high moisture content, high levels of contamination, overall heterogeneity, and distributed availability. The advantage of using MSW is that there is an extensive collection, transportation, and handling infrastructure already in place, and there is a need to find new alternative options for MSW disposal in many locations. However, the main economic valuation of MSW is in its weight, and the infrastructure of materials recovery facilities (MRFs) deals primarily with volume. Conversion technologies have specifications beyond volume and yield necessary for the integrity of the process, as well as for the production of high-quality feedstocks.

Some strategies that the 2019 report identified to address these challenges include:

- Characterization and sensing methods of MSW

[3] EPA. 2020. "National Overview."
[4] 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.

- Development of discrete and quantifiable process quality control parameters relating feedstock composition to conversion performance attributes
- Development of pretreatment processes (e.g., chemical, electrochemical, biological, or other hybrid options) to selectively remove problematic constituents at early process stages and reduce feedstock variability.

For the cost-effective conversion of waste to fuels, chemicals, and products, conversion processes require prior separation of recyclable materials to achieve optimal resource recovery; preprocessing to reduce waste feedstock variability, optimal handling, and quality control of various components of MSW; and trade-off analysis of waste feedstock supply, logistics, preprocessing, and feedstock quality control that result in economic viability. By focusing on improvements to MSW characterization, preprocessing, and analyses of value, these strategies will enable the economic viability, efficiency, and sustainability of current and future waste management and utilization industries.

1.2 Workshop Objectives

The workshop examined the potential of MSW-to-feedstock production. Workshop presentations and breakout sessions focused on characterization, preprocessing, and valorization of non-recycled MSW, specifically the organic and plastic constituents of the waste stream going to the landfill. For the purposes of the workshop, the term “MSW” referred to waste that is not considered or used for recycling and is disposed in landfills (e.g., household garbage, yard trimmings, industrial residues from different areas). The primary objective of the workshop was to have workshop participants consider and discuss the state of the art, gaps, and challenges and opportunities in the following:

1. Characterization of MSW and the potential effects of feedstock quality on conversion process yield, kinetics, and economics
2. Logistics and preprocessing of MSW, including collection and handling technologies and infrastructure
3. MSW valorization and sustainability considerations, specifically cost and life cycle implications.

To increase the economic viability of using MSW as a feedstock, it is important to develop advanced sorting and preprocessing technologies. The “waste to conversion-ready feedstock” concept aims to leverage the abundant sources of MSW to increase the volume of available feedstock for a variety of conversion pathways at the lowest possible cost.

1.3 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. 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.

1.4 Parallels Between Municipal Solid Waste and Biomass

BETO has developed tools for optimizing and reducing the variability of lignocellulosic biomass. Because of similar challenges with MSW concerning aspects like variability, moisture content, and energy content, these tools can be applied to MSW. For example, chemical preprocessing and thermal preprocessing can improve energy content and reduce moisture. 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 is to identify synergies between technology development for biomass and for MSW.

2 Workshop Structure

On February 19–20, 2020, BETO hosted the "Advancing the Bioeconomy: From Waste to Conversion-Ready Feedstocks" workshop at the DoubleTree by Hilton hotel in Arlington, Virginia. The purpose of the 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 characterization, logistics, and valorization with the purpose of converting MSW to feedstock for fuels, chemicals, and products. This workshop builds off previous BETO-sponsored and co-sponsored workshops focusing on wastes, such as "Plastics for a Circular Economy"[5] and "Biofuels and Bioproducts from Wet and Gaseous Waste Streams."[6]

The attendees represented a wide range of stakeholders and experts, represented in Figure 3.

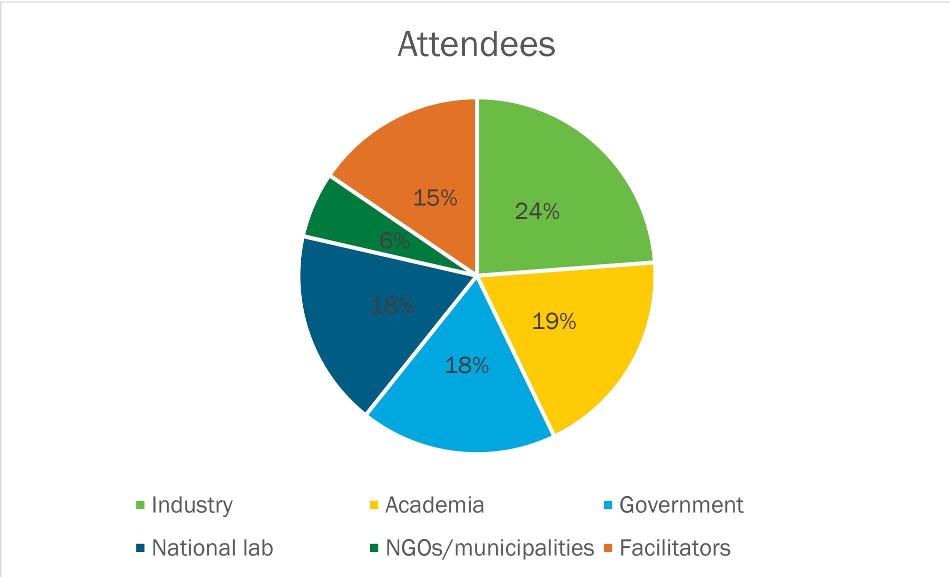

Figure 3. Workshop attendees by affiliation

The workshop consisted of presentations reviewing the Quality by Design (QbD) framework as well as the state of the art, challenges, and opportunities in MSW feedstock development. These presentations provided valuable framing and knowledge to inform breakout session discussions focusing on the critical areas—MSW characteristics and characterization, preprocessing and logistics, and valorization—and discussing the state of the art, gaps and challenges, and opportunities and prioritization of R&D.

2.1 Presentations

The workshop began with presentations to frame the breakout session discussions for workshop attendees. This included welcome statements from BETO; a primer and case study introducing QbD, a foundational

[5] BETO. 2020. *Plastics for a Circular Economy Workshop: Summary Report*. Washington, D.C.: EERE. DOE/EE–2074. https://www.energy.gov/sites/prod/files/2020/08/f77/beto-amo-mars-plastics-wksp-rpt-final.pdf.

[6] BETO. 2017. *Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities*. Washington, D.C.: EERE. 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.

research design concept developed most significantly by the pharmaceutical industry; 12 speakers in three plenary sessions; and six 3 × 5 presentations.

The plenary session speakers addressed the following core issues and questions:

- How Does Current Technology and Infrastructure for MSW Processing Work?
- Critical Material Attributes of MSW for Conversion Pathways: Technology Development to Support Diverse End Uses
- The Value of Waste: Consequences and Opportunities in Valorizing MSW as a Feedstock.

These plenaries provided context for the current state of the art of waste management; various R&D pathways considering feedstock characterization, logistics, and conversion readiness; and the social, economic, and environmental impacts and contexts of waste utilization. On the second day of the workshop, the "3 × 5" presenters had 5 minutes and approximately 3 slides to share feedstock challenges and MSW handling approaches from industry and national laboratory research perspectives.

2.1.1 Quality by Design Framework

Zia Abdullah, Laboratory Program Manager in Biological Science, National Renewable Energy Laboratory

Quality by Design: A Primer

Dr. Abdullah presented an overview of the Quality by Design approach in relation to bioenergy production. The pharmaceutical industry originally developed and utilized the QbD approach in the production of medical tablets (see Figure 4). The QbD approach can be analogous to biorefinery operations because multiple variables must be understood and controlled for to create a high-quality final product.

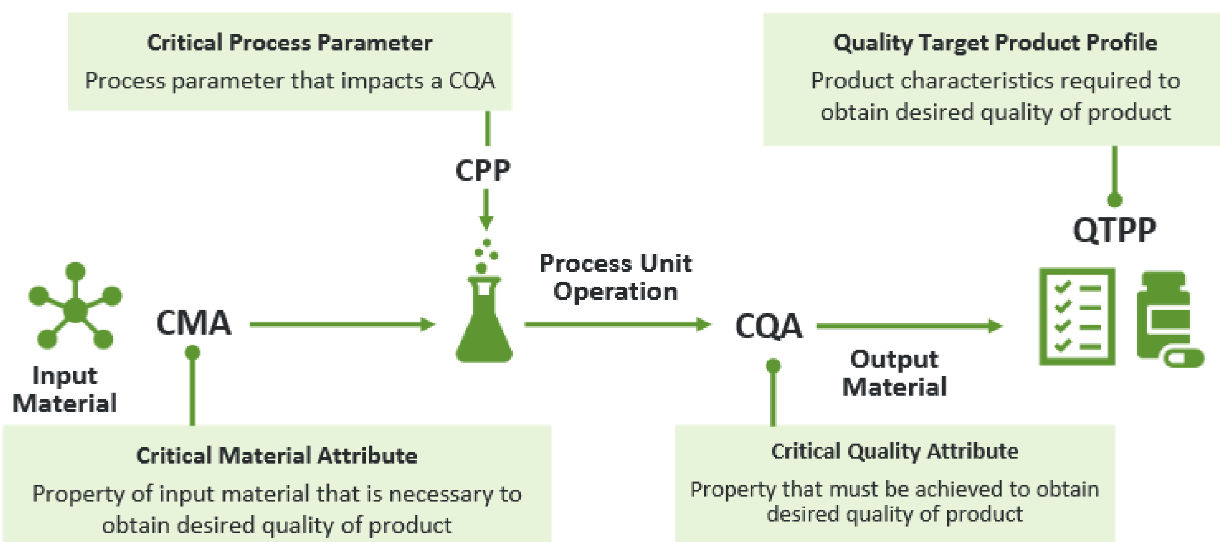

Figure 4. The QbD approach begins with the end product and focuses on meeting targeted critical quality attributes

Illustration from Zia Abdullah, National Renewable Energy Laboratory

Converting feedstocks to products is designed to process multiple inputs. Significant variability in feedstocks—like moisture and rheological properties, such as particle size and shape—present significant challenges for feedstock flowability, a major challenge identified by biorefinery stakeholders.[7] To help address these challenges, BETO created the Feedstock-Conversion Interface Consortium. Its objective is to develop science-based knowledge and tools to understand and mitigate the effects of biomass feedstock and process variability on biorefineries. The framework of QbD has researchers and engineers consider three concepts—critical material attributes (CMAs), critical quality attributes (CQAs), and critical process parameters (CPPs). A CMA is a physical, chemical, biological, or microbiological property or characteristic of an input material that has an impact on the output materials or product. A CQA is any physical, chemical, biological, or microbiological property or characteristic that must be within a limit or range to ensure the product meets the required attributes. CPPs refer to the variation within the process producing a final product that can impact the CQA and should therefore be monitored. As MSW is also highly variable, a QbD approach to characterizing and processing this waste could be a valuable exercise in determining the most efficient methods to process and convert MSW for various end uses.

