DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

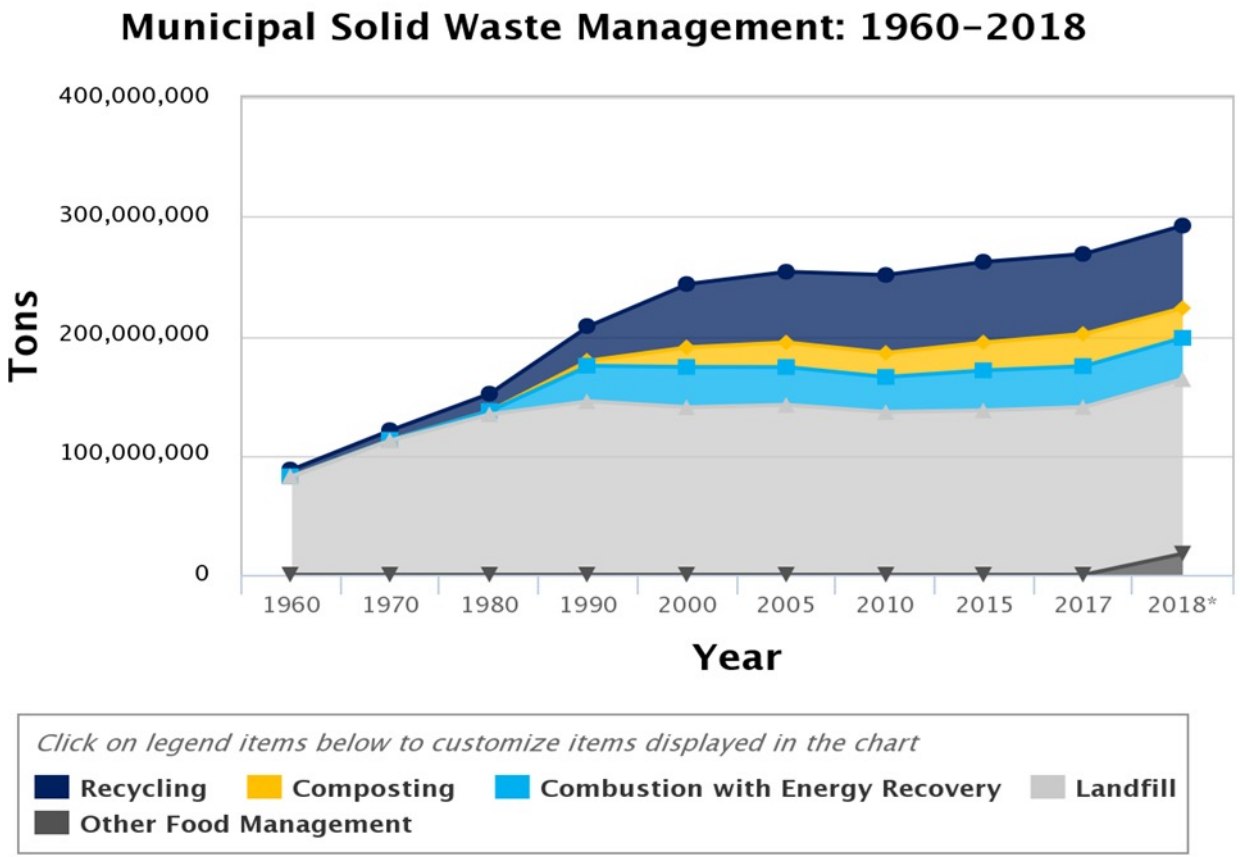
AI-Enabled Hyperspectral Imaging Augmented with Multi-Sensory Information for Rapid/Real-time Analysis of Non-Recyclable Heterogeneous MSW for Conversion to Energy

April 04, 2023
Feedstock Technologies Session

Principal Investigator: Lokendra Pal
Organization: NC State University

NC STATE UNIVERSITY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
IBM RTP Center for Advanced Studies
Town of Cary
U.S. DEPARTMENT OF ENERGY

Project Background

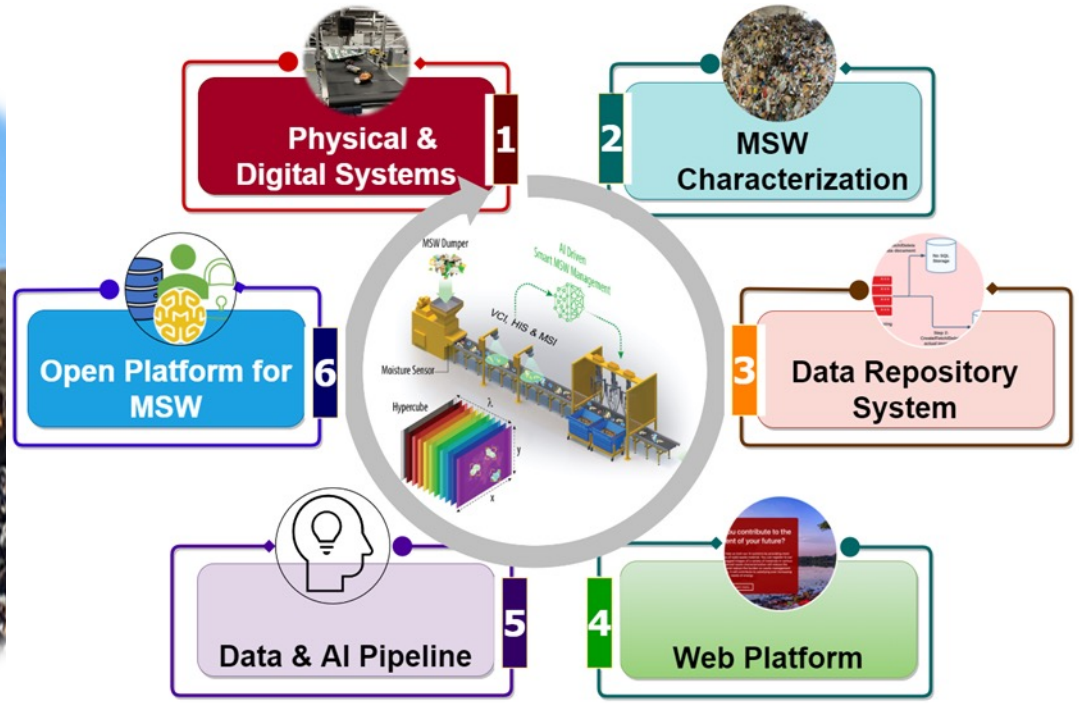


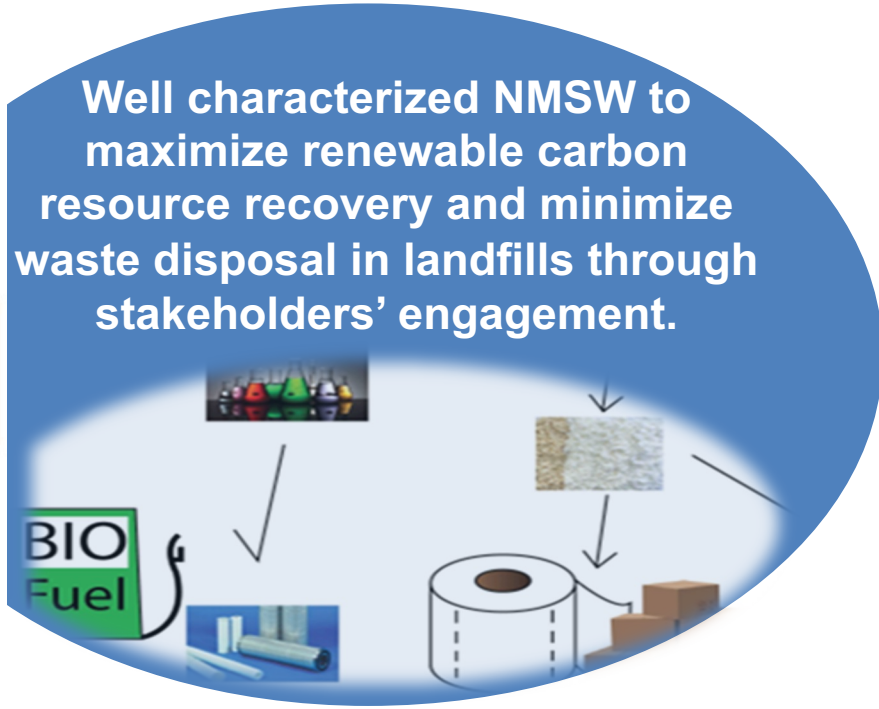
- **50%** of MSW **landfilled,** accounting for **82% of emissions** for the waste sector and **17% of all methane (CH_4)** emissions in the US.
- Significant organic content available for upcycling to high value biofuels, biopower, biochemicals, and bioproducts.
- However, a robust, low-cost intelligent system is needed to characterize these highly contaminated waste fractions.

- https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials
- Jain P, Wally J, Townsend TG, Krause M, Tolaymat T (2021) Greenhouse gas reporting data improves understanding of regional climate impact on landfill methane production and collection. S ONE 16(2): e0246334. https://doi.org/10.1371/journal.pone.0246334

Project Overview

The aim of this work is to develop and demonstrate a fully functional AI-enabled hyperspectral imaging (HSI) spectroscopy/object recognition-based technique for rapid/real time characterization of organic fractions (e.g., paper, plastic, food, and textiles) of non-recycled MSW (NMSW) in real time at multiple conveyer speeds.



