DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Characterization of Mechanical Biomass Particle-Particle and Particle-Wall Interactions

April 5th, 2023

Feedstock Technology

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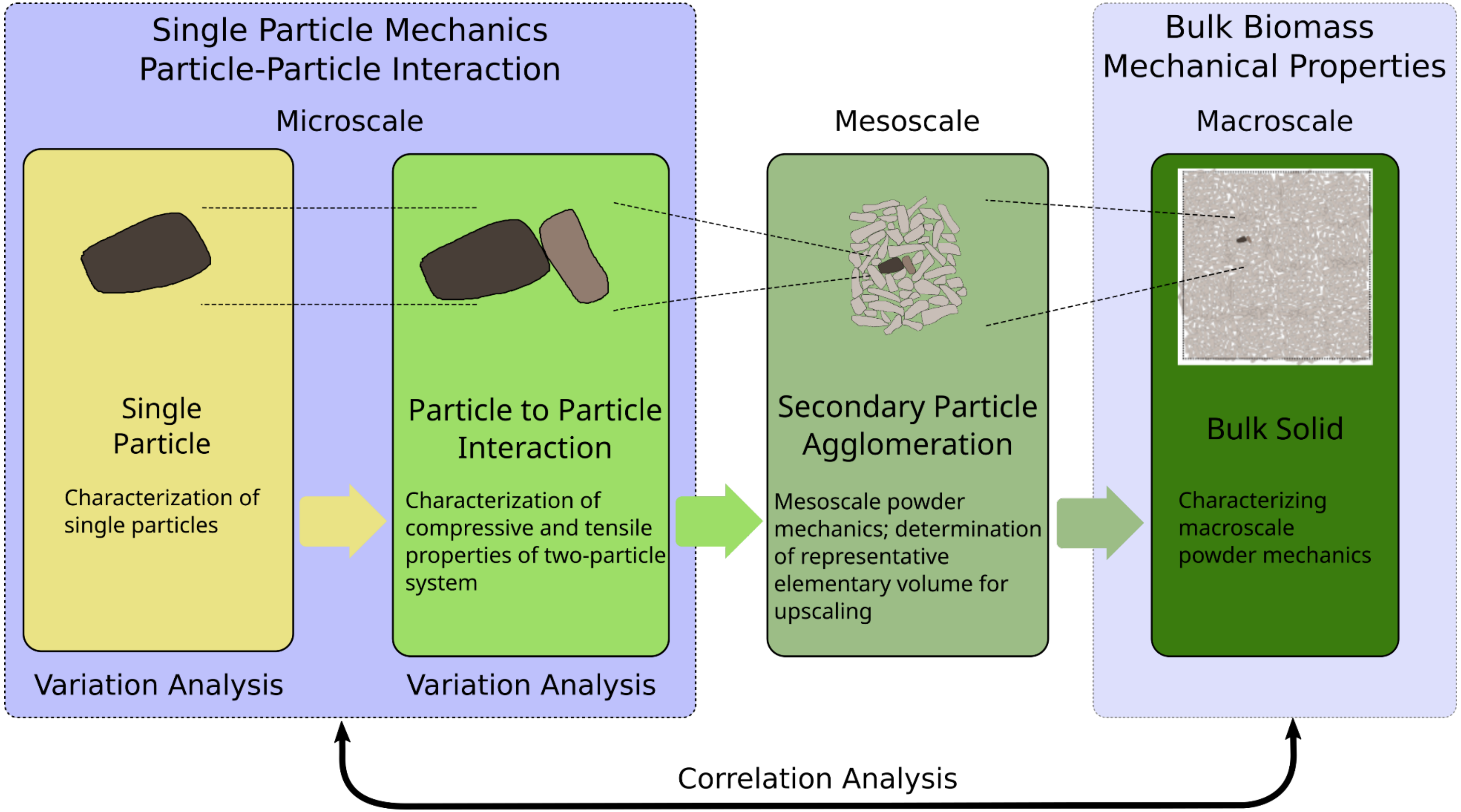
Project Overview

- **2019 Multi-topic FOA: Feedstock Supply and Logistics AOI of Biomass Component Variability and Feedstock Conversion Interface**
  - **BETO Priority of Feedstock Supply and Logistics**: increasing conversion-ready feedstock and sustainable aviation fuel production
  - Early stage research on the physical and chemical characteristics with individual tissue components of corn stover and Southern pine forest residues
  - Addressing **biomass feedstock handling challenges** in producing advanced bioenergy from terrestrial biomass
  - Addressing FCIC research foci on the **feedstock variability and materials handling**
- ***Understanding how feedstock handling performance emerges from the mechanical interactions between biomass particles***
  - Develop a novel experimental method to characterize the friction and adhesion of biomass particles
  - Determining friction and adhesion properties, and their variabilities of Southern pine residue and corn stover particles relative to tissue type
  - Correlation analysis between the friction and adhesion between biomass particles and bulk flow properties