Jordan Klinger, Staff Researcher, Idaho National Laboratory (INL)

QbD Case Study: Densification of Municipal Solid Wastes and Residues

Dr. Klinger presented a QbD case study on MSW preprocessing and mitigation of feedstock variability. Among various preprocessing and fractionation technologies that are necessary to transform MSW into conversion-ready feedstocks, his case study primarily focused on blending and densification of mixed paper and plastics wastes into high-energy fuel pellets. Densification of waste materials offers the technical benefits to improve the bulk and energy density and flow properties, as well as to obtain durable and uniform pellets for cost-effective transportation and conversion. The QbD approach provides a fundamental understanding of what qualities the end product—high-energy fuel pellets—should have, and how the waste material would be processed and tested to meet these desired qualities attributes.

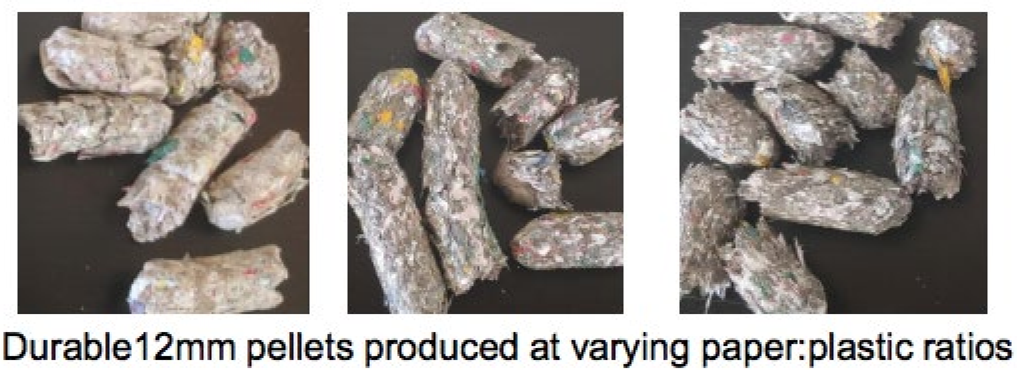

Figure 5. MSW pellets

Photo from Jordan Klinger, INL

From the feedstock perspective, the distribution between the blended plastic waste and the paper waste, as well as the initial particle sizes, were critical attributes of the material that led to the output of high-energy content and formation of a homogenous and durable pellet. At the proper blending ratios and processing temperature, plastic can act as an effective binder and moisture repellant. The application of densification and the control of

[7] EERE. 2016. *Biorefinery Optimization Workshop Summary Report*. Washington, D.C.: EERE. DOE/EE-1514. https://www.energy.gov/eere/bioenergy/downloads/biorefinery-optimization-workshop-summary-report.

the CPPs of die aspect ratio and material heating temperature in a flat die mill can achieve pellets with over 90% durability and <5% moisture uptake. Following the QbD paradigm, the fundamental knowledge to control the production process increased, which benefited from identification of CMAs and CPPs and their interactions and impacts on the product quality, so as to achieve optimized and desired product CQAs.

2.1.2 **Plenary Presentation Summaries**

The plenaries covered three main topics: (1) the state of the art of MSW management, (2) characteristics of MSW and their impact on feedstock potential and conversion processes, and (3) valorization of MSW. Presenters focused on the technological challenges associated with using portions of sorted MSW as feedstocks.

Plenary 1: How Does Current Technology and Infrastructure for MSW Processing Work?

Brad Kelley, Senior Project Engineer, Gershman, Brickner, and Bratton, Inc.

State of Technology for MSW Processing: Smart Technologies for Processing MSW

Mr. Kelley described the infrastructure of facilities and resources that currently exist in the United States, including 9,000 source separation collections, 736 MRFs, 51 mixed-waste processing facilities, and 1,908 landfills. Mr. Kelley primarily focused on mixed-waste processing facilities, including geographic distribution and the general layout.

A common U.S. process at mixed-waste processing facilities is to begin with the separated sources and send them to mechanical and biological treatment facilities that create end products such as recyclables, compost, biogas, electricity, and refuse-derived fuels and engineered fuels. Mr. Kelley also described the future of MRF systems. This could include systems that are able to process more than one and even multiple streams, systems that use optical systems and "smart" technologies rather than screens, and even those that rely on robotic sorters for quality control and pre-sorting. The smart technologies can recover materials such as fiber, flexible packaging, and film due to shape recognition, improved algorithms, and attention to air flow characteristics. He did caution that although these smart technologies like quality control robotic sorters have better speed, accuracy, and decent return on investment, they are also expensive, have uncertain life spans and maintenance needs, and still have limitations in their identification and processing of materials. He predicted that the lines between processing single streams, MSW, and construction and demolition waste will become blurred as systems become capable of processing multiple waste streams. These new systems will create new commodity streams, which will require these more adept processing facilities to be part of a larger materials recovery process.

Magdi Azer, Chief Technology Officer, REMADE Institute

State-of-the-Art Sorting Technologies

Dr. Azer introduced the DOE Advanced Manufacturing Office-funded REMADE Institute (Reducing EMbodied-energy And Decreasing Emissions), a public/private consortium developing transformational technologies to accelerate the United States' transition to a circular economy for plastics, metals, fibers, and e-waste. REMADE's strategic goals are to enable greater utilization of secondary feedstocks, reduce consumption of primary materials, and promote use of new technologies that expand material recycling, reuse, remanufacturing, and recovery. At the time of the workshop, REMADE had invested $15 million in 30 projects and 45 collaborating organizations. Dr. Azer focused on plastics and plastic waste recycling. One process for recovering plastics includes size reduction, plastic cleaning, removal of non-plastics, plastic-plastic separation, and transforming plastic into a feedstock. Each step in this process may require multiple methods.

For example, separating plastics may use a combination of density, reflectance signatures, and/or electrostatic properties to effectively sort plastics. Near-infrared lasers cannot "see" black plastics, and some plastics have similar densities. Each method has limitations and benefits based on the material stream and the targeted end product.

Plenary 2: Critical Material Attributes of MSW for Conversion Pathways: Technology Development to Support Diverse End Uses

James Dooley, Chief Technology Officer and Co-Founder, Forest Concepts, LLC

Adapting 20 Years of Biomass Feedstock Supply Chain Innovations to MSW (and Recyclables): A Dramatically Shorter Development Cycle Resulting from Cumulative Know-How, Science, and Engineering

Dr. Dooley provided a history of woody feedstock development since the 1970s. He emphasized that the trend for bio-based material production is solid and accelerating and will require that these firms have access to raw materials and high-quality, sustainably produced, cost-effective renewable feedstocks. In 1970, woody biomass resources were primarily mill residuals and, less often, biomass removed for forest health. By 1995, this supply had doubled from 100 to 200 million tons, removing dead trees, forest residuals, resources from wildfire prevention, and plantations. In 2020, there were 400 million tons of woody biomass available, adding biomass from orchards and utility vegetation management to the previous sources. This increase in supply-side volume has significantly decreased the relative cost to a bioeconomy user within 50 miles. Dr. Dooley also covered major innovations within DOE-funded supply-chain technologies, including logistics modeling; characterization; milling, screening, drying, washing, and leaching technologies; and the development of uniform-format feedstocks through densification, homogenization, and blending. This also includes Forest Concepts' DOE-funded development of Crumbler® technology. He focused on the benefits of uniform-format feedstocks, specifically their highly flowable and efficient bulk handling characteristics. He also discussed the benefits of creating designer blends with miscible feedstocks, such as a blend using uniformly formatted feedstocks of Amazon boxes, Amazon mailers, soda bottles, water bottles, and wood chips. Initial R&D demonstrates that MSW is also amenable to these types of processes.

Ezra Bar-Ziv, Professor, Mechanical Engineering, Michigan Technological University

Feedstock Preparation for MSW Valorization

Dr. Bar-Ziv framed his talk by highlighting that current technologies, with some required integration and modification, can valorize waste. He emphasized a new concept may be needed, with emphasis on novel products and necessary feedstocks. He categorized waste as household waste, plant-based materials, and fossil-based polymers. Commonalities between them are the high level of heterogeneity and inconsistency and difficult flowability. However, each has unique intersecting challenges. Valorizing household waste is challenging, in part, due to health risks associated with existing bacteria, high moisture content, and presence of hazardous materials such as chlorine, sulfur, and mercury. For plant-based materials, the high moisture content, ash, minerals, hazardous materials content, and potential biohazards all comprise challenges for waste-derived feedstock development. For fossil-based polymers, contaminants and cross-contaminants present challenges. Dr. Bar-Ziv also identified necessary CQAs for each group. For example, household waste-based feedstocks (in this case homogenized pellets) need to be dry, lacking bacteria, uniform, consistent, flowable, and have no elements like chlorine or sulfur. Michigan Technological University's pilot plant with Convergen Energy has conducted R&D, particularly on torrefaction and removal of chlorine.

Armando McDonald, Professor, Renewable Materials Chemistry, University of Idaho

Mixed Plastic Waste Deconstruction & Reconstruction

In collaboration with Dr. Bar-Ziv, Dr. McDonald presented on mixed plastic deconstruction and reconstruction. Plastic mixtures are often complex and can consist of polyethylene, polypropylene, nylon, polyethylene terephthalate, and others. Thermochemical deconstruction is generally low-cost and robust, whereas catalytic thermochemical deconstruction has the cost of the catalyst and catalyst regeneration to consider. Dr. McDonald identified that reconstruction options are based on thermochemical conversion product profiles and focused on mixed plastics from composites and producing higher-molecular-weight polymers from both long- and short-chain olefin/diene oligomers by epoxy intermediates.