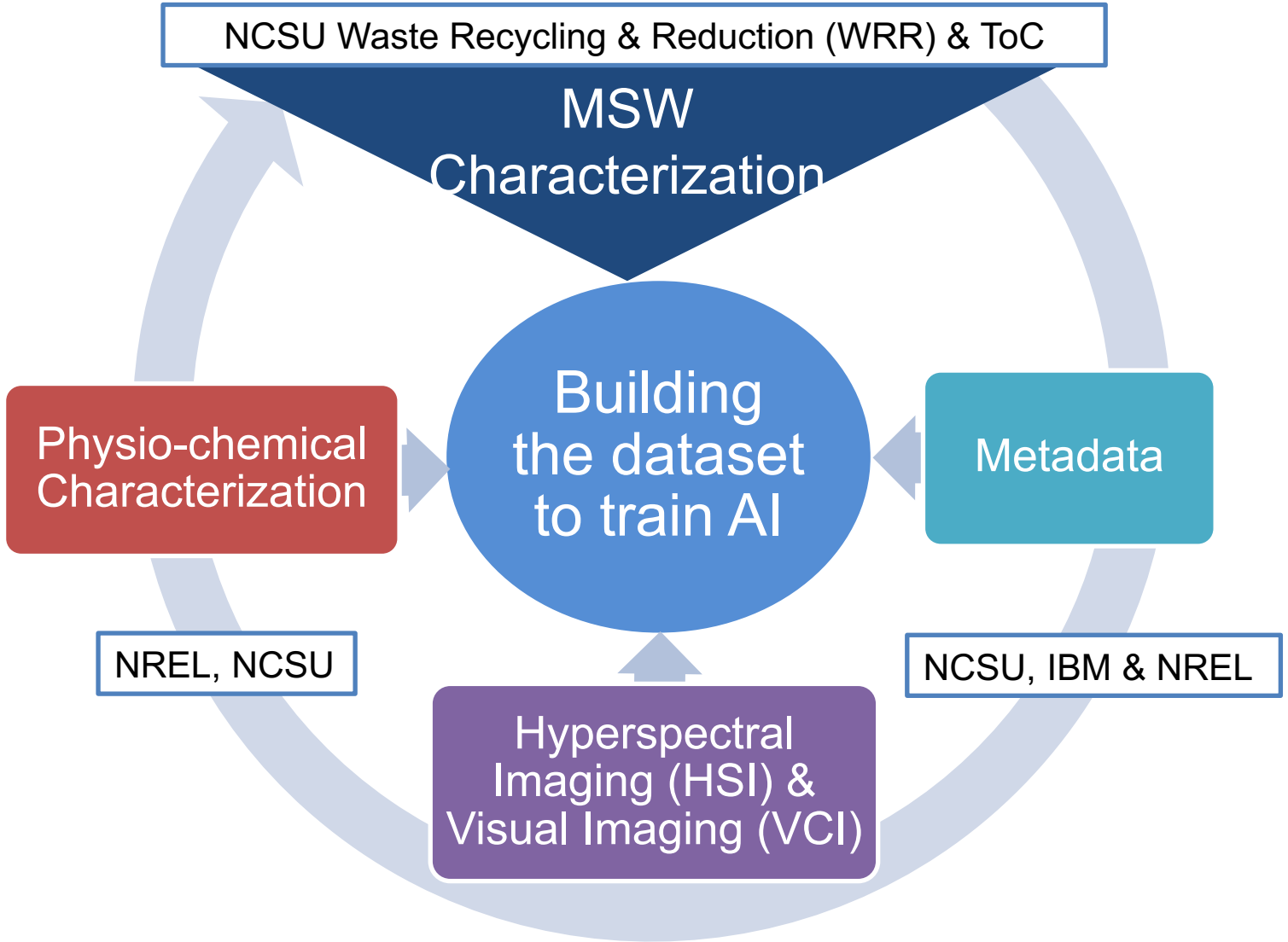


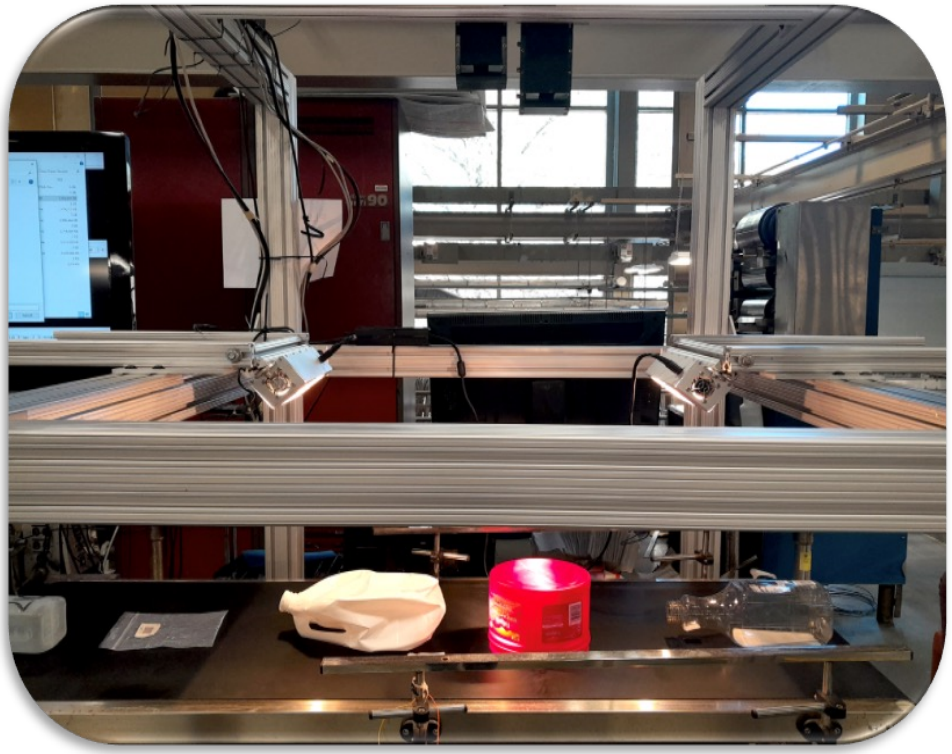
The project is at month 12 of 33 after initial verification.

1 – Approach

- **Building unique datasets for AI-enabled real-time characterization of NMSW**
  - Physical and digital systems setup and integration for NMSW characterization – static and dynamic
  - Robust data repository of raw image and image description (metadata) file – frontend/backend API, storage and databases
  - Scalable data and AI pipeline – data cleaning, labeling and annotation, model frameworks, training, deployment and continuous improvement on prem & Cloud
  - Open AI web platform and stakeholders' engagement – access control, API driven, dashboard and visualization for product pathways, TEA and environmental LCA, informal education/citizen science.
- **Key challenges and risk-mitigation strategies**
  - Relevant pre-existing data availability (e.g., gaps for non-recycled MSW) – rapid development of data collection infrastructure, image augmentation, partnership with municipalities and industry
  - Safety and compliance for non-recycled MSW handling – comprehensive training and SOPs.
  - Heterogeneity of the non-recycled MSW – multi-sampling for spatio-temporal analysis, relevant preprocessing and testing
- **Project management and stakeholders' engagement**
  - Strong communication between project members (NCSU, NREL, IBM, the Town of Cary (ToC)), DOE- BETO management, industry, and other stakeholders through weekly and monthly meetings.

1 – Approach: Physical and Digital Systems Setup and Integration for NMSW Characterization





1 – Approach: Robust Data Repository System

Goal

Creation of Robust Data Repository for non-recycled MSW Characterization

Data

Images, videos, and other sensor data description of images (metadata)

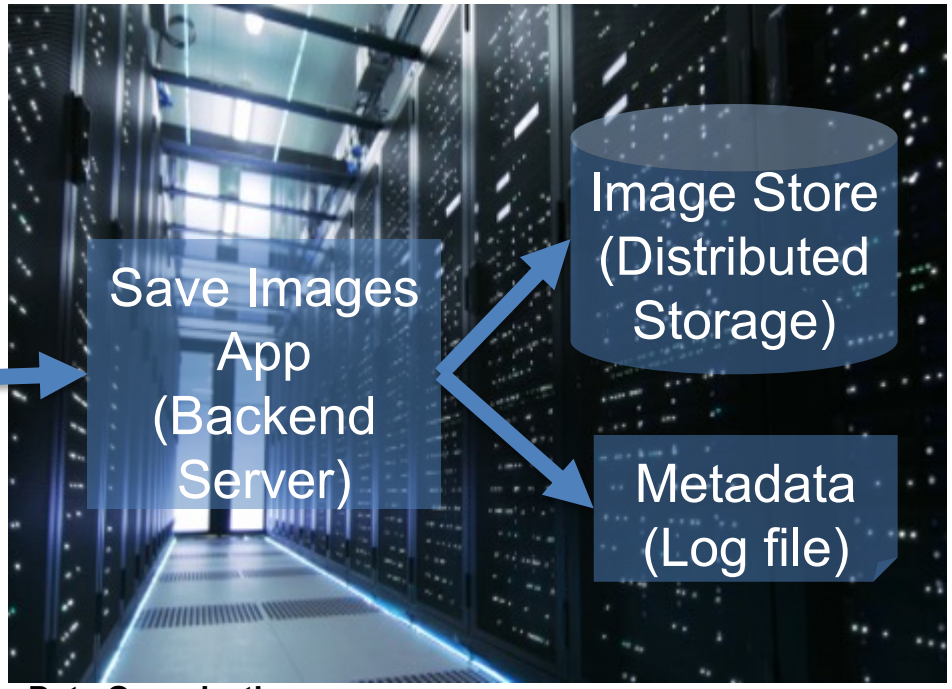
Data Capture Source

Live capture from VCI, HSI, MSI, & Other Sensors

Existing data repositories

Client Application

1. Add context information to sensors data
2. Connectors for sending the data to local environment and Cloud
3. API/GUI based interface



Data Organization

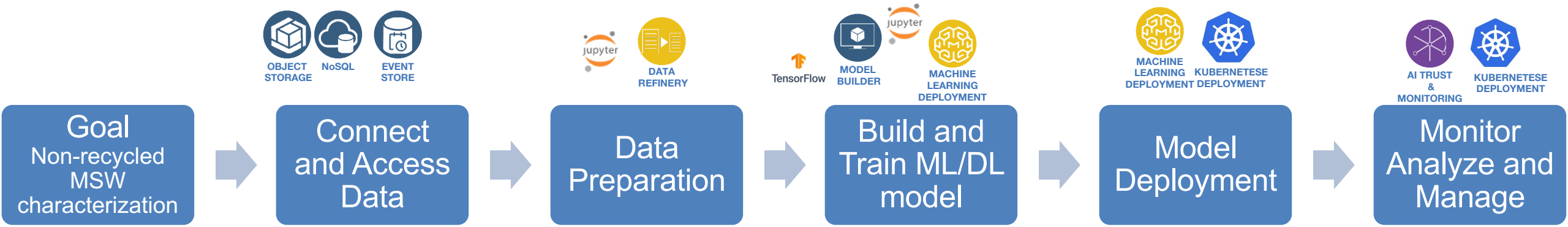
- Labelled, raw, per experiments, environment, user, etc.