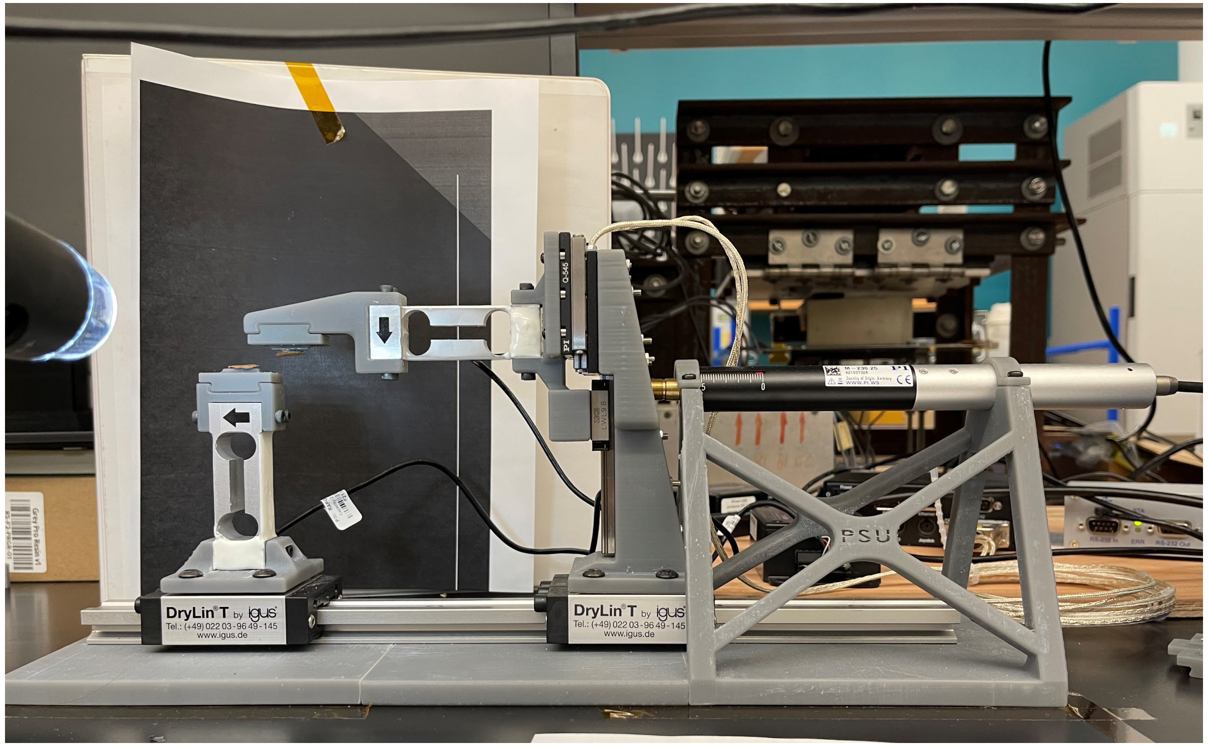
1 – Approach; Background

- **Bulk biomass feedstocks behavior arises from underlying mechanics of particles**



1 – Approach; Develop an inter-particle mechanics tester

- Successfully used for characterizing mechanical properties of plant and biological samples of sub-millimeter size (Zamil et al., 2013, 2014, 2015; Kim et al., 2015)
- New design to accommodate biomass particle samples with length ranging from 1 to 10 mm



Major Components

1. Test particle mount holder
2. Precision linear stage
3. High-Precision Linear Actuator
4. Movement stage
5. Main support frame
6. Digital microscopy
7. Force sensor
8. Test particle mount

1 – Approach; Biomass Sampling Strategy

- **Collected biomass samples are manually fractionated and crumbled**

• **Southern Pine Forest Residues Material**	• **Corn Stover**
• Commingled ground/chipped residues	• Commingled processed from bales
• Clean wood chips	• Stalks with nodes and pith
• Needles	• Leaves
• Bark	• Husks
• Milled twigs and small branches with bark	• Cobs

Raw pine residue anatomical fractions

Reactor-ready milled pine fractions

Raw corn stover anatomical fractions

Reactor-ready milled corn stover fractions

1 – Approach; Biomass Feedstock Samples

chip

needle

bark

twig

4 mm Crumbled Southern pine forest residue

stalk

leaf

husk

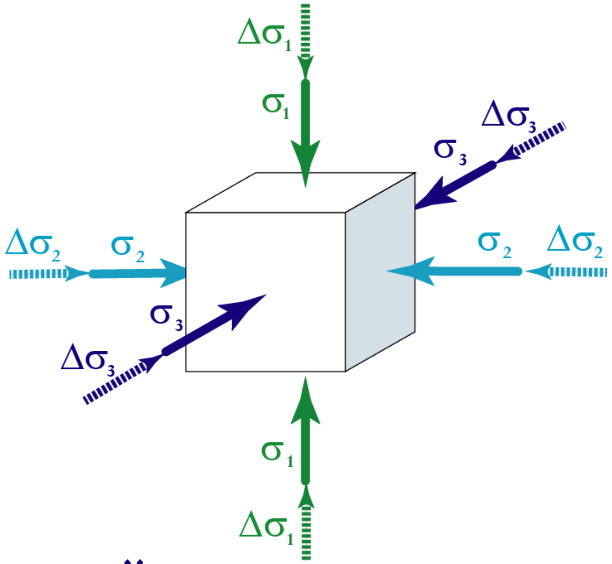
cob

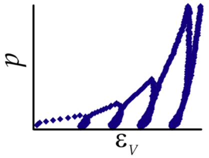
4 mm Crumble Corn stover

- Southern pine residue was collected from Screven, GA (November 2021)
- Antares Corn Stover bales collected from Hardin Iowa (August 2020)
- Samples are hand separated by Forest Concepts LLC. according to anatomical origins and crumbled