Bruno Miller, Managing Director – Fuels, Fulcrum Bioenergy

Fulcrum Bioenergy processes around 400,000 tons of MSW per year to make fuel. Benefits of utilizing MSW for feedstock include its proximity to urban centers, its aggregation in large quantities, and its very low cost. However, MSW contains high levels of components that are not good for making fuel, making sorting vital. Fulcrum took an existing MRF and rearranged its infrastructure to suit its needs. For example, Fulcrum shreds materials via conveyor belts, densifies materials with magnets, and uses optical sorters. The end product contains fibrous materials, food and yard waste, and plastics, the latter being difficult to remove. Although plastics have good energy content (hydrogen) and increases the end-product yields, life cycle assessments show that having more plastics also increases greenhouse emissions. One of Fulcrum's objectives is to determine the ratio of the right amount of plastic for environmental benefit and energy content.

Grace Chen, Assistant Professor, Plastics Engineering, University of Massachusetts-Lowell

Material Attributes of MSW that Impact the Quality for Hydrothermal Processes: Pathways and Feedstock End Uses

Dr. Chen presented on material attributes of MSW, specifically the plastic and food components, that impact hydrothermal processes. Her lab, the Plastics and Environment Research Laboratory, investigates plastic recycling and bioplastic development, primarily using hydrothermal processing (HTP) to convert waste into various products. Benefits of HTP include that it can process wet feedstocks and produce a product similar to crude oil with higher energy density than the products from other conversion processes such as pyrolysis and gasification. A challenge of HTP is the high pressure required for the process. In her lab, HTP of proven feedstocks (e.g., algae, animal waste, sewage sludge, food waste, plastic waste) produces a gas product (10%), post-conversion wet waste (20%–40%), solid residue (10%–30%), and biocrude oil product (20%–50%). In her presentation, Dr. Chen reviewed two research questions her lab explored: the impact of ash content and the impact of fat content on HTP. Their work found that when the crude fat in food waste increased, the biocrude oil yield increased. Additionally, HTP can tolerate high ash content from food waste.

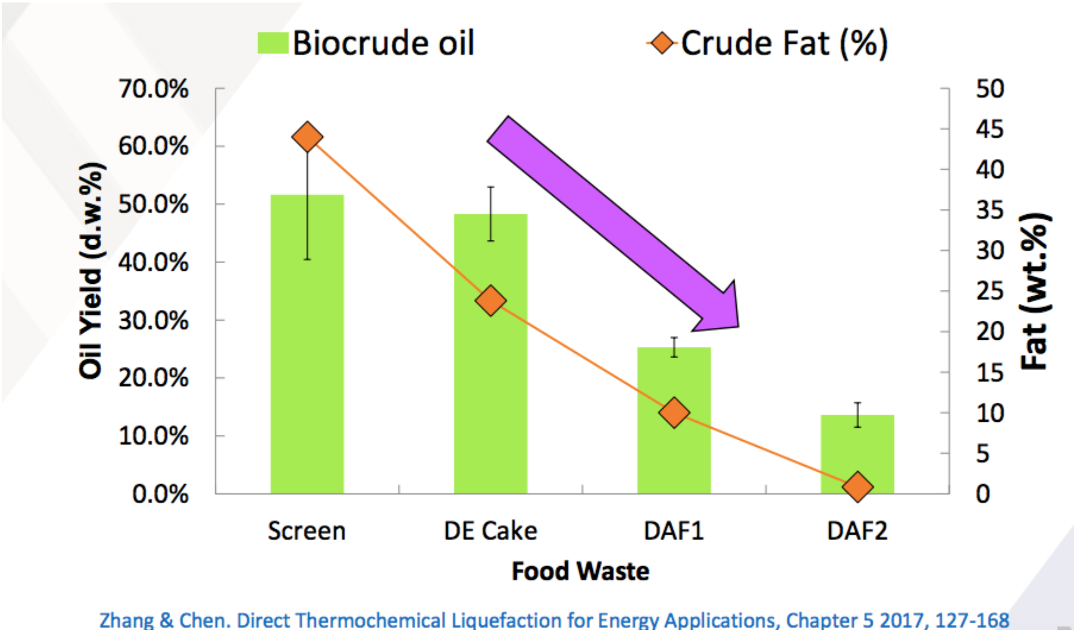

Figure 6. Impact of crude fat content on biocrude oil yield from food waste, 280°C at 30 minutes[8]

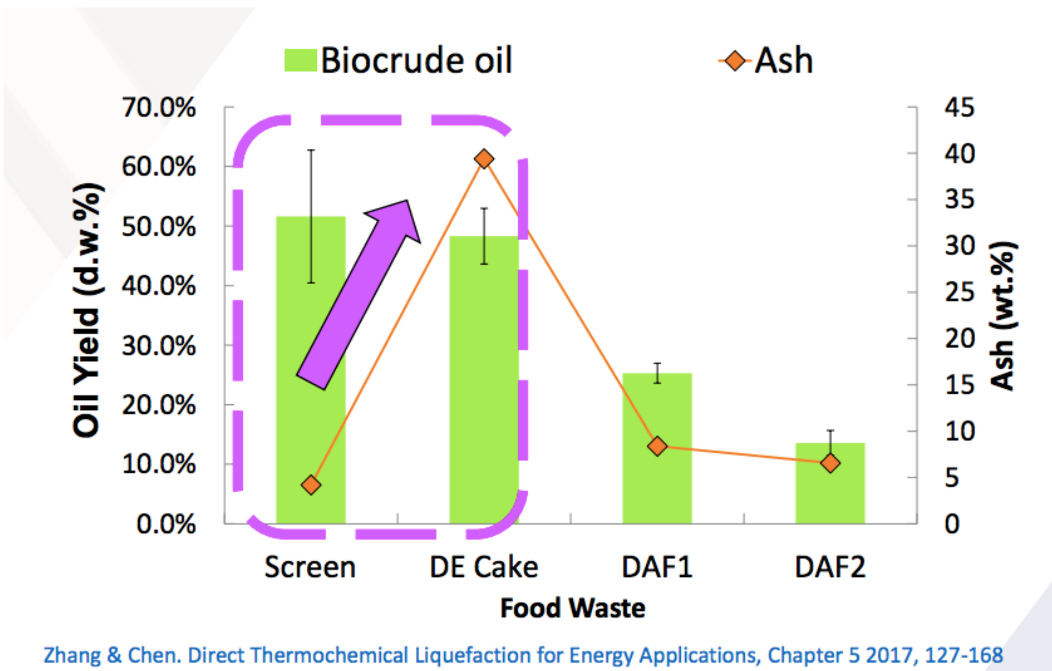

Figure 7. Impact of ash content on biocrude oil yield from food waste, 280°C at 30 minutes[9]

Her lab continues to seek answers to the questions around the most abundant ash types and their content in MSW, as well as the impact of different ash contents on HTP. More research is needed to elucidate HTP's tolerance levels for contaminants like plastic additives (e.g., plasticizers and flame retardants). Finally, research is also needed to elucidate the interaction between food waste and plastic waste. Once the plastic and

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[8] Zhang, Y. and W.-T. Chen. 2018. "Hydrothermal Liquefaction of Protein-Containing Feedstocks." In *Direct Thermochemical Liquefaction for Energy Applications*, edited by L. Rosendahl, 127–168. Cambridge: Woodhead Publishing.
[9] Zhang and Chen. 2018. "Hydrothermal Liquefaction."

food wastes cross-contaminate, they cannot be recovered by conventional methods. The presence of plastic waste slows down the composting and anaerobic digestion (AD) processes and pollutes the AD products, so identifying methods that can simultaneously deal with plastic and food wastes is key to effectively processing MSW.

Toufiq Reza, Assistant Professor, Florida Institute of Technology

Hydrothermal Carbonization: A Thermochemical Pathway to Convert Wastes to Conversion-Ready Feedstocks

Dr. Reza identified barriers to the use of MSW as a feedstock for energy and co-product production. These barriers that his research team at Florida Tech are addressing include heterogeneity, moisture content, poor mechanical dewaterability characteristics, high ash content, low bulk density, grindability, and contaminants to upstream processes. Dr. Reza presented work performed on the organic fraction of MSW using AD, but focused on a newer technology, hydrothermal carbonization. Hydrothermal carbonization uses temperature and pressure to produce a liquid fraction that appears to have potential as a fertilizer and a solid fraction, which he described as hydrochar, that has many characteristics that could make it a suitable feedstock for energy or conversion to fuels. Hydrochar is more homogeneous, hydrophilic, and amenable to pelletization and contains less ash and other contaminants than the organic fraction of MSW. Dr. Reza discussed future research efforts being undertaken to refine hydrothermal carbonization and adding process steps to produce a conversion-ready feedstock.

Charles Tremblay, Vice President of Project Delivery, Enerkem

Waste to Conversion-Ready Feedstock Requirement

Mr. Tremblay presented on Enerkem's technology for converting waste into valuable clean fuel and renewable chemicals. The Enerkem process uses gasification to produce a synthesis gas that is converted to methanol. The methanol can be further refined to ethanol using Enerkem proprietary technology. Enerkem targets MSW, plastics, agricultural residues, and woody biomass for feedstocks. By using these feedstocks, they reduce waste going to landfills, which avoids methane emissions. Critical feedstock properties that impact the syngas and product yield include caloric value, ash content, moisture content, density, and biogenicity content (carbon content from organic source). In addition, chlorine, sulfur, and heavy metals contained in the waste have significant economic impact for management and water treatment. Gasification stability requires adequate control of waste heterogeneity through mechanical buffering, feedstock preparation, and feeding process. MSW is a carbon-rich resource to produce a gasification feedstock for the Enerkem process. The carbon comes primarily from two sources in MSW, plastics and the biogenic fraction. Currently, only the biogenic portion of the carbon stream is incentivized through government policies like the Renewable Fuel Standard, Low Carbon Fuel Standard, landfill bans, or taxes reflected in tipping fees. Plastic and other fossil-based waste generate more yield in the conversion process but still need incentive to compete with virgin fossil-based carbon.