Backend App

- Allow connection from client application
- Validation checks on data received
- Store and organize data
- Add additional context (metadata)
- Authenticate Users
- Robust, reliable, scalable, and secure

1 – Approach: Scalable Data and AI Pipeline

Setting up the Data and AI pipeline and related infrastructure for AI-based characterization of MSW.



1 – Approach: Open AI Web Platform and Stakeholders Engagement

Build and host open data and AI platform for MSW valorization

User and access management through our Web platform to allow search, upload, and download images

Provide access to cleaned and trusted datasets through our web platform and secure APIs, Display visual dashboard for statistics for current platform status, TEA, and product pathways

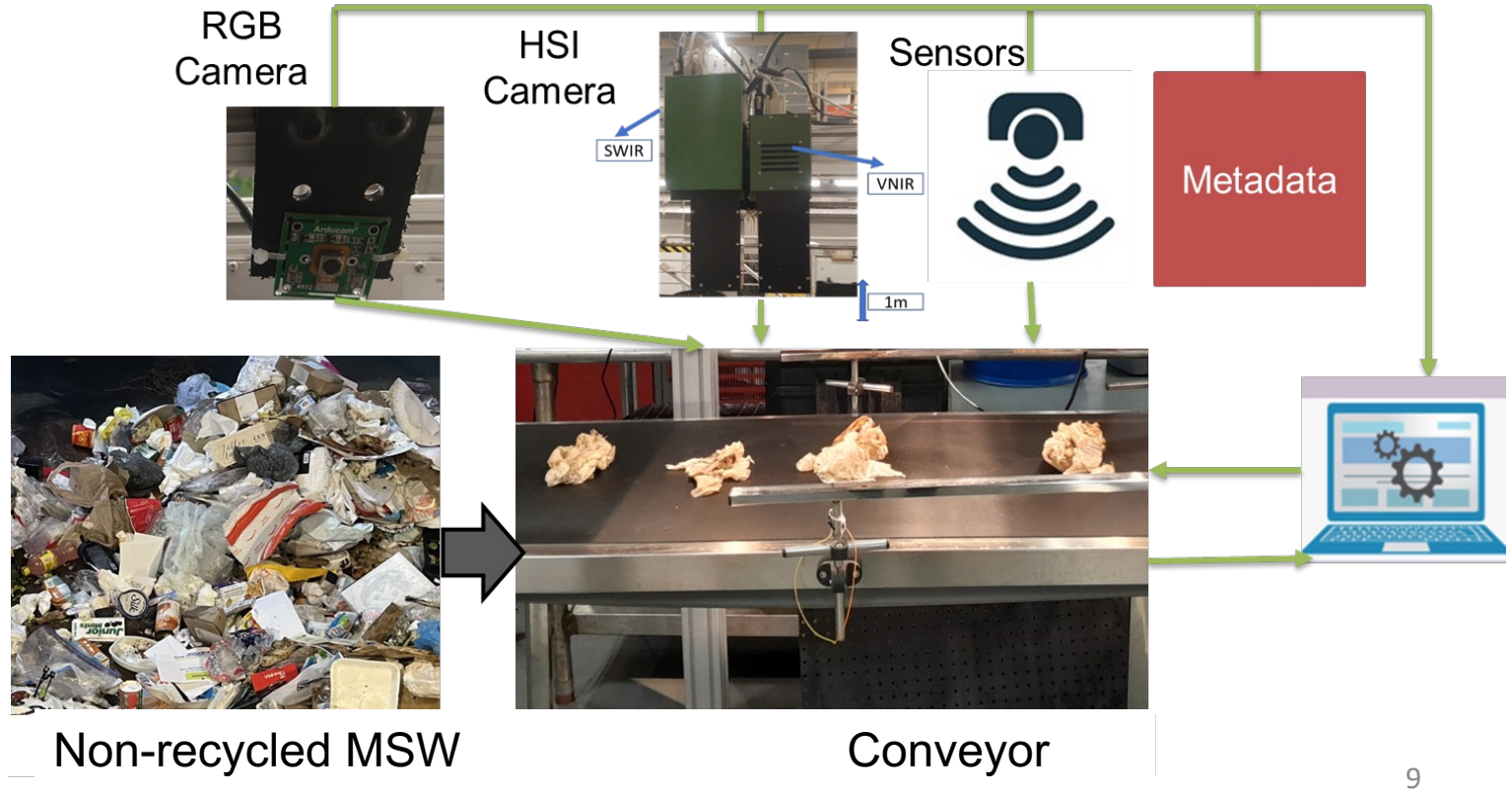
Share sample AI models, code patterns, and projects through our Web platform

Enable live prediction about MSW with a deployed AI model for citizen education, outreach, and DEI efforts as well as broader engagement of the research community

2 – Progress and Outcomes: Physical and Digital Systems Setup and Integration

Task 2/Milestone 2: Procurement of HSI and VCI cameras, sensors, and accessories, and completion of system integration and performance verification (Sept. 2022).

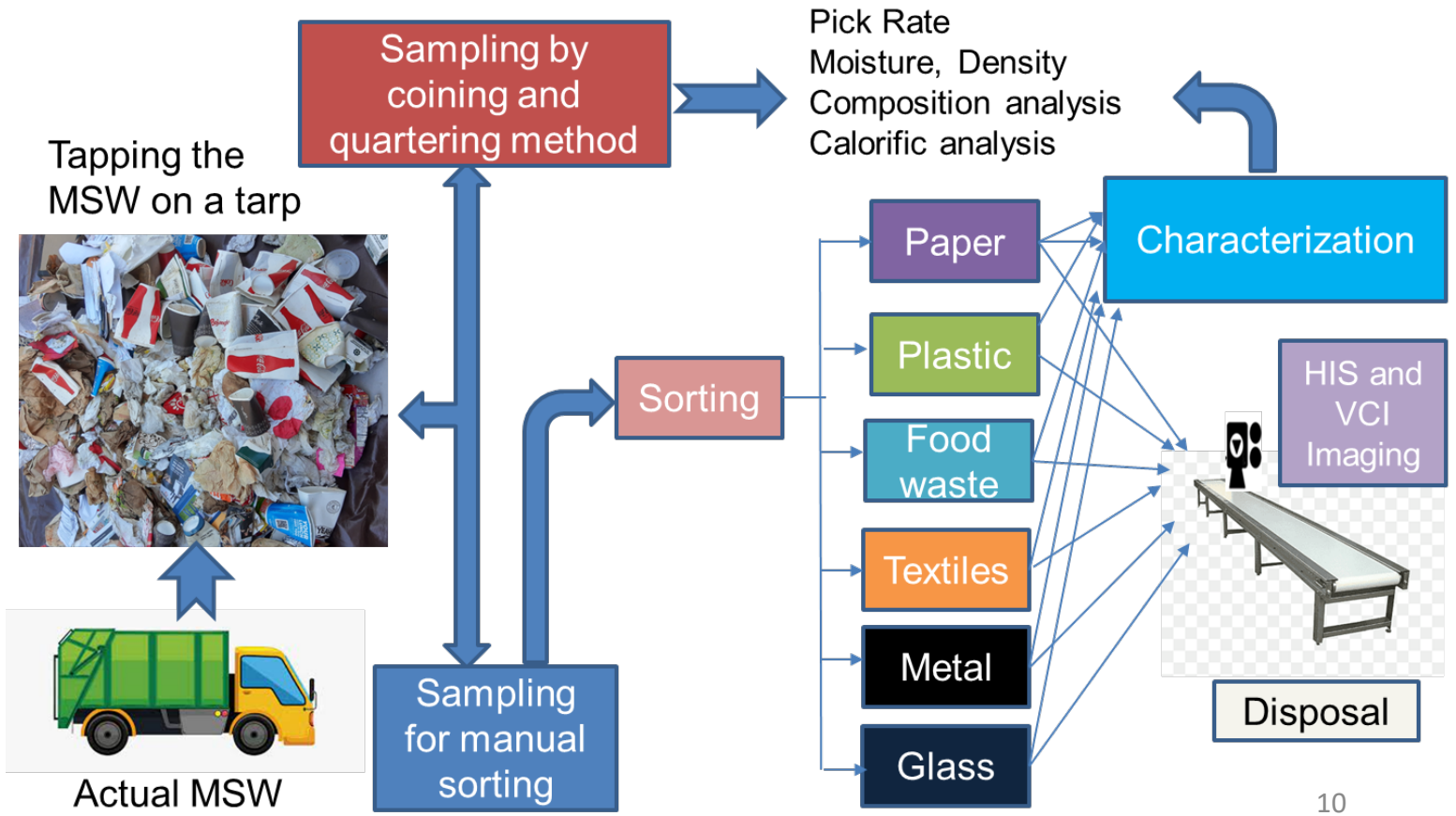
- Procured HSI and VCI cameras, sensors, and accessories
- Completed system integration and performance verification
- Personnel training and SOPs development
- Streamlined process of MSW collection and imaging with support of key partners