1 – Approach; Biomass Feedstock Flow Property Characterization

Hydrostatic Triaxial Compression (HTC) Test

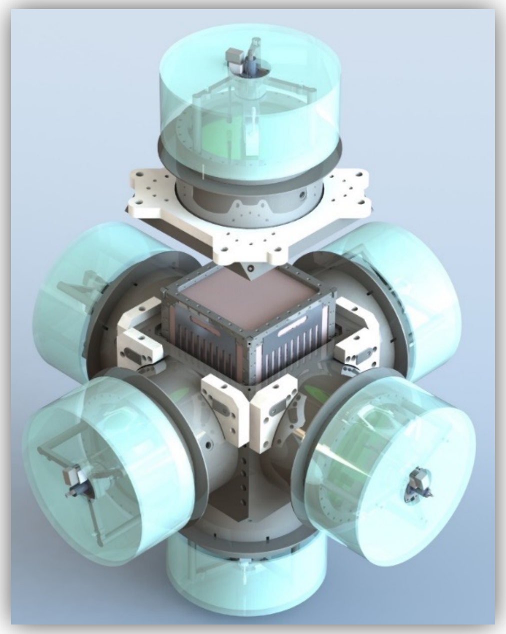




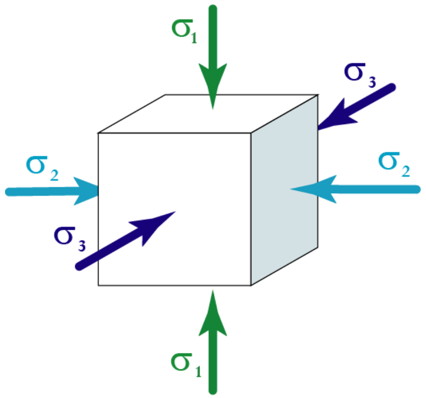
$\sigma_1 = \sigma_2 = \sigma_3$

$\Delta\sigma_1 = \Delta\sigma_2 = \Delta\sigma_3$

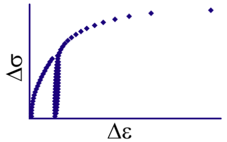
fcCTT
(Forest Concepts Cubical Triaxial Tester)

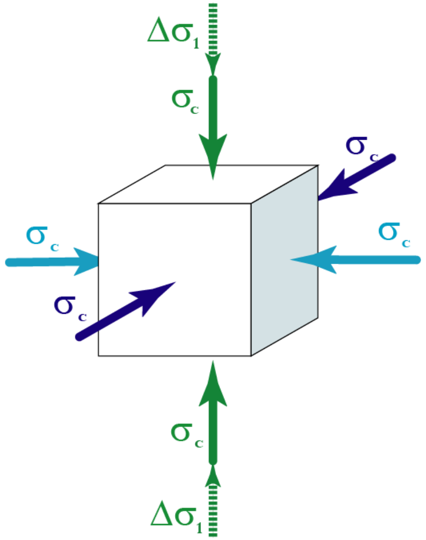


Conventional Triaxial Compression (CTC) Test



$\sigma_1 = \sigma_2 = \sigma_3 = \sigma_{confining}$





$\Delta\sigma_1 > 0$

$\Delta\sigma_2 = \Delta\sigma_3 = 0$

1 – Approach; Management

Penn State

- Characterization and modeling of biological and particulate materials
  - Physical and Mechanical Properties of Ag. and Bio. Materials
  - Powder Mechanics; Storage, Conveying, Flow, Segregation, and Compaction
- Personnel
  - Project Director: Dr. Hojae Yi, PhD
  - Yiming Li, (PhD Student)
  - James Slosson (MS Student)
- Developing inter-particle tester and conducting experiments

Forest Concepts, LLC.

- Biomass technology company
  - Toll-processing plant
  - Design, build, sell feedstock preprocessing equipment
  - Strong relationships with labs and universities
- Personnel
  - Project Director: Dr. Jim Dooley, PhD, PE
  - Project Lead: Chris Lanning, PE
- Feedstock collection, fractionation, and size reduction (milling)

1 – **Approach;** Management plan

- **Management Plan**
  - Minimizing risks by **employing respective expertise and regular communications** (Monthly via Zoom or MS Teams)
  - Project progress management: **Quarterly progress update** meeting and reports with program officer and monitor
  - **Go/No-Go decision meeting** to ensure meeting the proposed deliverables
  - **Incorporating BETO Peer Review comments** to improve project impact
    - Focusing on 4 mm crumble samples instead of 2 mm crumble samples
    - Including Bayesian statistics to aid decision making on feedstock collection and handling
- **Potential challenges facing the technical approach** (mitigation plan in the next slide)
    - Design and commission of a novel interparticle mechanics test device in a timely manner
    - Sample size to ensure the variability measurement at an appropriate confidence level
    - Conducting test with biomass samples with elevated moisture content
- **Critical Success Criteria**
    - Test device design and protocol for biomass particle interactions
    - High confidence level data set of corn stover and southern pine residue interparticle and particle-wall interactions
- **DEI efforts**
    - Recruiting graduate students from underrepresented group