Plenary 3: The Value of Waste: Consequences and Opportunities in Valorizing MSW as a Feedstock

Vicki Thompson, Distinguished Staff Engineer, INL

Valorizing MSW into Conversion-Ready Feedstocks

Dr. Thompson reviewed the rationale behind and strategies for valorizing MSW and creating conversion-ready feedstocks. Her presentation highlighted challenges and opportunities associated with the changes in recycling and waste management policy. Other countries have enacted environmental and trade policies that limit and even ban the importation of particular kinds of waste. These trade restrictions compound the accumulation of waste in the United States, in part, because many states are implementing food and yard waste bans from landfills. Understanding the impact of waste availability and contamination issues is crucial for valorization. She highlighted previous research funded by BETO that blending corn stover and MSW for feedstock production can meet both cost targets ($80/ton or less) across geographic regions and quality requirements for conversion processes in terms of ash, glucan, and xylan contents. For biochemical conversion, appropriate feedstocks for study include aseptic and polycoats (e.g., juice boxes, milk containers, wax-coated materials), food-soiled paper and cardboard (e.g., pizza boxes, paper towels), shredded paper, and yard waste (e.g., grass clippings, leaves). In lab trials for biochemical conversion of MSW versus corn stover, the yields of xylan and glucan are lower in components of raw MSW, likely due to contaminants and coatings. However, stover and MSW blends had comparable yields to stover, likely due to synergistic effects within blend compositions. For thermochemical conversion, appropriate feedstocks for study include yard waste (e.g., branches, tree trimmings), construction and demolition waste (e.g., plywood, microlams, waferboard, fiberboard), and new construction versus demolition materials. For a pyrolysis study of microlam, plywood, waferboard, and fiberboard, oil yields ranged between 65%–82%, char yields 10%–25%, and contaminants included glue, wax, and adhesive. Dr. Thompson presented the capabilities and upgrades to the Biomass Feedstock National User Facility—a DOE-funded user facility housed at INL—for material sorting, milling, advanced fractionation, and chemical preprocessing. Her demonstrated research findings include that chemical preprocessing and air classification decreased contaminant contents, increased bio-oil yields from pyrolysis, and reduced wear on equipment. Finally, she also introduced REMADE work funded by DOE's Advanced Manufacturing Office on MSW sorting, e-waste recycling, and spatial, process, and supply chain modeling, showing lab capabilities funded by DOE and potential synergies across different program offices.

David Shonnard, Professor of Chemical Engineering and Director of the Sustainable Futures Institute, Michigan Technological University

Sustainability of Valorizing MSW

Dr. Shonnard presented on the sustainability of valorizing MSW with a focus on waste plastics. He described various conversion technologies for both mechanical and chemical recycling of waste plastics and summarized up-to-date life cycle analysis (LCA) results of mechanical recycling of waste plastics (polyethylene terephthalate, high-density polyethylene [HDPE], and polypropylene), which exhibit energy and greenhouse gas emissions savings compared to virgin resins obtained from fossil feedstocks. For the case study of thermochemical conversion of waste HDPE, he presented results of a techno-economic analysis based on process simulation of a multi-product refinery process for conversion of waste HDPE into monomers, aromatics, and hydrocarbon liquid products using pyrolysis. The facility was modeled to be profitable with a large positive net present value, and scenario analyses showed the effects of waste HDPE feedstock price and internal rate of return on net present value. LCA results (greenhouse gas emissions) indicated savings compared to equivalent fossil products for the waste HDPE refinery products and the importance of the electricity grid on the greenhouse gas savings. The presentation identified a number of knowledge gaps, including the lack of process data as well as techno-economic analysis and LCA results for emerging chemical recycling process technologies. These gaps in knowledge limit the ability to compare economic and environmental performance of emerging waste plastic valorization approaches compared to current production methods that rely on fossil feedstocks for plastics production and conventional end-of-life treatments (mostly landfilling).

Scott Bouchie, Director, City of Mesa Environmental Management & Sustainability Department

City of Mesa Food-to-Energy Program

As the director of Mesa's Environmental Management & Sustainability Department, Mr. Bouchie shared the case study of the city's program to convert food waste into energy. Mesa is a city close to Phoenix, Arizona, and has its own water treatment plant and natural gas utility. In 2019, the City of Mesa landfilled 240,000 tons of MSW and recycled 30,000 tons (contamination levels in the recycled material were at 10%–13%). The landfill serves 120,000 residential customers and 1,100 commercial accounts. This resource base gave Mesa the unique ability to conduct a feasibility study for a food-to-energy program that would use locally generated waste to power its facilities. For the feasibility study, food waste was sourced from organizations like schools and universities, a food bank, and a hotel to be converted to a renewable natural gas, also known as biogas, using anaerobic digestion. Equipment and facilities to remove packaging before sending the food waste to the digester constituted a high capital cost. To be economically viable, all of the commercial food waste was necessary to meet capacity needs of the proposed AD facility. The project then did bench-scale lab work on AD, which found that composition could significantly alter AD conditions, such as increases in volatile fatty acids, decreased pH, and increased methane production. The project also looked at the end product, biogas, determining quality needs and economic feasibility. For economic feasibility, they examined power generation, heating value, and D3 and D5 renewable identification numbers (RINs). A RIN is a credit used for compliance and the currency (with a monetary value) of the Renewable Fuel Standard program. D3 RINs are for cellulosic biofuels and D5 RINs are for advanced biofuels. Claiming the renewable natural gas generated from the AD system as an advanced biofuel, which receives D5 RINs, has the most impact on CO_2 reduction (4,789 metric tons) but also high initial capital cost ($18 million) and the longest payback period (37.6 years). Claiming the renewable natural gas as a cellulosic biofuel with D3 RINs has the lowest capital cost and payback period ($4 million and 10.9 years) with the second-largest impact for CO_2 reduction (1,662 metrics tons). Moving forward, this project will be looking into opportunities and partners to address the D3/D5 split, develop methodology for quantifying cellulose conversion to methane in complex waste streams, and evaluate more waste streams for renewable natural gas for end use and financial feasibility.

2.1.3 3 × 5 Presentations: MSW Handling and MSW Challenges

Morton Barlaz, Professor, Civil, Construction, and Environmental Engineering, North Carolina State University

Dr. Barlaz shared his expertise in landfill processes and LCA application to solid waste management. The latter includes creating and optimizing process models for each unit operation of solid waste management (i.e., generation, collection, transport, separation, biological and thermal treatment, landfill disposal) and assessing the environmental impact of existing and new technologies. One of his case studies examined life cycle modeling of nutrient and energy recovery within mixed-waste processing systems. Results showed that (1) gasification to electricity resulted in the lowest environmental impacts compared to gasification, Fischer-Tropsch, and landfill processes; (2) separating organics for composting or AD increased the environmental impacts; and (3) the level of syngas compression caused higher greenhouse gas emissions in gasification and the Fischer-Tropsch process compared to other waste-to-energy processes (Figure 8).

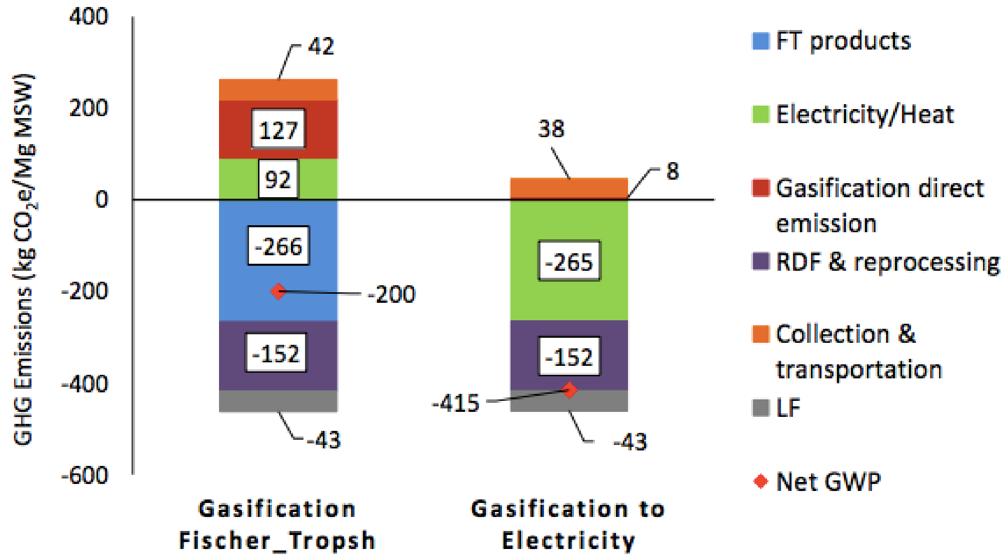

Figure 8. Life cycle analysis of nutrient and energy recovery of mixed-waste systems

Figure from Morton Barlaz, North Carolina State University

Ning Sun, Biological Engineer Research Scientist, Advanced Biofuels Process Development Unit, Lawrence Berkeley National Laboratory

Dr. Sun presented the Advanced Biofuels Process Development Unit's capabilities in recycling (mechanical separation, upgrading, and conversion) post-consumer absorbent hygiene products (e.g., diapers) and organic wastes. In collaboration with Recology, a MSW resource recovery company in San Francisco, her team performed detailed chemical and biological (using 16S rRNA sequencing) characterization of paper- and food-rich MSW streams to understand major chemical composition, microbial communities, and their biological reactivity for conversion into monomeric sugars and organic acids. She also presented a case study in collaboration with INL on evaluating MSW and lignocellulosic blends for biochemical conversion, and their results showed that the low-cost waste stream is a promising blending reagent to reduce feedstock cost and improve the quality for biochemical conversion, as compared to other lignocellulosic feedstocks.