2 – Progress and Outcomes: NMSW Collection and Characterization

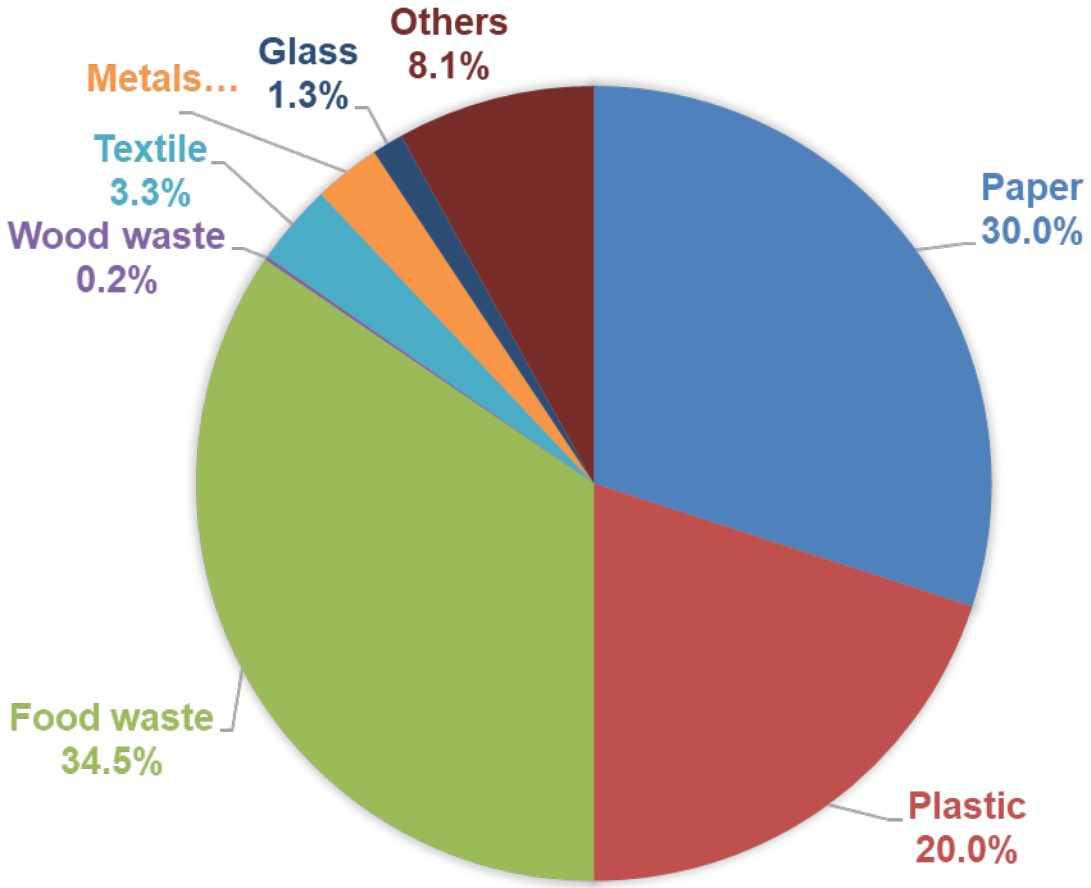
Task 3/Milestone 3.1: Procurement, identification, separation and concentration of various fractions of MSW (June 2022)

- Developed plan for MSW sampling to access spatio-temporal heterogeneity
- Procured, characterized, separated and concentrated various fractions of MSW
- Captured images from clean and simulated (controlled-contaminated) fractions of MSW
- Collected and pushed labelled data sets from actual MSW to the data repository system



2 – Progress and Outcomes: NMSW Sorting Results of Major Classes

Task 3/Milestone 3.2: Procurement, identification, separation and concentration of various fractions of MSW (March 2023)



NMSW Fractions (AS IS)

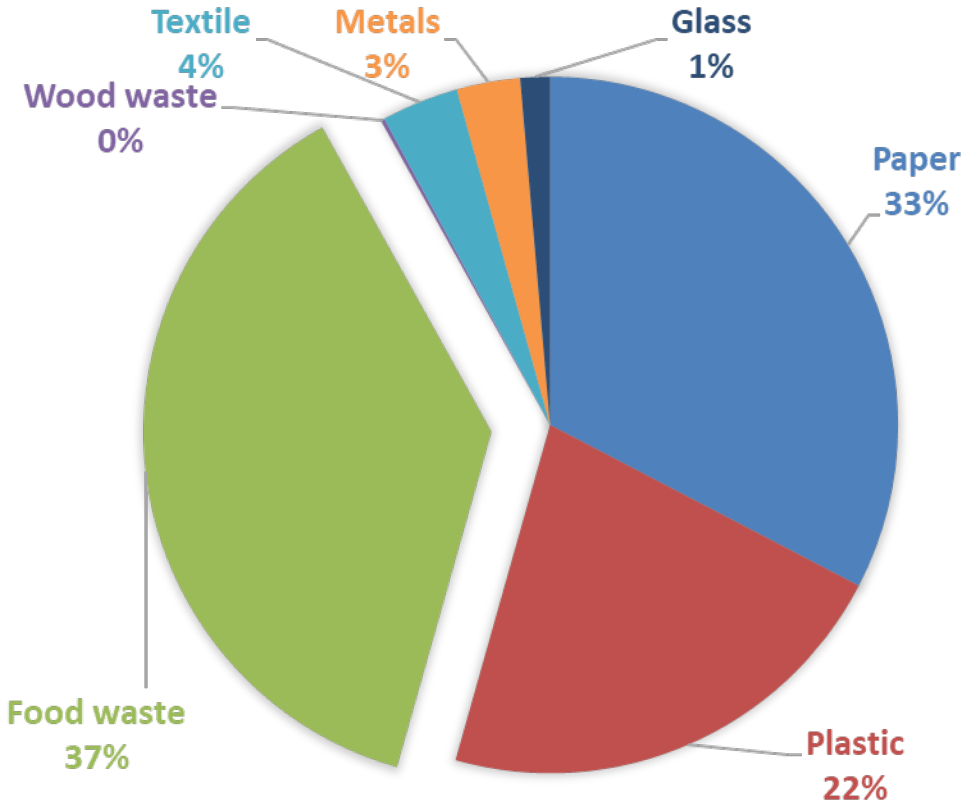
Sorting as per ASTM D5231 standards

1) First, remove any hazardous
2) Categories waste in major fractions
   - Paper
   - Plastic
   - Food Waste
   - Textile
   - Metals
   - Glass
   - Yard Waste
   - Wood waste
   - Others

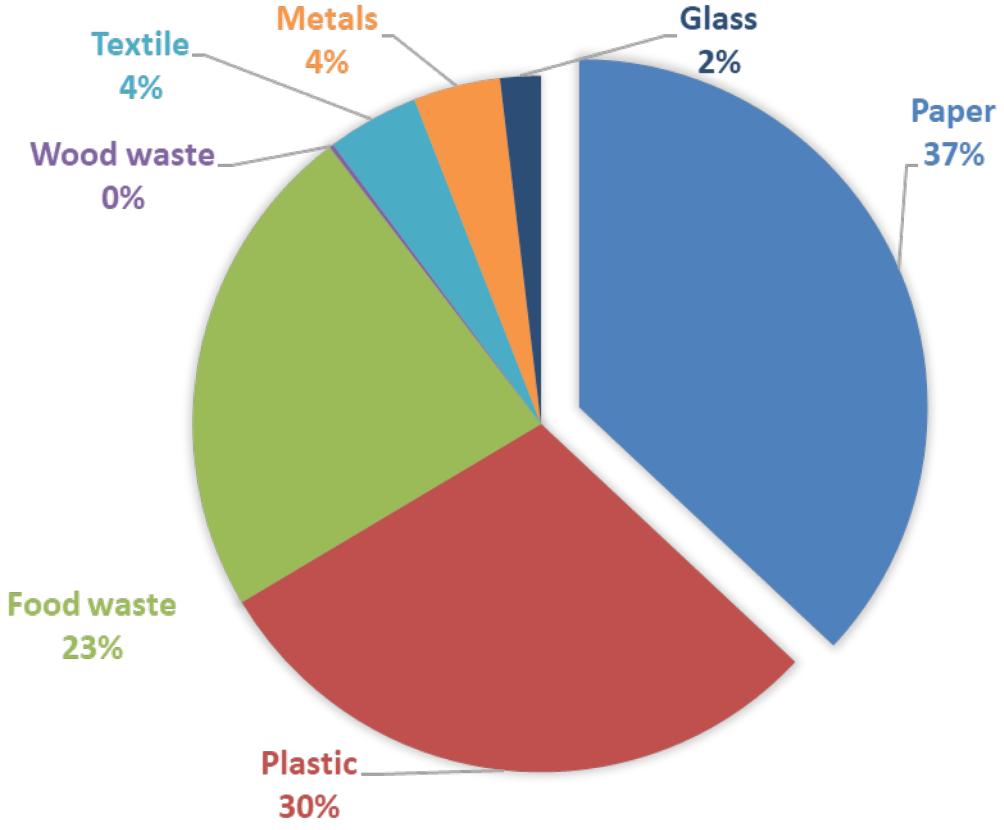
Others include potential hazardous materials, grease containing materials, razor, enclosed containers, diapers, car parts and others which are not included above

2 – Progress and Outcomes: Comparison of NMSW Weight Fractions on Wet and Dry Basis

Task 3/Milestone 3.2: Procurement, identification, separation and concentration of various fractions of MSW (March 2023)



Wet basis (excluding others)

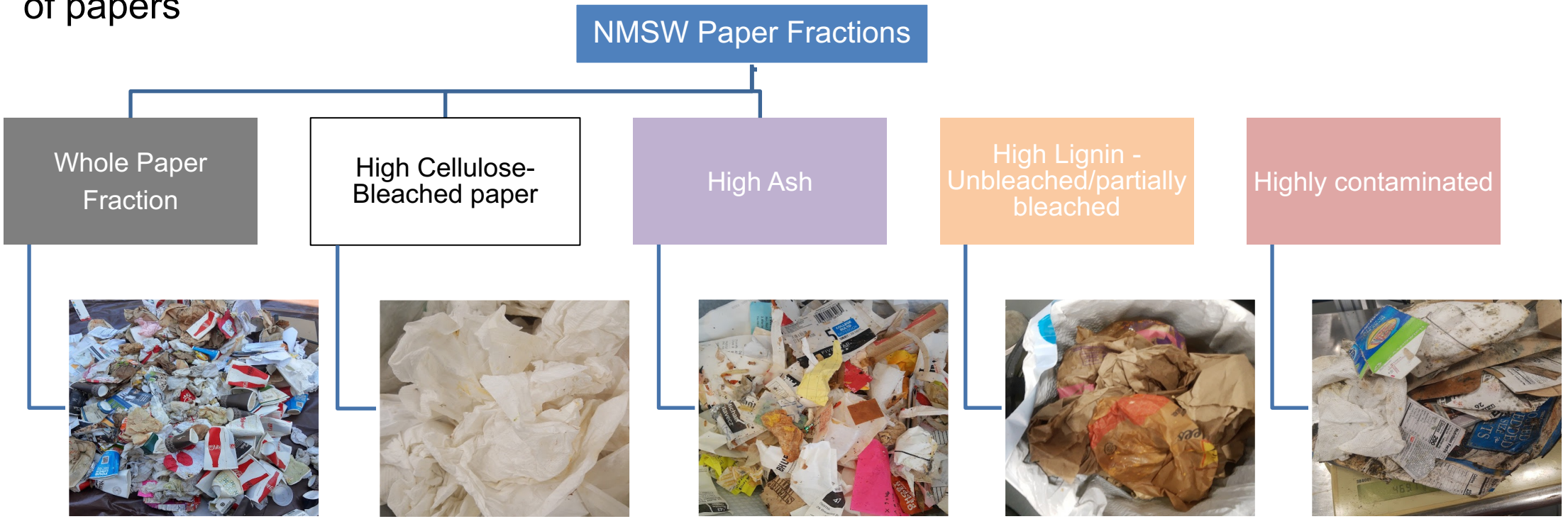


Oven dry basis (excluding others)