1 – Approach; Risk analysis and mitigation strategies

- **Design and commission of a novel interparticle mechanics tester in a timely manner**
  - Risk: No similar device exists for samples of this dimension
  - Mitigation strategy: Adopting rapid prototyping with additive manufacturing, i.e., in-house 3D printing,
- **Sample size to ensure the variability measurement with enough confidence level**
  - Risk: Typical replications (n = 3 to 5) may not be large enough to ensure high confidence level
  - Mitigation strategy: Achieve larger sample size (n >= 20) by the modular design of the interparticle mechanics tester and by taking advantage of the modern actuator and load cell design
- **Conducting test with biomass samples with elevated moisture content**
  - Risk: Loss of moisture of conditioned biomass particle samples during experiment
  - Mitigation Strategy: Conducting tests inside environmental chamber
- **Utility of the obtained data set in the field**
  - Risk: The dataset may have limited applicability in day-to-day biomass feedstock operations
  - Mitigation Strategy:
    Include Bayesian statistics that can be used in the development of guideline or standard. Increase the sample size to 20 for each treatment and study the effect of the sample size on the determined variability.

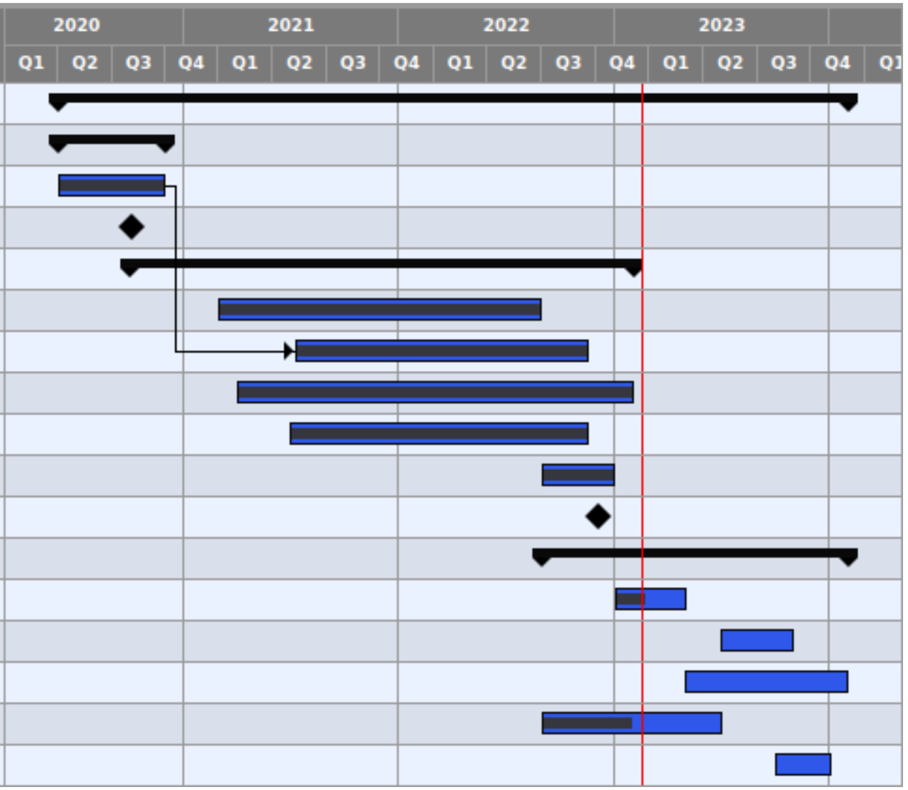
1 – Approach; Management plan

- **BP-2 Go/No-Go Decision Meeting (Dec 1, 2022) :**
  - **Demonstrate the ability to determine friction and adhesion between biomass particles of corn stover and southern pine residue with five successful replications.**
    - **Friction coefficient and adhesion force determined** for air-dried and hydrated at 95% relative humidity for corn stover particles (cob, husk, leaf, and stalk) and Southern pine residue particles (bark, chip, needle, and twig), respectively with 20 replicates for each anatomical fractions.
    - **These data were statistically analyses** using the conventional frequency statistics with 1%, 5%, 10%, and 20% confidence levels and Bayesian statistics.

2 – Progress and Outcomes

- **Progress of the project (May 2020 – April 2024)**

Name	Start	End	Completion
DOE-BETO Inter-particle Mechanics Project	**2020-06-01**	**2024-01-31**	**76%**
Budget Period 1	**2020-06-01**	**2020-11-28**	**100%**
Task 1: Project Verification: Host virtual meeting with all project members ...	2020-06-01	2020-11-28	100%
Budget Period 1 Go/No-Go Decision Point: Presentation delivered and feedback...	2020-09-30	2020-09-30	100%
Budget Period 2	**2020-10-01**	**2023-01-30**	**100%**
Task 3 Design, build, and commission of a Micro-Mechanical Extensometer (MME..	**2021-03-01**	**2022-08-29**	**100%**
Task 2 Obtain representative raw biomass samples of corn stover and southern...	**2021-07-09**	**2022-11-15**	**100%**
Milestones	**2021-03-31**	**2023-01-30**	**100%**
Task 4 Develop a force-displacement analysis protocol from acquired images o...	**2021-07-01**	**2022-11-15**	**100%**
Task 5 Conduct experiments of mechanical properties of corn stover and south...	**2022-09-01**	**2022-12-29**	**100%**
Budget Period 2 Go/No-Go Decision Point: Complete the mechanical physical an...	2022-12-01	2022-12-01	100%
Budget Period 3	**2022-09-01**	**2024-01-31**	**29%**
Task 8 Correlation analysis between biomass particle experiment and bulk bio...	**2023-01-01**	**2023-04-30**	**42%**
Task 7 Measurement of friction and adhesion between corn stover and southern...	**2023-07-01**	**2023-10-31**	**0%**
Milestones	**2023-04-30**	**2024-01-31**	**0%**
Task 6 Conduct experiments of friction and adhesion between corn stover and ...	**2022-09-01**	**2023-06-30**	**50%**
Task 9 Analyze the variabilities in the measured friction and adhesion betwe...	**2023-10-01**	**2023-12-31**	**0%**