Meltem Urgun-Demirtas, Group Leader, Bioprocesses and Reactive Separations, Argonne National Laboratory

Lessons Learned from Handling and Utilization of the Organic Fraction of MSW (OFMSW)

Dr. Urgun-Demirtas presented challenges with MSW-based feedstocks in co-digestion at wastewater treatment plants, resource assessment, and sample complexity for analysis. She also shared key issues learned from handling and utilization of OFMSW in co-digestion with sludge at wastewater treatment plants. Infrastructure at these plants needs retrofitting and new design criteria for future plants to make co-digestion viable. High feedstock variability, foaming issues, and inhibitory substances generated during AD, as well as process upsets, all present challenges to effectively utilize OFMSW. Her previous analysis of an Illinois wastewater treatment plant demonstrated that co-digestion of OFMSW (up to 20% solid organic loading) could increase biogas production by ~59%. Agencies and industry use different metrics and approaches in handling waste, making determination of the right blend for bioprocesses difficult and complicated (e.g., total/volatile solid content versus carbon content). EPA and the U.S. Department of Agriculture arrive at different outcomes for their food waste resource assessments based on their selected boundaries and interpretation of uncertainties, and DOE's national labs (National Renewable Energy Laboratory and Pacific Northwest National Laboratory) also developed food waste resource assessment at the county level. Finally, MSW's complexity and high variability often require utilization of three or four analytical methods together to understand biodegradation trends, and analytical reproducibility is difficult even in the same sample. Overall, challenges are present at molecular, macro, and policy scales for OFMSW utilization.

Manuel Garcia, Vice President, nanoRANCH UHV Technologies

Low-Cost, Scalable, Modular Sorting Technology for Municipal Solid Waste

Mr. Garcia, on behalf of Dr. Nalin Kumar, presented on nanoRANCH UHV Technologies' recently developed AI technology that visually characterizes MSW, specifically metals. "Looks" can be programmed for sorting of various categories of MSW, such as aluminum cans, glass bottles, and plastic bottles. The technology has capacity for multiple output streams for as many as 16–32 product categories. Nearly 100% accuracy is possible, and running more materials improves accuracy. In addition, the technology is user-friendly and can be trained for any "look" of materials. The visual identification is then compatible with various sorting mechanisms, such as vacuum, air-jet, electromagnetic force, and robotics. Sorting scrap metal increases value, as one analysis showed with unsorted scrap valued at $40,000 and sorted scrap at $60,000 (Figure 9). This includes a coin sorter they developed, as cars may contain $10–$100 in coins. AI technology can improve value within MSW streams.

Sorting of a Truckload (40,000 lbs) of Automotive Metal Scrap

		Weight (lbs)	Price $/lb	Value $	TOTAL $
Un-Sorted Scrap		40,679	$ 1.00	40,679	$ 40,679
	Copper	14,170	$ 2.20	$ 31,174.00	
	Brass	8,890	$ 1.80	$ 16,002.00	
	Zinc	12,270	$ 0.75	$ 9,202.50	
	Aluminum	4,583	$ 0.55	$ 2,520.65	
	Coins	70	$ 15.00	$ 1,050.00	
	PCBs	12	$ 1.00	$ 12.00	
	SS	10	$ 1.50	$ 15.00	
	Leftover	674	$ 0.25	$ 168.50	
SORTED Scrap			TOTAL		$ 60,145

Figure 9. Analysis of value of sorted versus unsorted scrap metals

Figure by Nalin Kumar, nanoRANCH UHV Technologies

Ted Hansen, Chemical Engineer and CEO, Convergen Energy

Producing Renewable Fuels and Power for Sustainable Businesses

Convergen Energy processes and converts non-recyclable industrial byproducts into renewable fuel pellets engineered to be combusted in solid fuel boilers. Convergen supports over 100 companies and has diverted over 400,000 tons of non-recyclable wastes from local landfills, producing over 250,000 MW of renewable power, or enough electricity to power almost 20,000 homes for a year. Currently, the company processes

>7,000 tons per month of non-recyclable industrial byproducts. Mr. Hansen noted similar challenges in MSW quality and handling as highlighted throughout the workshop, such as high moisture, low energy content, high variability, high levels of contaminants like chlorine, and presence of mercury and fluorine. To address these challenges, Convergen has selected a narrower scope of feedstock (industrial byproduct) and developed various preprocessing technologies so as to create product specifications that meet permitting requirements, perform well in boilers, and have low moisture and contaminant levels. Convergen aims to use the R&D enabled by their current process to move to processing complex MSW into value-added products.

Chad Haynes, Senior Intellectual Property Manager, LanzaTech

Dr. Haynes shared LanzaTech's perspective that unsorted, non-recyclable MSW represents a significant resource for making fuels and chemicals. He noted that conversion of plastic waste and refuse-derived fuel to syngas is already practiced in some places, like Japan. Current MSW operations are primarily landfilling or incineration, which are not sensitive to composition; as such, very little long-term composition data exist. Particularly, data are lacking regarding feedstock composition and its impact on downstream conversion into syngas or other intermediates. Successful MSW utilization projects would require investment in MSW processing technologies and large-scale demonstrations, and policy support that prioritize high-value products over power. Dr. Haynes presented LanzaTech's core technology, a microbial gas fermentation process that converts syngas to over 100 commodity chemicals and fuels. The gas feedstock can be taken directly from waste industrial emissions or produced via gasification of biomass residues and MSW. LanzaTech is currently running a multiyear pilot-scale demonstration outside of the United States to produce ethanol from MSW-derived syngas.

2.2 Major Themes and Takeaways from the Presentations

Technical presentations at the three plenary and 3 × 5 sessions provided valuable context for all workshop participants to understand, discuss, and exchange knowledge on MSW quality variability, the current processing state of technology and infrastructure, opportunities in valorizing MSW feedstock, MSW handling, and challenges with management and utilization. All participants recognized that MSW is a promising low-cost feedstock resource, but its variability poses significant challenges for downstream conversion. Various conversion pathways have different feedstock quality specification requirements, and detailed characterization and compositional data are still lacking to understand and manage MSW variability. Multiple speakers noted that infrastructure for MSW collection, transportation, and handling already exist in waste management and MRFs, and it is important to develop sorting and preprocessing technologies to increase the economic viability of these facilities and industries. Data gaps in MSW resource composition, handling, preprocessing, and conversion processes limit the ability to evaluate the economic and environmental performance of current and emergent waste utilization technologies.

3 Breakout Session Summaries

Four breakout sessions were organized to cover three focus areas touching several key overarching aspects of MSW streams and feedstocks during the two-day workshop. The objective of the breakout sessions was to bring BETO staff, researchers, and industry stakeholders together to discuss the current state of technology and infrastructure for MSW characterization, preprocessing, and utilization; challenges and opportunities; potential economic, social, and environmental values; and stakeholder perspectives on the priorities in advancing MSW R&D.

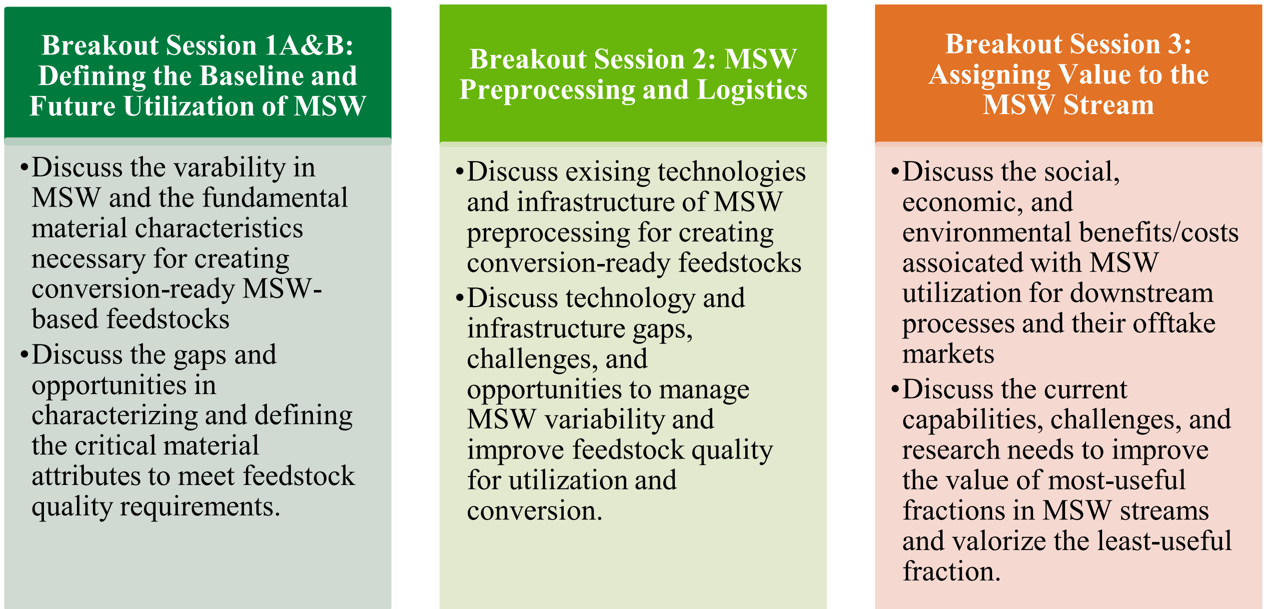

Figure 10. Breakout session topics and discussion focus

3.1 Group 1: Defining the Baseline and Future Utilization of MSW

3.1.1 Objective

During this breakout session, participants discussed the following:

- Current state of the art in measuring MSW variability, and potentially impactful material attributes for conversion processes
- Available and still-needed characterization techniques
- Prioritized R&D challenges and opportunities for transforming MSW streams into conversion-ready feedstocks for downstream processes to produce biofuels and bioproducts.

3.1.2 Current State-of-the Art Characterization of MSW Streams

MSW represents a low-cost, abundant, heterogeneous resource containing materials with widely varying chemical compositions and physical (e.g., particle size distribution, shape, surface hardness) and biological properties (e.g., toxicity, pathogenicity).

The members of Groups 1A and 1B recognized and discussed:

- The current waste management industry and MRFs focus on collection of various waste sources including residential, commercial, construction and demolition, and nonhazardous industrial waste. MSW is characterized as part of the sorting process and often because of government policy for waste management.
- Waste may be sorted by properties such as density, weight, color, size, or type of waste present in the streams, including metals, glass, plastics, electronics, and rocks. Waste is often characterized through visual inspection and manual sorting and separation.
- Chemical composition of MSW, after being hand-sorted into categories, can be measured in analytic labs using available methods such as proximate/ultimate analysis and ASTM International methods for moisture, sugar, fiber, plastics, and ash/mineral species and contents, which are of interest to the sorters or downstream conversion processes. However, nearly all current sorting methods are based on visual,

density, and magnetic properties in nature and rely on resin identification codes and industry knowledge to sort the categories.