2 – Progress and Outcomes: NMSW Characterization – Paper Fractions

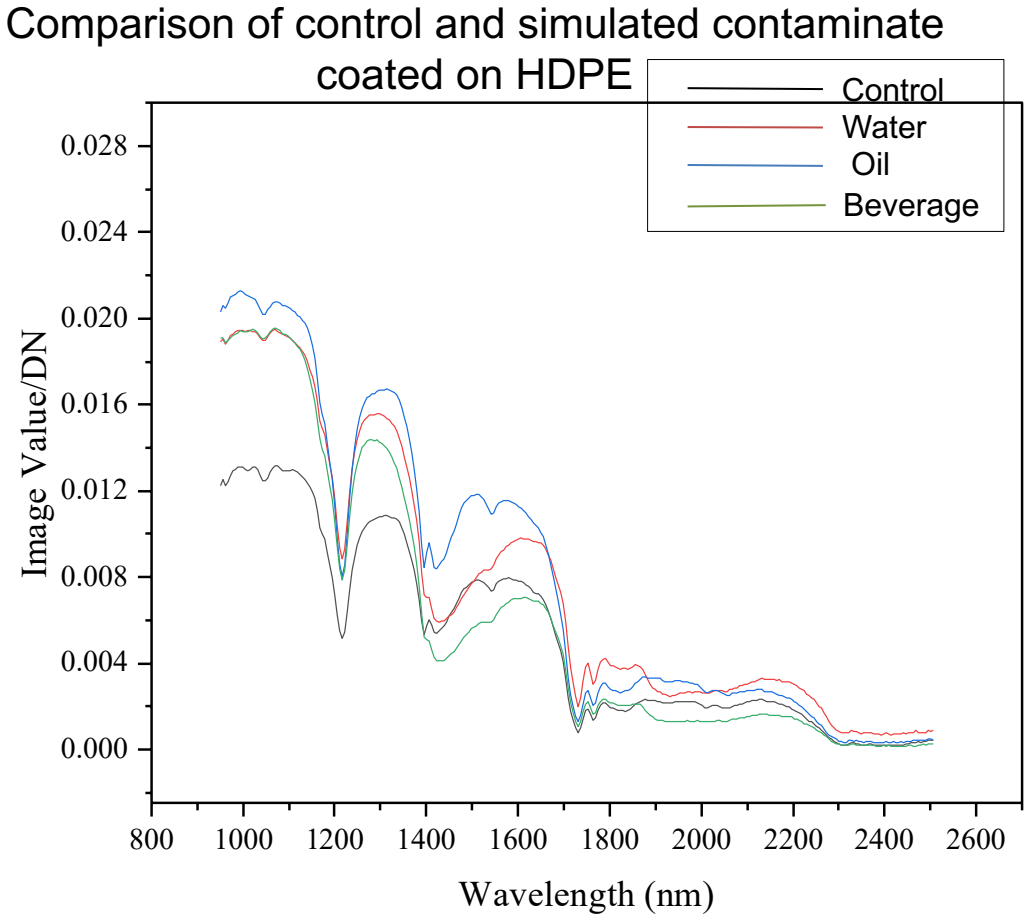
Task 3/Milestone 3.2: Procurement, identification, separation and concentration of various fractions of MSW (March 2023)

- Paper is the highest percentage of MSW on oven dry basis.
- Development of innovative process of reclassification and characterization of various subclasses of papers



2 – Progress and Outcomes: Visual and Hyperspectral Imaging

Task 4/Milestones 4.1 - 4.3: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)

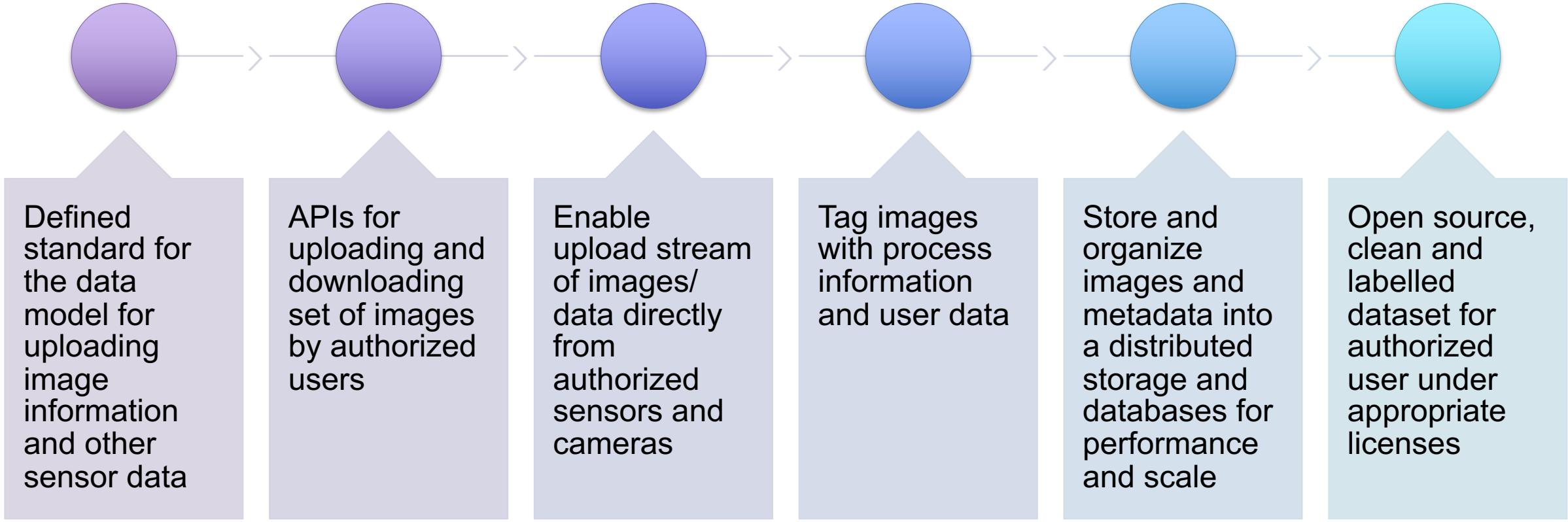


Significance of Hyperspectral Imaging

- Capturing chemical signature
- Real-time MSW characterization
- Contamination determination

2 – Progress and Outcomes: Robust Data Repository System

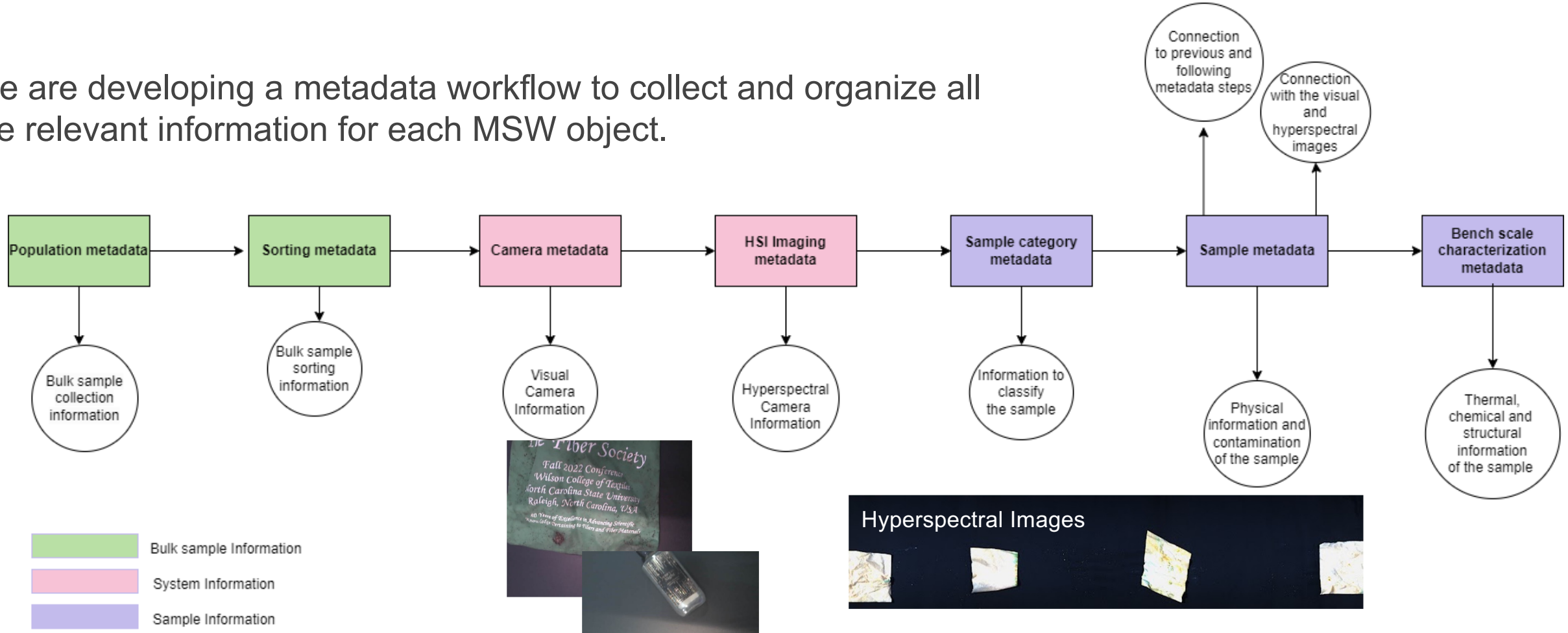
Task 4/Milestones 4.2 - 4.3: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)



2 – Progress and Outcomes: Image Metadata & Organization

Task 4/Milestones 4.2 - 4.3: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)

We are developing a metadata workflow to collect and organize all the relevant information for each MSW object.