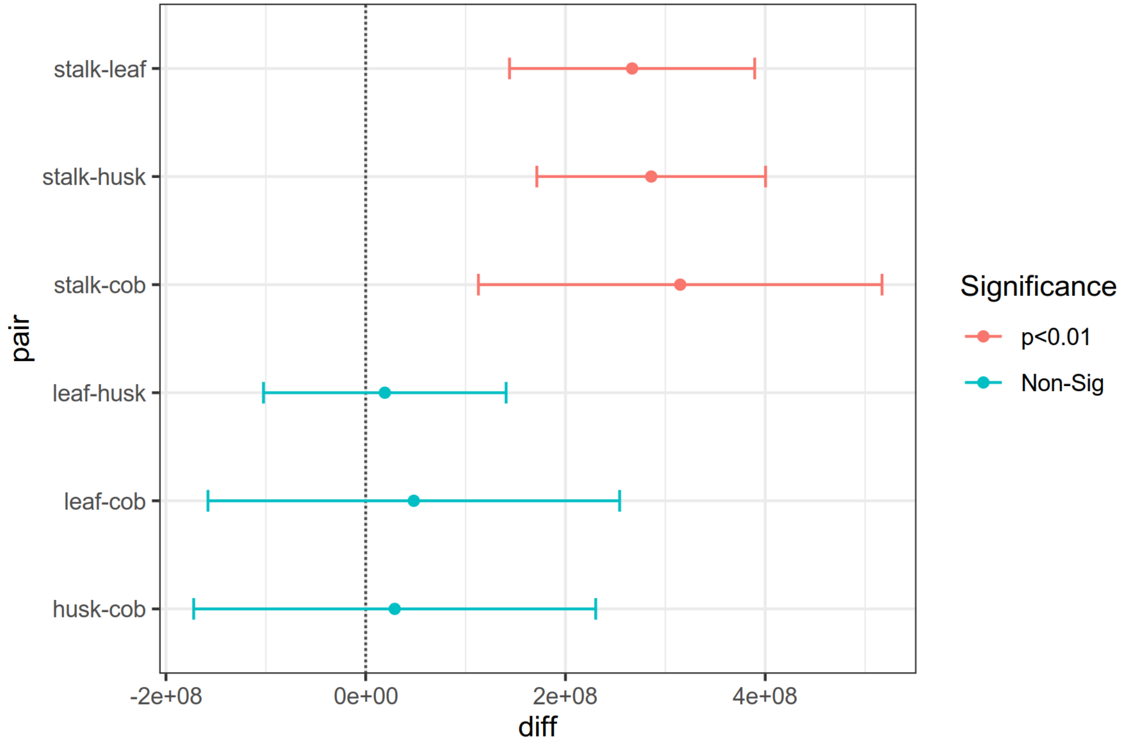
2 – Progress and Outcomes

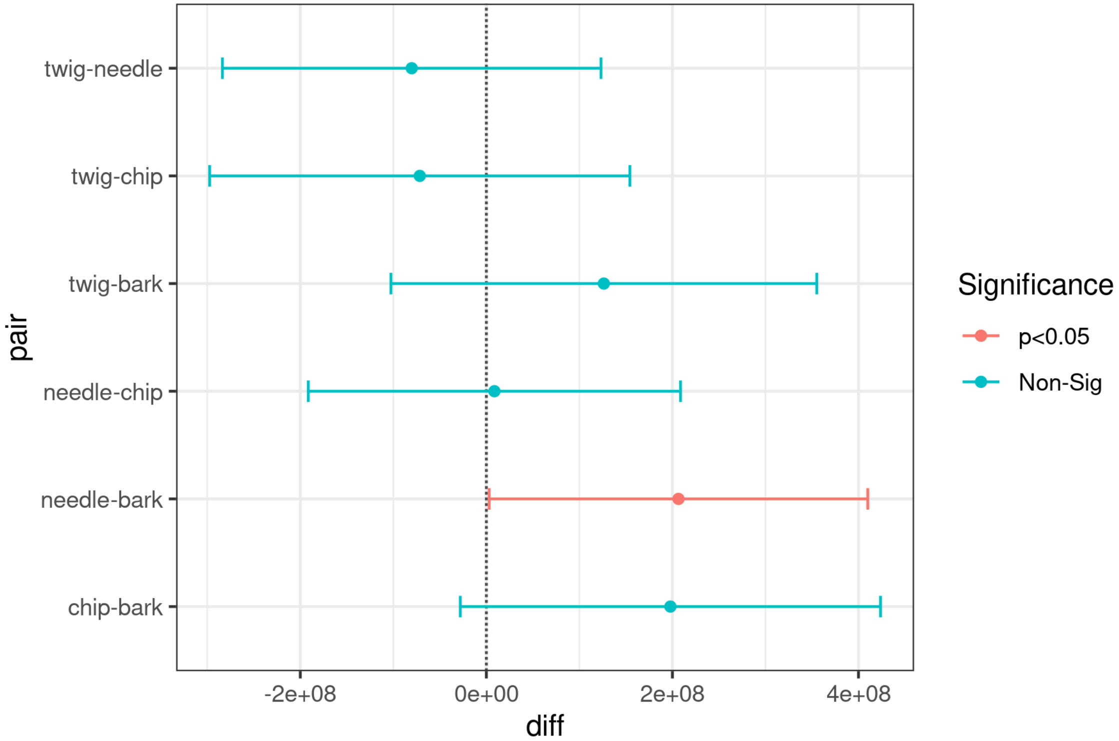
Key milestones

- Achieved Milestone 2.4 (M15/M45) Delivery of milled corn stover and southern pine residue of commingled and pure lots of anatomical fractions
- Completed Milestone 2.5 (M24/M45) Characterization of physical and mechanical properties of corn stover and southern pine residue
- Achieved Milestone 3 (M15/M45) Completion of fabricating 10 units of biomass particle tester to conduct mechanical experiments with biomass particles, particle friction and adhesion
- Achieved Milestone 4.1 & 4.2 (M17/M45) Determination of mechanical properties and friction/adhesion of commingled corn stover and southern pine residue particles with at least one successful run of biomass particle tester
- Achieved Milestone 4.3 (M24/M45) Determination of friction and adhesion properties between commingled corn stover and southern pine residue particles and a typical biomass handling system wall material (stainless-steel foil with a mean surface roughness of 0.85 micrometer)
- Expected Achievement of Milestone 5.2 (M27/M45) Completing determination of mechanical properties of corn stover and southern pine residue particles with at least 5 replicates for each sample treatment