- Although emerging technologies such as spectroscopy (e.g., near-infrared, mid-infrared, X-ray) and sensors are being developed to characterize organic and inorganic constituents in MSW based on models built from ultimate analysis and other standard wet chemistry methods, they are still at the early stages of being validated and adopted by industry.
- Obtaining detailed chemical composition as well as physical and biological property data still relies on time-consuming sample preparation, offline measurement, and comprehensive analytics in the lab.

3.1.3 Gaps and Challenges

The heterogeneous nature of MSW streams creates challenges for developing standard analytical protocols to identify and quantify CMAs and CQAs, as well as for establishing quality target product profiles toward downstream conversion into fuels, chemicals, and products. The quantity and quality of MSW streams can vary depending on many factors, including source, location, weather, and collection practices (e.g., sorting, separation).

The gaps and challenges discussed at the breakout sessions include:

- The current characterization for sorting and utilization is limited at the industry scale, and there is a fundamental lack of understanding of MSW variability in terms of the wide range of chemical, physical, and biological attributes at macro, micro, and molecular scales. Specifically:
    - Current MSW characterization for sorting and separation are mostly limited to density/color/visual inspection
    - There is a lack of characterization of chemical stability, microbial stability, and biohazards (other than wastewater toxicity and pathogenicity).
- There is a lack of standard sampling and analytical protocols to define and quantify the MSW CMAs and their downstream impacts.
- There is a lack of comprehensive MSW material attribute databases and public data-sharing mechanisms to support tool development for characterization.
- The required feedstock CQAs for different biofuel conversion pathways vary.
- There is a lack of computation tools to correlate material attributes with downstream performance and evaluate the criticality.

3.1.4 Opportunities for MSW Characterization

Material attributes of MSW (including physical, chemical, and biological) require fundamental understanding and characterization tools at multiple scales (including macro, micro, and molecular) and across the supply chain from the source of collection and preprocessing to conversion/utilization.

Multi-Scale MSW properties

Members of Groups 1A and 1B discussed that most currently measured MSW properties are at the macro and/or micro scale, rather than the molecular scale. There are MSW properties (i.e., bio-electrochemical properties, microplastics, microstructure, physiological characteristics, surface characteristics) that are undervalued and underexamined by industries, MRFs, and research entities. Table 1 represents a compiled list of potentially important feedstock characteristics at various scales discussed at the breakout sessions.

Table 1. Influential MSW Feedstock Characteristics at Multiple Scales

General Properties	Scale	Influential MSW Material Attributes
Physical Properties	Macro Scale	Flowability, size, color, bulk density, optical density, material types, magnetic property, solids, liquids, volume, quantity
	Micro Scale	Cohesion, friction, particle-particle interaction, aspect ratio, hardness, shape, size, mechanical/tensile properties, thermal properties, rheological properties
	Molecular Scale	Surface characteristics, hydrophobicity
Chemical Properties	Macro Scale	Material types, organic wastes (i.e., fiber, food waste, cardboard, paper, plastic polymer types, fats, oils, grease, waste sludge), inorganic wastes (i.e., metals, sharps, dusts, glass shards, electronics), construction and demolition wastes, radioactive materials, corrosive materials, moisture content, chemical stability
	Micro Scale	Microplastics pollutants, electrochemical properties, heavy metals, toxic metals, pH, flammability, miscibility, free water, bound water
	Molecular Scale	Elemental composition (ultimate and proximate analysis), degree of polymerization, crystallinity, high-value rare-earth metals, combustion properties (e.g., calorimetry, thermogravimetric analysis, flash point), off-gassing constituents, type and number of contaminants (e.g., lithium ion, halogens, inert speciation), ash and inorganic speciation, organic speciation (e.g., carbohydrate and lignocellulosic content), perfluoroalkyl and polyfluoroalkyl substances
Biological Properties	Macro Scale	Biohazardous materials, animal waste, pharmaceutical products, odor, respiratory hazards, gas emissions (e.g., airborne molds, aerosols), leachate from landfills, biodegradability and storability
	Micro Scale	Bioavailable sugars, bio-electrochemical properties, microbial consortia, pathogenicity, biological reactivity (porosity, pore volume), cell adhesion, protein attachment, tissue and structure characteristics
	Molecular Scale	Biogenic and non-biogenic carbon, protein content, lipid profile, nutrient content, carbohydrate profile, biological reactivity, toxins

Multi-Scale Characterization and Rapid Analysis

Development of characterization tools to measure various properties of MSW at multiple scales is critical to manage the feedstock variability and understand their downstream impacts for efficient conversion and utilization. Opportunities for MSW characterization and tool development identified by Groups 1A and 1B include:

- Developing robust, low-cost, nondestructive, rapid analysis and sensing methods for online, real-time analysis of chemical composition and physical and biological properties at multiple scales.

- Coupling the real-time characterization tools with sorting (i.e., AI integrated with real-time sensors and robotics for optical or vision-based sorting), separation, decontamination, and on-belt preprocessing technologies to obtain on-stream data acquisition and manage MSW quality so as to create on-spec feedstocks.
- Computational and modeling research and tool development to characterize, adaptively control in real-time, and manage the properties for collection, sorting, separation, and preprocessing.

Advanced Data Analytics and Data Sharing

- Assemble a robust process of gathering information and developing a research implementation plan and communicate with state agencies and private-sector stakeholders.
- Facilitate sharing for data collection, storage, and administration from characterization studies (publicly accessible library database).

3.1.5 Conclusions

The heterogeneous nature of materials in MSW streams requires detailed understanding and standard characterization protocols to measure critical physical, chemical, and biological attributes at macro, micro, and molecular scales. These critical material attributes are vital to inform the sorting, separation, handling, and decontamination preprocessing systems necessary to manage MSW variability and create conversion-ready, on-spec feedstocks for downstream conversion technologies. Rapid analysis and sensor development integrated with AI adaptive control is also important to manage and increase MSW quality and reduce feedstock costs. Computational tools, advanced data analytics, and data sharing all need coordinated efforts from government, academia, and industry. Groups 1A and 1B highlighted the need for developing and coordinating research efforts on advanced MSW characterization, tool development, and determination of the critical attributes and quality metrics targeting stakeholder-prioritized conversion pathways.

3.2 Group 2: MSW Preprocessing and Logistics

3.2.1 Objective

The objective of this breakout group was to:

- Discuss the state of the art of preprocessing and logistics for waste management
- Identify challenges, opportunities, and R&D priorities for advancing feedstock preprocessing and logistics capabilities for improving quality and conversion readiness of MSW feedstock.

3.2.2 Current State of the Art of MSW Preprocessing and Logistics

The current state of the art for MSW has developed around a well-established waste management industry for nonhazardous materials and the needs of existing recycling efforts. Recycling efforts have given rise to MRFs and other approaches to separate out the material streams to be recycled from the rest of the MSW.

There are two basic types of MRFs: clean and dirty. A clean MRF accepts MSW that has been separated at the source (e.g., residential homes, businesses). Typically, the sorted material is commingled recyclables such as ferrous metal, aluminum, plastics (e.g., polyethylene terephthalate and HDPE), glass, and mixed paper. A dirty MRF processes household trash containing wet organic material and plastic bags. A dirty MRF has a much lower recycling rate than a clean MRF, but a dirty MRF has a potentially wider range of recycled materials it can collect and process.

Clean and dirty MRFs use both manual and automated sorting methods in some combination. Manual sorting uses a conveyor belt between 50 and 100 feet long with 5–20 sorters spaced evenly apart. There are several types of automated sorting systems typically employed. Rotating drums, discs, and vibrating screens are used to sort by size. Air classifiers and ballistic separators are used to separate by density. Magnetics and magnetic currents in eddy separators are used to pull out ferrous and nonferrous metals.

After separation, the sorted fractions are further processed for sale and transportation. For paper and cardboard, this usually means using a ram-style baler to produce a bale of a specified size. Cans are typically flattened, glass is crushed by color to a specified size, and plastic bottles are typically perforated and baled or perforated and sent through a granulator.

MRFs are introducing AI capabilities in conjunction with various types of spectral sensors, picking robots, and existing types of separation technologies in an effort to produce cleaner recycled material streams more quickly and economically. Other new separation technologies include solvent extraction, hydrocarbonization, and torrefaction. These methods deconstruct all or parts of the waste stream, or specific fractions of the waste stream, to allow for ease of extraction of some components and homogenization of others. New and existing sorting and processing technologies and strategies identified by Group 2 include:

- Consumer sorting into blue bins
- Incentive collection
- Visual inspection by trash hauler
- Smart trash hauler truck camera systems
- Optical sorting: AI + vision
- Multi-sensor sorting
- Optical sensing of flexible films and packaging in MRFs
- Embedded markers in plastics
- Food depackaging technologies
- Magnetic separation
- Ability for some automated separation
- Advanced sorting: ballistic separators, disk screens, oscillating screens, robotic sorters, automated sorters
- Metering and feeding equipment into processes
- Size-reduction options (e.g., hammer mill, knife mill, rotary shear)
- Size reduction: typically low-RPM, high-torque shredding
- Wet grinding
- Drying and moisture reduction
- Washing
- Mass storage design for reliable recovery of materials
- Sorting, bundling, baling
- Densification by extrusion

- Densification by cubing and pelletizing
- Torrefaction
- Wet pyrolysis: hydrocarbonization.

3.2.3 Gaps and Challenges

In general, the level of purity of fractions produced using current separation technologies is not high enough for biofuel conversion technologies. In addition, plastics and paper products contain contaminants from their previous use that could be detrimental for biofuel conversion technologies. The reason for the low purity level is that the current markets have not been willing to pay a premium for cleaner feedstock and are able to cope with the inherent level of impurities and contaminants for current end uses.

A pathway to achieving greater purity is improved sorting. The combination of AI controlling the sorting process, improved spectral sensors with higher accuracy, and the development of fast-picking robots have the potential to greatly increase purity and efficiency. Several of the participants in Group 2 are associated with companies developing new sorting processes using these technologies.