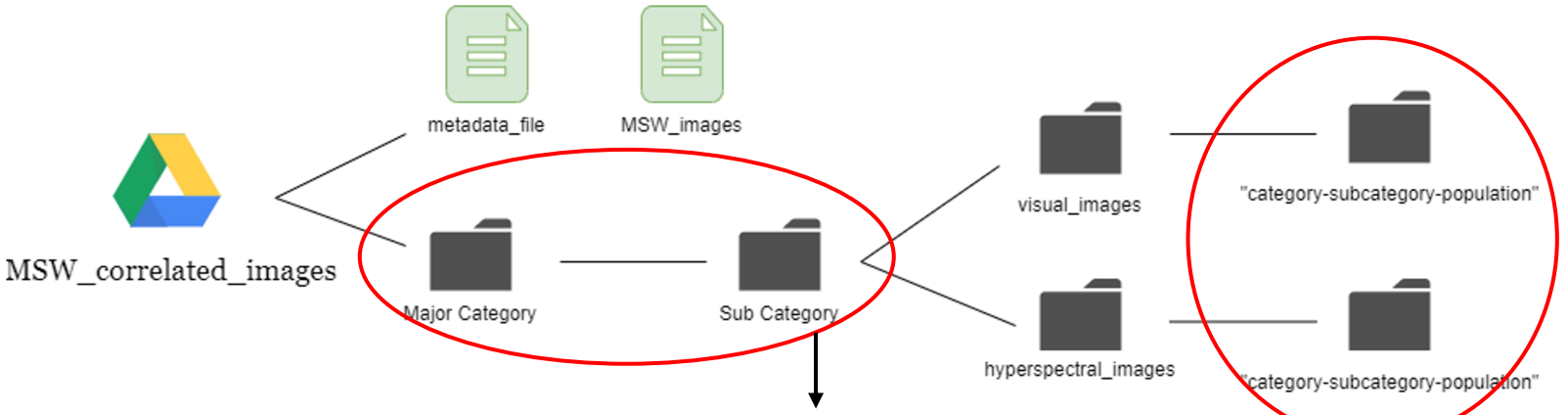


Hodge, G., & Smart, P. (2017). Developing a metadata framework for dataset descriptions in institutional repositories. Program: electronic library and information systems, 51(2), 144-167. doi: 10.1108/PROG-06-2016-0047

2 – Progress and Outcomes: Images & Metadata of Real MSW

Task 4/Milestones 4.2 - 4.5: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)

- Correlating the metadata, visual images, and hyperspectral data is an important step in building a comprehensive dataset that can be used to train and test machine learning models.
- Developing scripts Python and OpenCV to detect and delete blurred or duplicate images during the process of cleaning images.
- Obtaining high-quality visual images of every sample is one of the major challenges we face.



Following the previous hierarchy

Labels to organize and store the folders.

Géron, A. (2019). Hands-On Machine Learning with Scikit-Learn, Keras, and TensorFlow: Concepts, Tools, and Techniques to Build Intelligent Systems (2nd ed.). O'Reilly Media.

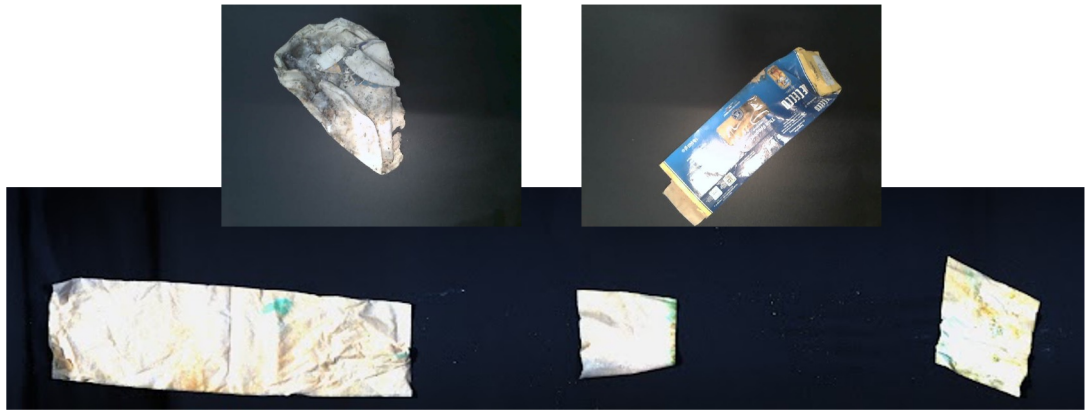
2 – Progress and Outcomes: Uniqueness of Our Dataset

Task 4/Milestones 4.1- 4.5: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)

	Publicly Available	This Project
Types of images	Random images	Real MSW samples
Number of classes	Max. 44 sub-categories in Huwei dataset	54 subclasses
Metadata for characterization	Not specified	Physical, thermal, chemical metadata are collected along with the images
Lighting condition for imaging	Not specified	Tracking the luminosity
Number of images	Max. 10,000 in Huwei dataset	81,266 images and continuing

Key features of our dataset

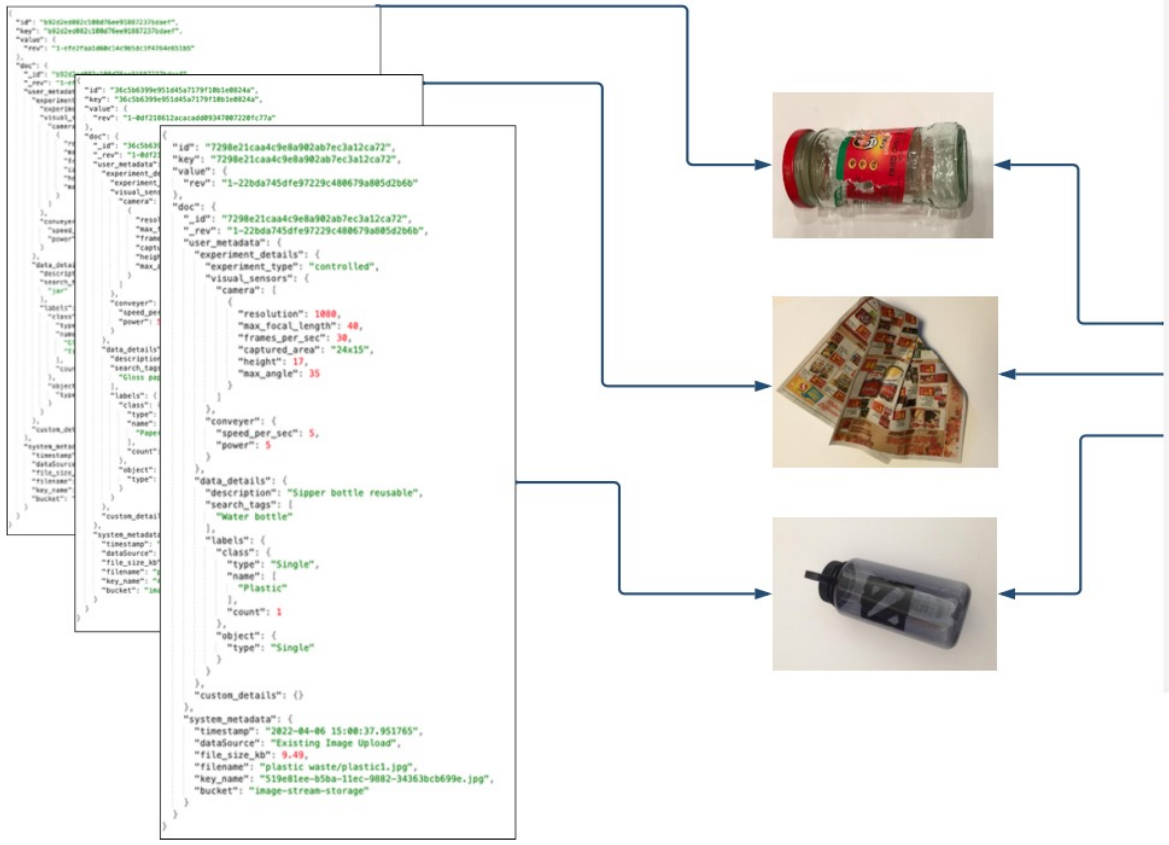
- Maximum subcategories of images
- More controlled visual imaging
- Including the characterization data
- Real waste sample destined for landfill
- Capturing spatio-temporal heterogeneity
- Capturing chemical signature