- Expected Achievement of Milestone 6 (M27/M45) Completing determination of friction and adhesion between corn stover and southern pine residue particles with at least 5 replicates

2 – Progress and Outcomes

Milestone 5.2: Determination of mechanical properties of air-dried Biomass Particles





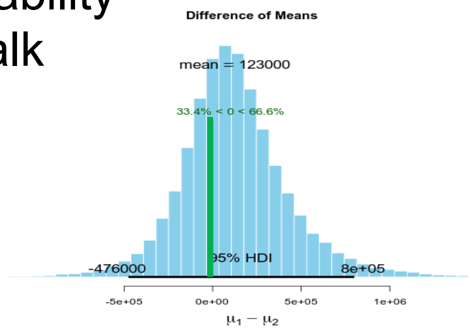
- Corn (left) and pine (right) particle Elastic modulus comparison by Tukey HSD (n = 20)
  - The tensile Elastic modulus of stalk particle is significantly ($p < 0.01$) different from leaf, husk, and cob particles.
  - The tensile Elastic modulus of needle particle and bark particle is significantly ($p < 0.05$) different.
  - The tensile Elastic modulus of other particles are not significantly different ($p > 0.05$)

2 – Progress and Outcomes

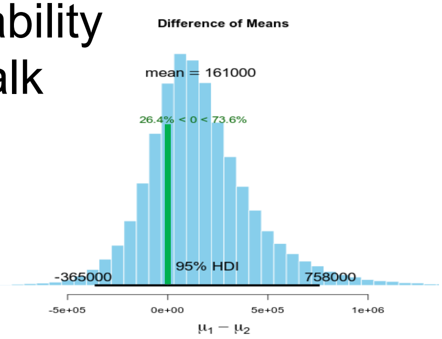
Milestone 5.2: Determination of mechanical properties of air-dried Biomass Particles (n=20)

- **Bayesian statistical analysis inform the probability of variances** (Kruschke, 2013)**, which can be used in decision making in feedstock collection, preprocessing, and handling**