Preprocessing of MSW fractions will be required for conversion into usable biofuels feedstocks. The actual specifications for the biofuel conversion technologies will vary, but the group agreed that there are certain attributes that will be important. These are moisture content, particle size distribution, inorganic content, and composition either at a molecular or atomic scale. No matter the specifications, there will most likely need to be processing of the MSW fraction done to them in terms of these attributes. Through the current R&D funded by BETO, there is information on how different milling, moisture removal, and densification technologies impact converting wood and herbaceous materials into biofuel feedstocks. In addition, the waste sector has knowledge on the production of MSW fractions to solid fuels. However, until a specific conversion technology is identified, there is uncertainty around these existing sources of technology producing a viable feedstock.

Similar to Groups 1A and 1B, the determination of material characteristics, their sources of variation, and developing rapid analysis techniques to resolve them more quickly is another important information gap. The members of Group 2 identified some of the important feedstock characteristics but acknowledged that this list is not all-inclusive. Significant characteristics are based on handling systems and the conversion technologies. Important handling system characteristics are contamination from hazardous chemical and biological constituents (e.g., bacteria, fungi, yeast), size distribution, density, flowability, compressibility, moisture content, and abrasiveness. Important feedstock characteristics for high-temperature thermal and hybrid conversion technologies are moisture content, energy content, ash content, and the proportions of hydrogen, nitrogen, oxygen, and carbon. Important feedstock characteristics for low-temperature fermentation conversion technologies are moisture content, ash content, carbohydrate/sugar content, contamination, and particle size distribution. Contamination from hazardous chemicals and biological constituents was called out specifically because of its potential for very detrimental effects on conversion technologies. As research on the handling logistics, preprocessing, and conversion technologies develops, the importance of the actual characteristics will change with improved information.

Major capability needs identified by Group 2 include:

- Sensing and sorting
- Material processing
- Decontamination
- Material handling
- Characterization.

3.2.4 Conclusions

The existing waste collection infrastructure is well defined and could be slightly modified to provide source-sorted fractions for use as a biofuel feedstock. Existing sorting technologies lack capacity to produce pure enough material streams for use to convert to biofuel feedstocks. Improving sorting technologies currently under development is a pathway to obtaining fraction purity levels that can meet biofuel feedstock specifications. There is a need to understand important characteristics necessary to handle and convert MSW-derived feedstocks into biofuels, and to resolve these characteristics as quickly as possible to provide the most effective preprocessing into on-specification material. Finally, the most efficient methods for preprocessing (milling, drying, sorting, homogenization, decontamination, and densification) of waste into biofuel feedstocks need to be identified.

3.3 Assigning Value to the MSW Stream

3.3.1 Objective

The objective of this breakout session was to identify:

- Economic, social, and environmental value from using MSW as a source to produce a biofuels feedstock, including current valorization of MSW
- Gaps and challenges in these analyses and knowledge
- Prioritization for valorization for advancing waste utilization.

3.3.2 Recycling Industry Current Valuations

This session focused primarily on economic valuation in the waste stream. The group participants agreed that in general, people in the United States are interested in recycling, which is primarily driven by environmental concerns. However, there was not consensus on how to assign an economic value to social or environmental benefits from recycling.

Some fractions of the waste stream have markets that are economically and policy-driven, which has resulted in high levels of recycling. Waste fractions such as lead-acid batteries, steel cans, aluminum cans, clean grades of paper and cardboard, and e-waste have either developed into commodity-type markets or appear on their way to reaching that goal. Having a commodity-type market provides the economic incentive to recycle to meet the demand, so determining value is more straightforward.

Other fractions of the MSW stream also have value, but their value is based on local demand. Fractions like yard trimmings, tires, glass containers, and some plastics (#1, #2, and #5) may have value if there is a local market. In the case of local markets, the value is determined by their supply and demand dynamics (how much is being produced and the size of the demand). In general, the demand for the MSW fraction will create supply by giving that supply value and thus promote recycling, but the value needs to be low enough to compete against virgin sources of feedstock. This generalization also assumes that quality is similar between virgin and waste sources.

The rate of recycling in 2012 is presented in Figure 11. This shows when export demand for some fractions of MSW created a supply-and-demand situation that promoted recycling.

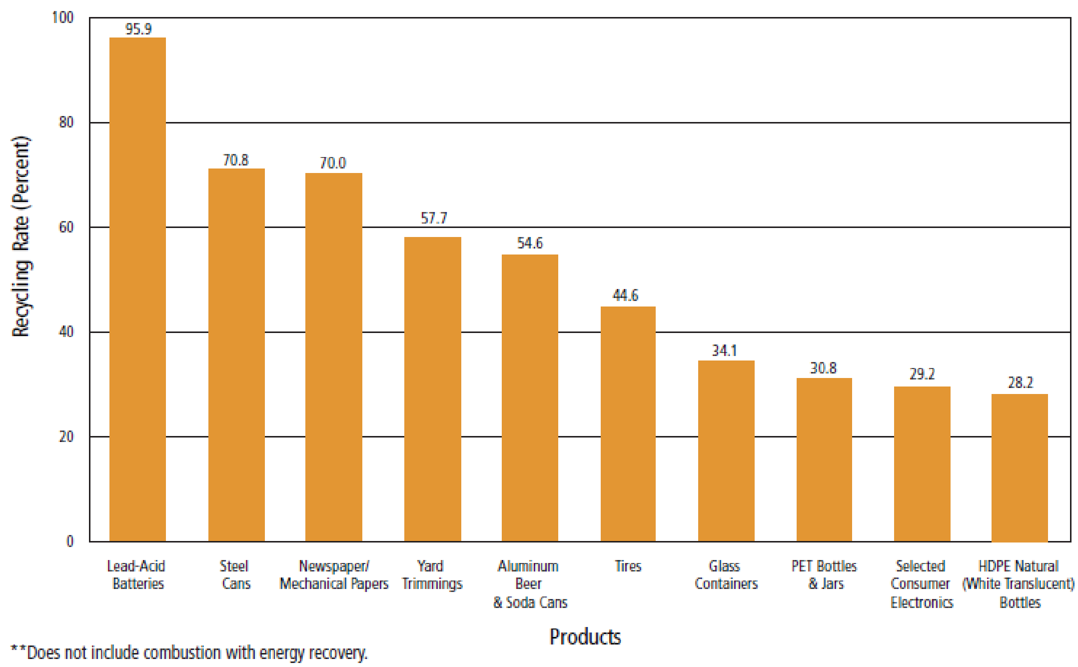

Figure 11. Rate of recycling in 2012[10]

3.3.3 Gaps and Challenges

The group ultimately identified four major challenges to valorization of MSW. These are economics of creating a feedstock from MSW, education of the public on recycling and use of fractions of the MSW stream to produce products, and the technology gap on how to sort and produce MSW fractions to use as a conversion feedstock. In addition, environmental valorization has not been a focus to date of generating products from waste and thus a challenge to valorization of MSW.

Economics – Lack of understanding of the economics of producing usable feedstocks from MSW was identified as a major challenge, as was transportation and handling of either the MSW or the fraction to be used to make the feedstock. Other economic issues identified were ownership/distribution of cost benefits from landfill avoidance and local/state/federal incentives to recycle. The importance of doing a techno-economic analysis on new technologies or a *pro forma* early in project development was emphasized by several members of Group 3. Finally, the externalities of social and environmental benefits have no way of capturing additional economic value without specific policies in place.

Education of Public – Education of the public on how and why to sort was identified as a major potential pathway to create a more homogenous stream for waste utilization. Sorting at the residential source is an inexpensive approach to produce less-contaminated, variable fractions of MSW. Because of existing labeling policies and lack of understanding by the public, the need for education is required to reduce and minimize confusion as to what is to be recycled and why. Additionally, there was a discussion about the education of manufacturers of disposable wrappers to the challenges of recycling those materials, bringing up a discussion of product stewardship.

[10] EPA. 2014. "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012." Washington, D.C.: EPA. EPA-530-F-14-001. https://www.epa.gov/sites/production/files/2015-09/documents/2012_msw_fs.pdf.

Technology – There were two types of technology gaps/challenges discussed by the group. One was the development and use of better sensor/AI/robotic technologies to sort MSW into different fractions. The replacement of manual separation lines in MRFs by improved technology is expected to increase purity of the sorted fractions and reduce cost. The other technology gap is the development of technologies to use recyclable but non-recycled materials (e.g., much of the plastic waste stream) as a feedstock, particularly the development of viable economic preprocessing steps required to produce a viable economic feed for conversion to a final product or intermediate.

Environmental – To date, minimal work has been done to determine LCA of carbon in recycling. There have been some LCA studies done on producing fuels from recycled plastic and waste wood to power, but there are many MSW streams using technologies that have not had LCAs done. LCA studies on other waste-using technologies, such as sludge to methane, were also cited as examples for understanding the benefit of greenhouse gas emission reduction. Other potential environmental benefits mentioned that could produce value were odor avoidance and water recycling for the use of some waste and sludge as a biofuel feedstock.

3.3.4 **Opportunities**

Group 3 developed a list of opportunities to address the identified gaps and challenges to obtain greater value from MSW and other waste streams. The identified opportunities tended to focus on current biofuel technologies (digestion of sewage sludge and/or food waste to methane) or products produced from MSW constituents, which the members of Group 3 are familiar with. Although some of the specifics may not be applicable for the production of biofuels, the general guidance provides insight into the challenges that members of the group have experienced in their endeavors to produce economically viable products from feedstocks derived from waste.

Table 2. Pathways to Valorizing MSW-Based Feedstocks

Category	Strategy	Rationale (As Given During Discussion)
Economic	Residential sorting before disposal	-Reduces contamination -Reduces downstream costs
	Higher utilization of low-cost feedstocks (e.g., food waste, sludge, manure)	-Can avoid high cost of landfilling -Organic waste has a high value -AD technology has progressed and can produce utility-grade renewable natural gas -Can provide environmental benefits
Social	Consumer education to support higher percentage of materials being recycled	Same as residential sorting
	Influence manufacturers to better align with reclamation techniques	Not addressed
Technical	Robotics and AI in sorting to improve quality and increase value	-Offset labor cost -Preserve knowledge of material categories in AI networks

		-Quick changes to processing control based on incoming feedstock -Increase throughput efficiency -Develop for specific streams
	Breaking down complex packaging into base components (e.g., plastics, metals)	Not addressed
	Tracking waste material from the MRF or landfill to use as a feedstock—bar codes and radio frequency identification (RFID)	Not addressed
Environmental	Incentivized carbon recycling	Not addressed
	Landfill bans	
	Waste reduction	

When Group 3 discussed necessary research efforts to produce greater value for MSW-derived fuels and products, their ideas fell into five categories:

- Develop and maintain methodologies and databases that are accessible to those who need the information
- Develop analytical methods to measure material characteristics important to material handling and various conversion technologies
- Understand the environmental benefits and LCAs of using waste to produce fuels and products and use this information to drive increased efficiency in measurements and production of environmental benefits.
- Develop low-cost rapid analysis sensors and artificial intelligence tools to separate and characterize MSW into usable fractions for conversion
- Develop improved and new conversion technologies specifically for MSW.