2 – Progress and Outcomes: Cloud Data Storage

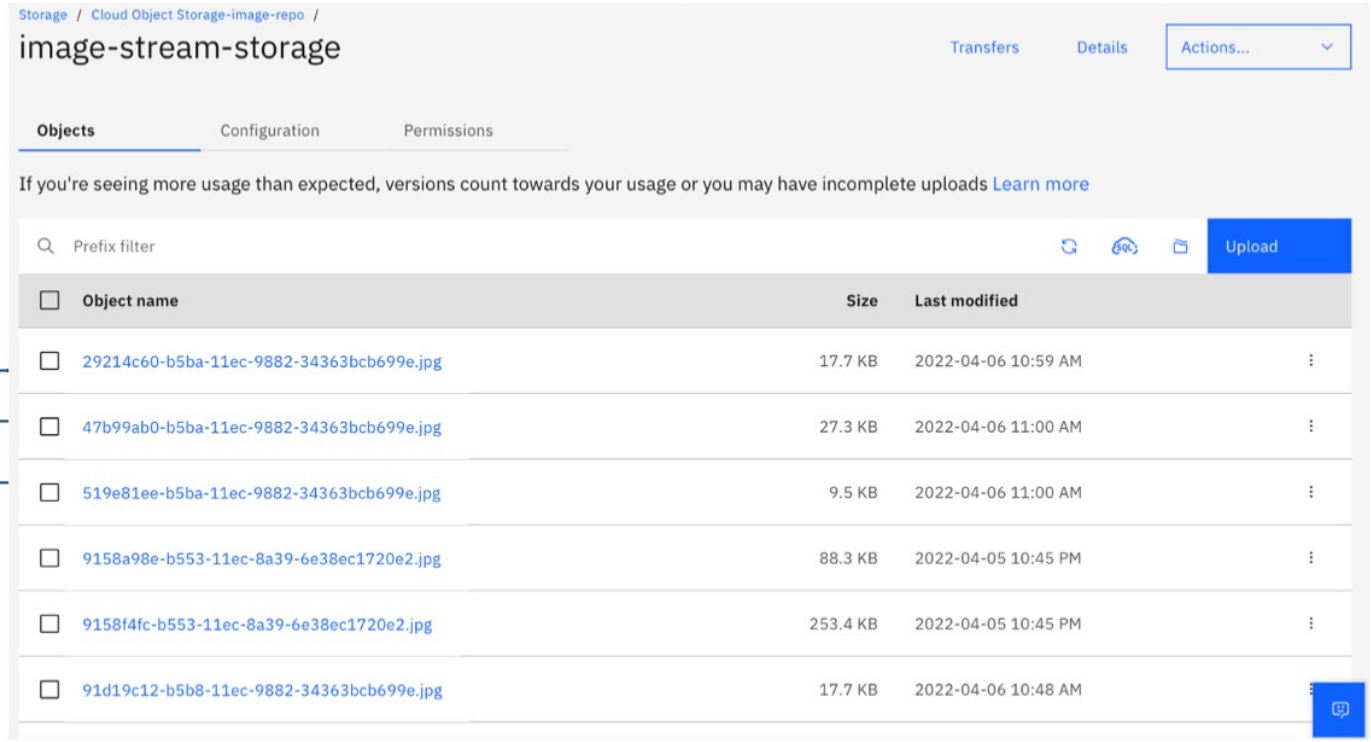
Task 4/Milestones 4.2- 4.5: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)

No SQL Storage
(Set of documents)



(Stores Metadata For Each Image)

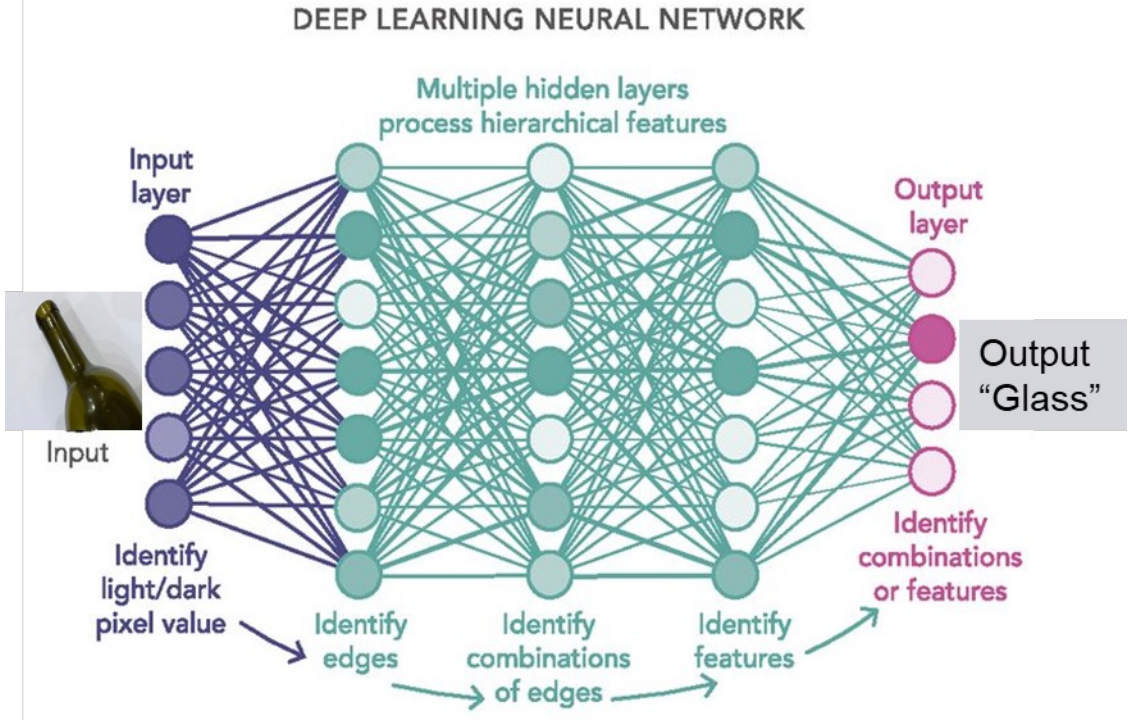
Cloud Object Storage



(Stores Actual Image Files)

2 – Progress and Outcomes: Scalable Data and AI Pipeline

Task 4/Milestones 4.2- 4.5: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)



Adopted from source https://www.pnas.org/doi/10.1073/pnas.1821594116

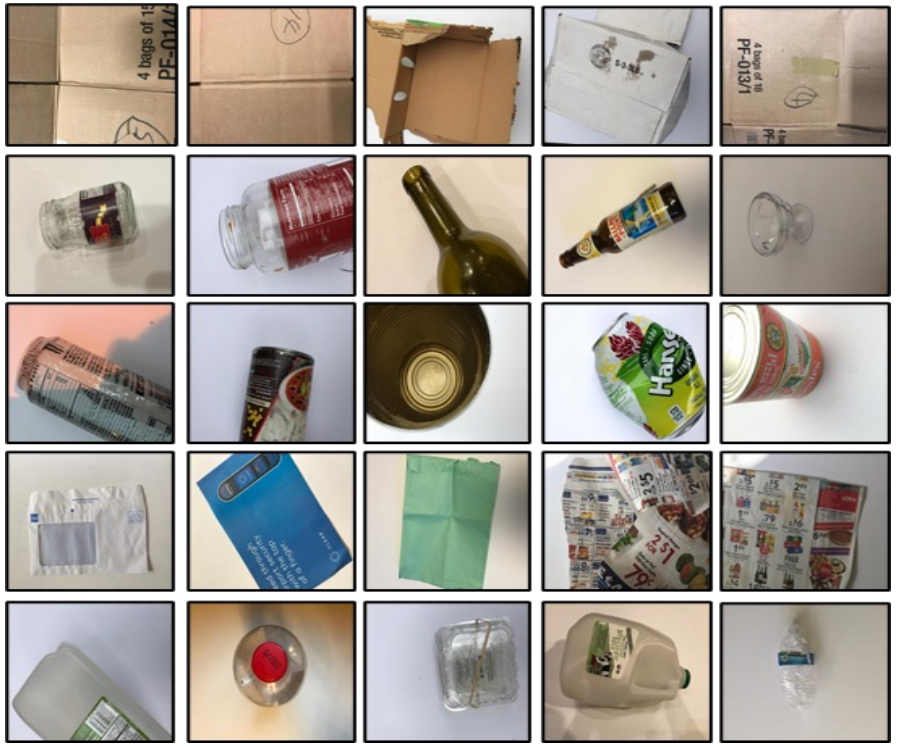


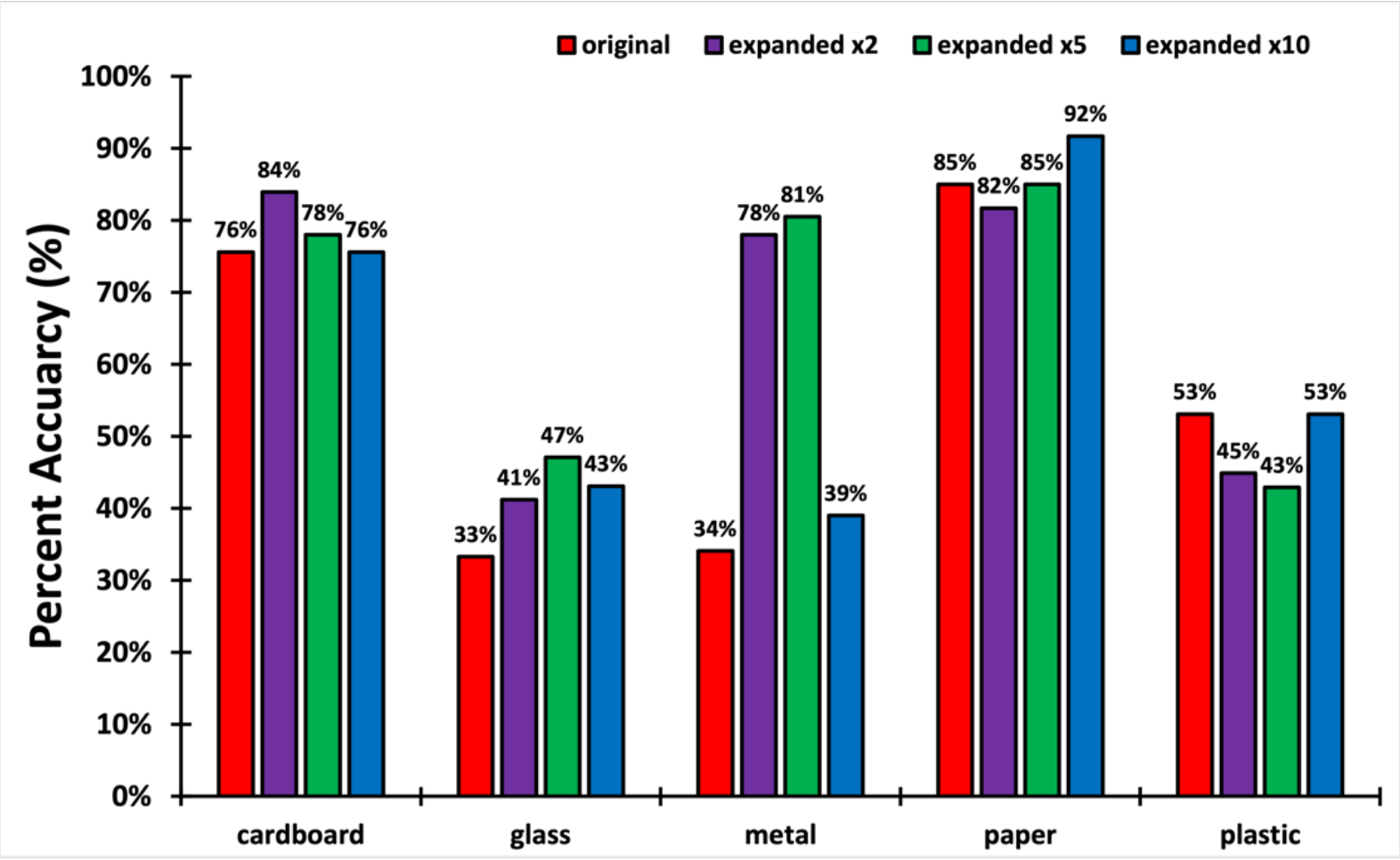
Image Source: https://www.kaggle.com/datasets/techsash/waste-classification-data