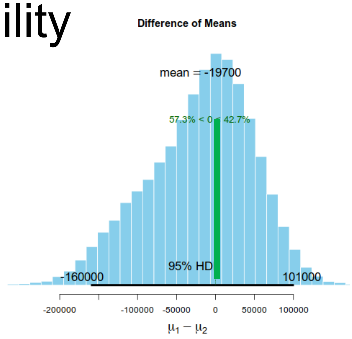
66.6% Probability
leaf < stalk



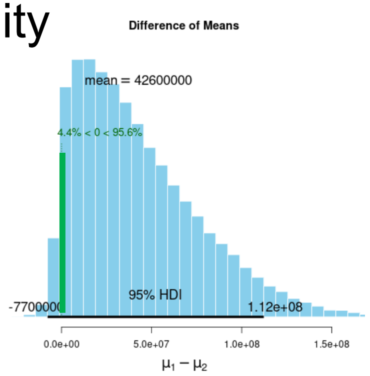
73.6% Probability
husk < stalk



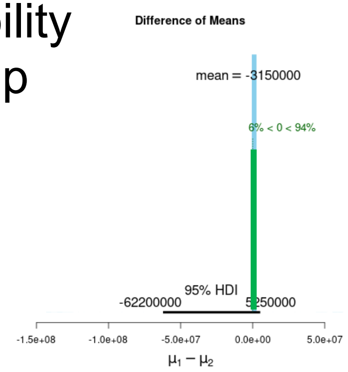
42.7% Probability
cob < stalk



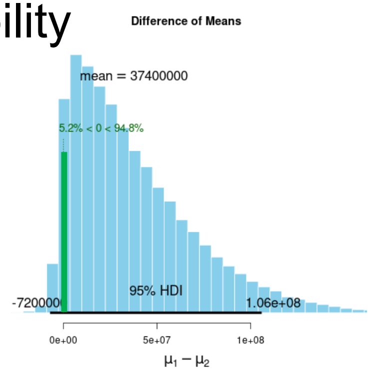
95.6% Probability
bark < chip



94.0% Probability
needle < chip



94.8% Probability
twig < chip



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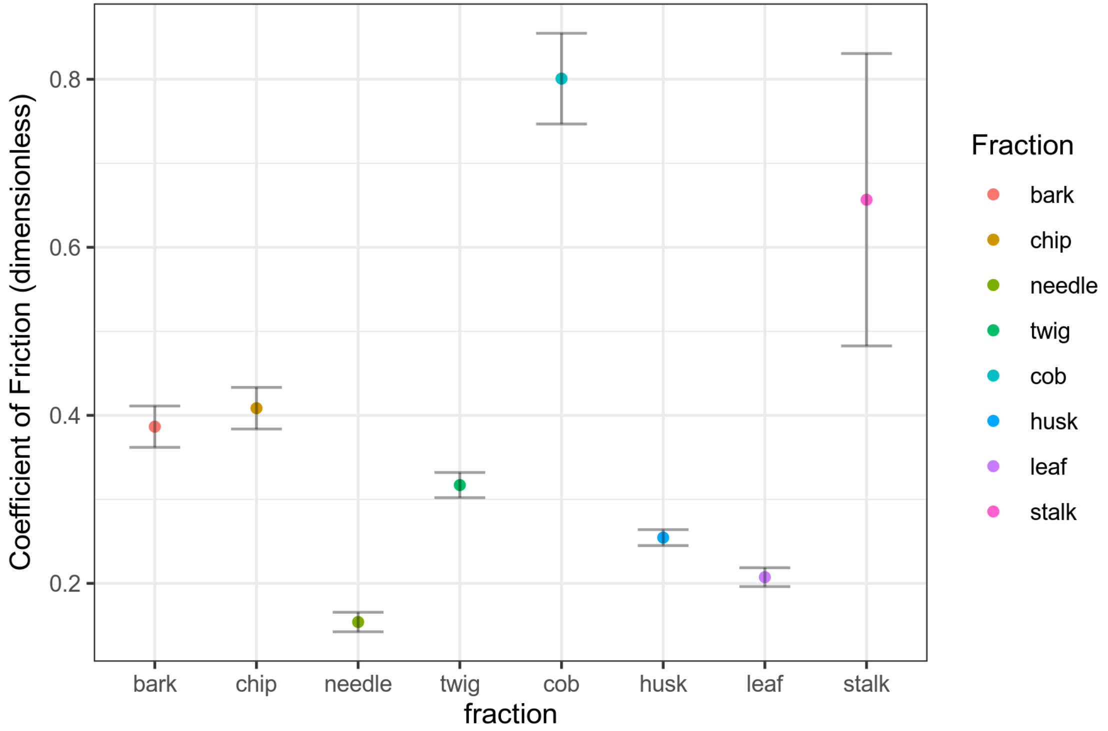
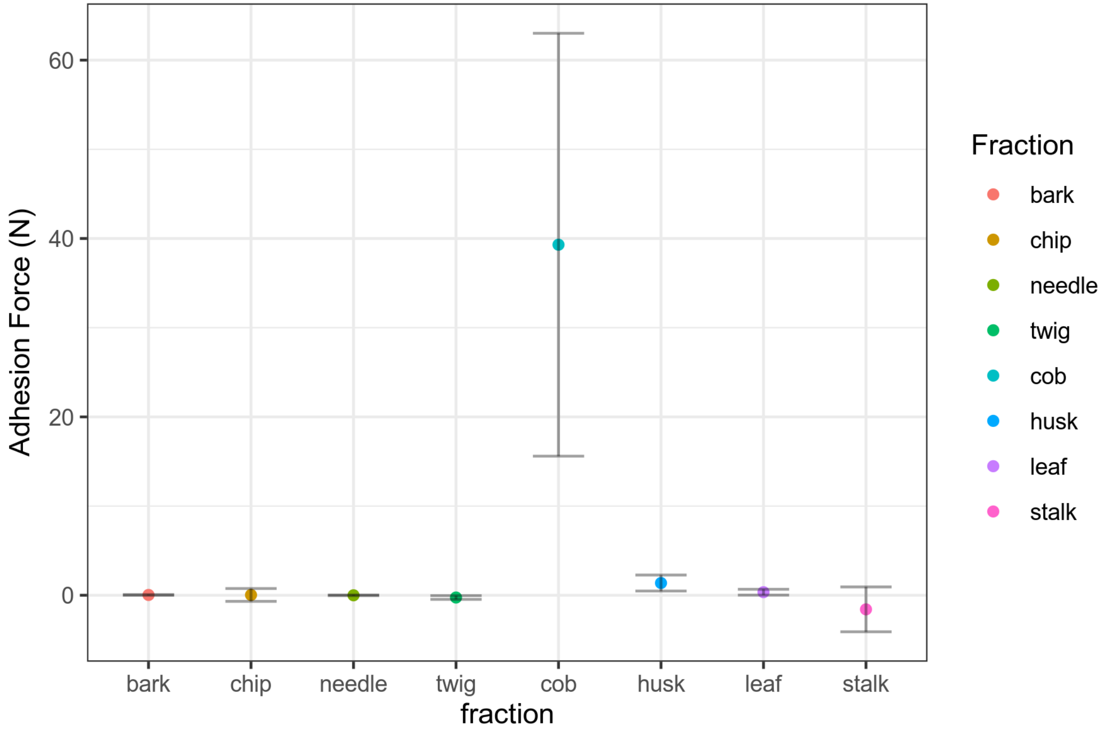
2 – Progress and Outcomes

Milestone 6 Completed determination of friction and adhesion of biomass particles (air-dried)





Coefficients of friction and adhesion

- Cobb and stalk particles show larger coefficients than husk and leaf particles (n=20).
- Cob particles show larger adhesion force than husk, leaf, and stalk particles (n=20).
- Pine particles show less variation and cob particles.