The first and main point Group 3 made is that there should be a concerted effort to share and coordinate federally funded R&D so that researchers can build on research findings through shared access to information. Repositories of experimental samples, data in useful formats, and articles and presentations will facilitate cohesive and progressive research efforts. BETO has the Bioenergy Knowledge Discovery Framework website at Oak Ridge National Laboratory where databases and articles can be uploaded; the Biomass Feedstock Library at INL, which houses samples and composition databases; and the Biofuels Information Center at the National Renewable Energy Laboratory, a platform that supports the Alternative Fuels Data Center and BioEnergy Atlas. With these available repositories and frameworks, Group 3 wanted to emphasize that there should be close coordination for MSW-related research efforts.

The group recognized that understanding the true value of using MSW/waste feedstocks requires the determination of the characteristics that will affect the operation of facilities using the wastes, and its ability to create a feedstock that meets the conversion technology's specifications. To do this, there should be a focus on the development and use of analytical methods necessary to measure these characteristics at the proper scale (i.e., molecular, micro, macro).

Group 3 was not aware of many LCAs done for MSW. Certain fractions of MSW, plastics, and waste sludge have had some LCA studies performed, but overall, waste lacks a robust number of LCAs. To develop an understanding of environmental benefits for the use of MSW as a source for biofuel feedstocks, Group 3 felt that more focus on LCA would provide the foundation to develop environmental value propositions for the use of MSW.

Members of the group with industry backgrounds felt that the development of rapid analysis methods in conjunction with AI and robotics technology is important to the near-term economic viability of using fractions of the MSW stream to produce feedstocks for any technology. Current manual methods and separation technologies for most fractions of the MSW stream are too expensive and produce a product that contains overly high percentages of contaminants. The development of better sensors/AI/robotics is required to produce an economically viable stream from MSW that will meet purity specifications of current and future conversion technologies.

Having viable markets for MSW-derived feedstocks is critical to producing value. Currently, commodity-type markets only exist for a few source-sorted components of the MSW stream. Group 3 felt that increasing the number of markets through either modifications of existing biofuel pathways to use MSW/waste-derived feedstocks or the development of new fuels are critical pathways to creating additional commodity-type markets.

3.3.5 **Conclusions**

The effort to understand value in the MSW stream focused on economics and market/demand dynamics. Group 3 decided that externalities from social and environmental benefits were not known well enough to contribute to the discussion. The group did identify information gaps, challenges, and opportunities to producing value.

The primary takeaway points from the discussion of gaps and challenges for valorization of MSW include:

- There is a lack of basic understanding of how to produce usable feedstocks from MSW and if it is economically viable.
- The education of the public on how to sort and why was identified as a major opportunity to produce economic value from the MSW stream through source sorting to produce a relatively clean, inexpensive material resource.
- The group discussed two types of technology gaps/challenges. One was the development and use of better sensor/AI/robotic technologies to sort MSW into different fractions. The other technology gap is the development of technologies to use recycled materials as a feedstock.
- To date, minimal work has been done to determine LCA of carbon and other environmental benefits from recycling.

4 Conclusion

Workshop participants recognized that MSW is a promising low-cost feedstock resource with two major barriers. Its variability poses significant challenges for downstream conversion. Various conversion pathways have different feedstock quality specification requirements, and detailed characterization and compositional data are still lacking to understand and manage MSW variability. Infrastructure for MSW collection, transportation, and handling already exist in waste management and MRFs, and it is important to develop sorting and preprocessing technologies to increase the economic viability of these facilities and industries. Data gaps in MSW resource composition, handling, preprocessing, and conversion processes limit the ability to evaluate the economic and environmental performance of current and emergent waste utilization technologies.

To address these challenges, workshop participants identified the following R&D activities as high priority:

- Develop real-time, "online" measurement of chemical composition, particularly of cellulosic materials in the MSW stream. The technology would need to have the capability of tagging and following the cellulose in an online system. Developing this technology would create a method for the researchers to quantify cellulose and create a profitable market for the industry.
- Publish an in-depth MSW resource assessment and characterization, analogous to the Billion-Ton Study,[11] to collect and administer data from characterization studies into a searchable database.
- Develop standardized feedstock specifications based on the conversion technologies.
- Mobilize carbon recycling by developing consistent methods and databases capable of calculating carbon emission and cost, including but not limited to LCAs.

It is important to note that all groups identified that it is essential to develop better fractionation technologies to separate MSW into distinct organic components (yard waste, paper, food waste, textiles, and plastics). The need for rapid-analysis technologies and the associated AI either for fraction of MSW or the identification of important characteristics was another common theme across groups. Lastly, all groups concluded that information on MSW characteristics required by a feedstock to meet specifications for conversion into biofuels is necessary. Information on feedstock specifications will inform which characteristics of MSW require preprocessing to make quality biofuel feedstocks.

[11] U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. Oak Ridge, TN: Oak Ridge National Laboratory. ORNL/TM-2016/160. http://energy.gov/eere/bioenergy/2016-billion-ton-report.

Appendix A: Workshop Agenda

U.S. Department of Energy ***Bioenergy Technologies Office (BETO)*** ***Advancing the Bioeconomy: From Waste to Conversion-Ready Feedstocks Workshop***		
Day 1 – February 19, 2020		
8:00 AM	**Registration and Coffee**	
8:30 AM	**Welcome**	Jonathan Male, DOE BETO
8:40 AM	**Introduction of Workshop Objectives and Format**	Alison Goss Eng DOE BETO
8:50 AM	**Quality by Design: A Primer with a Municipal Solid Waste (MSW) Case Study**	Zia Abdullah, National Renewable Energy Laboratory Jordan Klinger, INL
9:15 AM	**Plenary 1: How Does Current Technology and Infrastructure for MSW Processing Work?**	Bradley Kelley, Gershman, Brickner, & Bratton Magdi Azer, REMADE Institute
9:40 AM	**Q&A**	
9:50 AM	**Break**	
10:15 AM	**Plenary 2: Critical Material Attributes of MSW for Conversion Pathways: Technology Development to Support Diverse End Uses**	Jim Dooley, Forest Concepts Ezra Bar-Ziv, Michigan Technological University Armando McDonald, Michigan Technological University Bruno Miller, Fulcrum Bioenergy
11:05 AM	**Q&A**	
11:15 AM	**Plenary 2: Continued**	Alan Overcash, Southeastern Biochemicals. Inc. Grace Chen, University of Massachusetts-Lowell Toufiq Reza, Florida Institute of Technology Charles Tremblay, Enerkem
12:05 PM	**Q&A**	
12:15 PM	**Lunch**	
1:15 PM	**Plenary 3: The Value of Waste: consequence and Opportunities in Valorizing MSW as a Feedstock**	Vicki Thompson, INL David Shonnard, Michigan Technological University Scott Bouchie, City of Mesa
1:50 PM	**3 x 5 Presentation**	Morton Barlaz, North Carolina State University
1:55 PM	**Q&A**	
2:05 PM	**Introducing Breakout Sessions and ThinkTank**	Facilitator
2:15 PM	**Break**	
2:30 PM	**Simultaneous Breakouts:**	

	1A: Defining the Baseline and Future Utilization of MSW **1B: Defining the Baseline and Future Utilization of MSW** **2: MSW Preprocessing and Logistics** **3: Assigning Value to the MSW Stream**	
4:15 PM	**Report Outs and Discussion**	Breakout Session Leads
4:45 PM	**Day 1 Workshop Completion**	DOE BETO
	Day 2 – February 20, 2020	
8:00 AM	**Registration and Coffee**	
8:30 AM	**Summary of Day 1 Topics and Breakouts**	DOE BETO
8:45 AM	**3 x 5 Presentations on MSW Handling & Feedstock Challenges**	Ning Sun, Lawrence Berkeley National Laboratory Meltem Urgun-Demirtas, Argonne National Laboratory Manuel Garcia, nanoRANCH UHV Technologies Ted Hansen, Convergen Chad Haynes, LanzaTech
9:15 AM	**Break**	
9:45 AM	**Simultaneous Breakout: Role of Government in R&D** (same groups from Day 1)	
11:45 AM	**Wrap-Up:** Discussion Highlights with Larger Group and Final Closing Thoughts from BETO	DOE BETO

Appendix B: Workshop Participants

The following is a list of participants who elected to share their contact information in these proceedings:

Zia Abdullah National Renewable Energy Laboratory	Steve Csonka Commercial Aviation Alternative Fuels Initiative	Alison Goss Eng U.S. Department of Energy Bioenergy Technologies Office
Magdi Azer REMADE Institute	George Davidson American Biogas Council	Ted Hansen Convergen Energy
Morton Barlaz North Carolina State University	Jim Dooley Forest Concepts, LLC	Zia Haq U.S. Department of Energy Bioenergy Technologies Office
Ezra Bar-Ziv Michigan Technological University	Mark Elless U.S. Department of Energy Bioenergy Technologies Office	Chad Haynes LanzaTech
Mark Baybutt AMP Robotics	Abby Engelberth Purdue University	Robert Hershey Robert L. Hershey, P.E.
Scott Bouchie City of Mesa	Karl Englund Washington State University	Richard Hess Idaho National Laboratory
Nate Brown Federal Aviation Administration	Brianna Farber American Association for the Advancement of Science	Lauren Illing Best in Class Solutions, LLC
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Bruno Miller Fulcrum BioEnergy	Timothy Saunders Gas Technology Institute	Majbah Uddin Oak Ridge National Laboratory
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Anna Oldani Federal Aviation Administration	Brajendra Sharma University of Illinois-Urbana-Champaign	Lauren Valentino Argonne National Laboratory
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