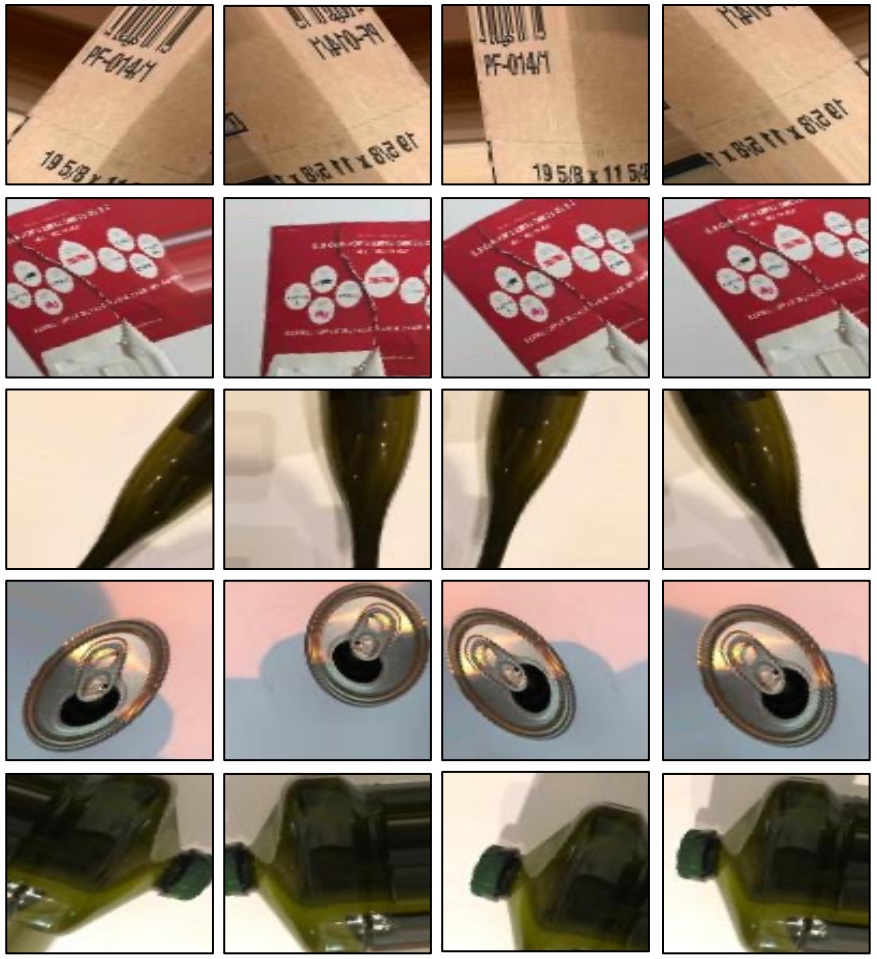
- Connect data sources (pre-existing and data repository system)
- Clean, label, and organize ML training data sets from pre-existing sources
- Build initial an AI pipeline and ML models trained with preexisting data
- Building initial ML classifier for cardboard, glass, metal, paper, and plastic from an online data repository

2 – Progress and Outcomes: Initial ML Visual Image Classifier

Task 4/Milestones 4.2- 4.5: Data mining, collection and building of training sets for HSI, VCI, & MSI (June 2023)

With limited pre-existing image data sets, we have built an image classifier for MSW that show high accuracy for paper and cardboard. Further, image augmentation increased the percent accuracy for other MSW fractions.





Handling

Sourcing

Characterization

Separation

Preprocessing

Homogenization

Utilization

Save the Date!

Waste to Advanced Resources (WAR)

Innovative Solutions, Challenges and Opportunities for Municipal Solid Waste (MSW) Renewable Carbon Resources Towards Net-Zero Bioeconomy

WORKSHOP DATE & LOCATION:

August 9 & 10th, 2023, from 9:00 a.m. to 5:00 p.m. EST

NC State University, Raleigh, NC.

WAR workshop will focus on exploring innovative solutions to maximize resource recovery and minimize waste disposal in landfills through engagement with representatives of industry, municipalities, national laboratories, federal and state agencies, & universities.

For questions or interest in WAR partnership opportunities, please contact: Dr. Lokendra Pal (lpal@ncsu.edu)

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

NC STATE UNIVERSITY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

IBM

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3 – Impacts

- Success of this project will contribute significantly to DOE BETO's mission to develop and transform non-recycled MSW into commercially viable, high-performance renewable carbon resources for conversion to biofuels, biopower, biochemicals, and bioproducts.
- Development of unique datasets with controlled visual and hyperspectral imaging to capture spatio-temporal heterogeneity of waste destined for landfill.
- Robust data and model repository system will enable sharing of data sets (raw and cleaned), various models, and analysis tools with broader research community and industry.
- Open-source AI-enabled cost-effective modular system can be developed and deployed for rapid/ real-time characterization of heterogeneous domestic MSW.
- Technology advancements from this project are being disseminated through stakeholders meeting and engagement, publication in high-impact peer-reviewed journals, conference presentations, seminars, and workshops within the open-source environment as well as coordination of the handling and licensing of IP that results from the project.
- Enable live prediction about MSW with a deployed AI model for citizen education, outreach, and DEI efforts.

Summary

1- Approaches

- Physical and digital systems setup and integration for NMSW characterization – static and dynamic
- Robust data repository of raw image and image description (metadata) file – frontend/backend API, storage and databases
- Scalable data and AI pipeline – data cleaning, labeling and annotation, model frameworks, training, deployment and continuous improvement on prem & Cloud
- Open AI web platform and stakeholders engagement – access control, API driven, dashboard and visualization for product pathways, TEA and environmental LCA, informal education/citizen science.

2- Progress and Outcomes

- Advancing state-of-the art by developing AI-enabled real-time characterization of NMSW.
- Building unique training datasets for AI-enabled real-time characterization of NMSW.
- Collected over 80,000 visual images from various non-recycled MSW samples.
- Milestones set for each task were met successfully.
- Filed a provisional patent, submitted a manuscript, an invited presentation, and organizing workshop.

3- Impacts

- Support DOE BETO's mission to develop and transform NMSW into renewable carbon resources.
- Enable all stakeholders and constituents, especially engage marginalized communities.
- Direct collaboration with municipality and industry for real world impacts.

Quad Chart Overview

Timeline

- *Project start date: October 1, 2021*
- *Project end date: December 31, 2024*

	FY22 Costed	Total Award
DOE Funding	*(10/01/2021 – 9/30/2022) ~$236,469*	*$2,839,819*
Project Cost Share	*~$60,118*	*$717,520*

TRL at Project Start: 2
TRL at Project End: 5

Project Partners

- Partner 1: NREL
- Partner 2: IBM
- Partner 3: Town of Cary

Project Goal

Demonstrate a fully functional, AI-enabled, HSI, VCI, and MSI ML models for rapid characterization of major fractions (paper and paperboard, textiles, food waste) of MSW in real time with at least 50% accuracy at multiple conveyor speeds (5, 20, and 50 fpm) on a pilot testbed at NCSU with integrated TEA and environmental LCA to produce conversion-ready feedstocks cost-effectively to ensure the sustainability of the process.

End of Project Milestone

Delivery of AI-Enabled, Hyperspectral Imaging Augmented Rapid/Real-time Analysis of MSW for Sustainable and Affordable Production of Conversion-Ready Feedstocks. Final demonstration of the proposed technology will be completed at the pilot facility at NCSU

Funding Mechanism

FY21 Feedstock Technologies and Algae FOA- DE-FOA-0002423
Topic 1b: focuses on developing rapid/real-time measurement techniques for MSW

Additional Slides

Publications, Patents, Presentations, Awards, and Commercialization

- **Patents**
  - Provisional patent filed: PROV-22-88, Application No 63/401,982 Novel MSW Processing System for Conversion-Ready Feedstocks for Materials and Energy Recovery

- **Publications / Presentations**
  - A Critical Review of Existing and Emerging Technologies and Systems to Optimize Solid Waste Management for Feedstocks and Energy Conversion" review article submitted to a high-impact factor journal.
  - Naimul Haque, Shudeepta Sarker, *Mariangeles Salas, Richard Venditti, Hasan Jameel, Anand Singh, Ashutosh Mittal, John M. Yarbrough, Lucian Lucia, Lokendra Pal* "Innovation in Waste Characterization and Homogenization for Valorization in Bioenergy and Bioproducts" Invited presentaiton at the 45th Symposium on Biomaterials, Fuels and Chemicals, April 30 – May 3, 2023

- **Waste to Advanced Resources (WAR) Workshop**
  - Waste to Advanced Resources (WAR) workshop organization on August 9 & 10th, 2023 in partnership with DOE BETO, NREL, Town of Cary, IBM, INL and other partners (see next slide)