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3 – Impact

Anticipated Impact

- Aid achieving BETO priority in **Feedstock Supply and Logistics**, i.e., increasing conversion-ready feedstock and sustainable aviation fuel production, through
  - Addressing **biomass feedstock handling challenges** in producing advanced bioenergy from terrestrial biomass
  - Addressing FCIC research foci on **the feedstock variability and materials handling**

Specific Impacts includes

- Novel characterization device that will expand the modeling capability (Discrete Element Modeling efforts by INL group)
- Quantitative data that can be used as a quality assurance metrics of biomass feedstocks
- Fundamental knowledge on the origin of flowability issue that can guide a decision making to improve the reliability of biomass handling
- Insight into the effect of sample size and variability of the mechanical properties of biomass

Dissemination strategies include peer-reviewed publication, conference presentation, patenting the developed test device, test standard development (ASABE or ASTM), characterization services for biomass processing industry

Summary

- This project aims to gain **insights on how biomass particle physical and mechanical characteristics are correlated to feedstock handling** performance
- This project is successfully **determining friction and adhesion properties, and their variabilities** of southern pine residue and corn stover particles from different tissue type
  - **Fractionated** southern pine residue and corn stover per anatomical origin
  - Developed **a novel inter-particle mechanics tester** that allows quick and accurate measurements of friction and adhesion properties of fractionated biomass particles
  - Determining **inter-particle and particle-wall mechanical properties with 20 replicates** for each treatment (species, anatomical origin, and two different moisture levels)
  - Conducting conventional frequency statistical analysis and Bayesian statistics to determine the **variability** of determined interparticle properties and the **correlation to the bulk mechanical properties** pertinent to the biomass handling
- We expect that the successful completion of this project will have broad **impacts in improving biomass handling** by engineering biomass preprocesses with quantitative data of biomass particles for advanced modeling approaches, e.g., discrete element modeling or analytical biomass flow models

Quad Chart Overview

Timeline
- *1/1/2021*
- *3/31/2024*

	FY22 Costed	Total Award
DOE Funding		
Project Cost Share *		

TRL at Project Start: 3
TRL at Project End: 4

*Only fill out if applicable.

Project Goal
The goal of the proposed project is to contribute to the understanding of key characteristics of southern pine and corn stover anatomical fractions and their variabilities to enable engineering of biomass supply systems to handle, store, and deliver conversion-ready feedstocks reliably.

End of Project Milestone
Micro-Mechanical Extensometer and particle scale test protocol

Variability of friction and adhesion of corn stover and southern pine residue particles

Variability of friction and adhesion of biomass particles and a wall material

Funding Mechanism
DE-FOA-0002029 DOE BETO 2019 Multi-topic FOA

Topic Area 2a: Relating Biomass Physical and Chemical Characteristics to Feedstock Performance in Handling and Conversion Operations

Project Partners*
- Forest Concepts, LLC.

Additional Slides

Responses to Previous Reviewers' Comments

- One of repeated questions of the peer review 2021 is how the data and test protocol produced from this project can be used in the biomass processing and handling.
  - This project includes tasks of determining the bulk scale biomass feedstock handling characteristics, which has completed. We will conduct correlation analysis between particle scale data and bulk scale data. This will produce probability of predicted handling issues with a given composition of biomass feedstock relative to the tissue type.
  - This quantitative knowledge can be used in the collection of biomass to remove problematic fractions. Or a sorting process can be incorporated before milling so that the ground biomass have improved handling characteristics.
- Another repeated suggestion of the peer review 2021 is to consider commercialization of the tester.
  - We are pursuing the patent of the device. We also have a plan to establish characterization service possibly connecting with the Forest Concepts biomass cubical triaxial tester.
- BP2 Go/No-Go Review suggested to conduct a friction and adhesion experiment for 50 replications at least one treatment to investigate the sample size effect on the variability, which is on-going.

Publications, Patents, Presentations, Awards, and Commercialization

- Presentations
  - Li, Yiming, James C. Slosson, and Hojae Yi. “Microscale Mechanical Testing of Biomass Particles Using Image Analysis Method.” Houston, Texas: ASABE Paper No. 2200583. St Joseph, MI: ASABE
  - Slosson, James C., Yiming Li, and Hojae Yi. “Determining Friction Coefficient and Traction Adhesion Force Between Corn Stover Particles of Anatomical Fractions.” Houston, Texas: ASABE Paper No. 2200704. St Joseph, MI: ASABE
- Describe the status of any technology transfer or commercialization efforts
  - We are pursuing a patent of the interparticle mechanics tester and will explore commercialization of the device or characterization service