DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Feedstock Technologies Session

April 5, 2023

Modeling Feedstock Performance and Conversion Operations

1.2.2.103_EE00008910_Purdue University

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Our Team

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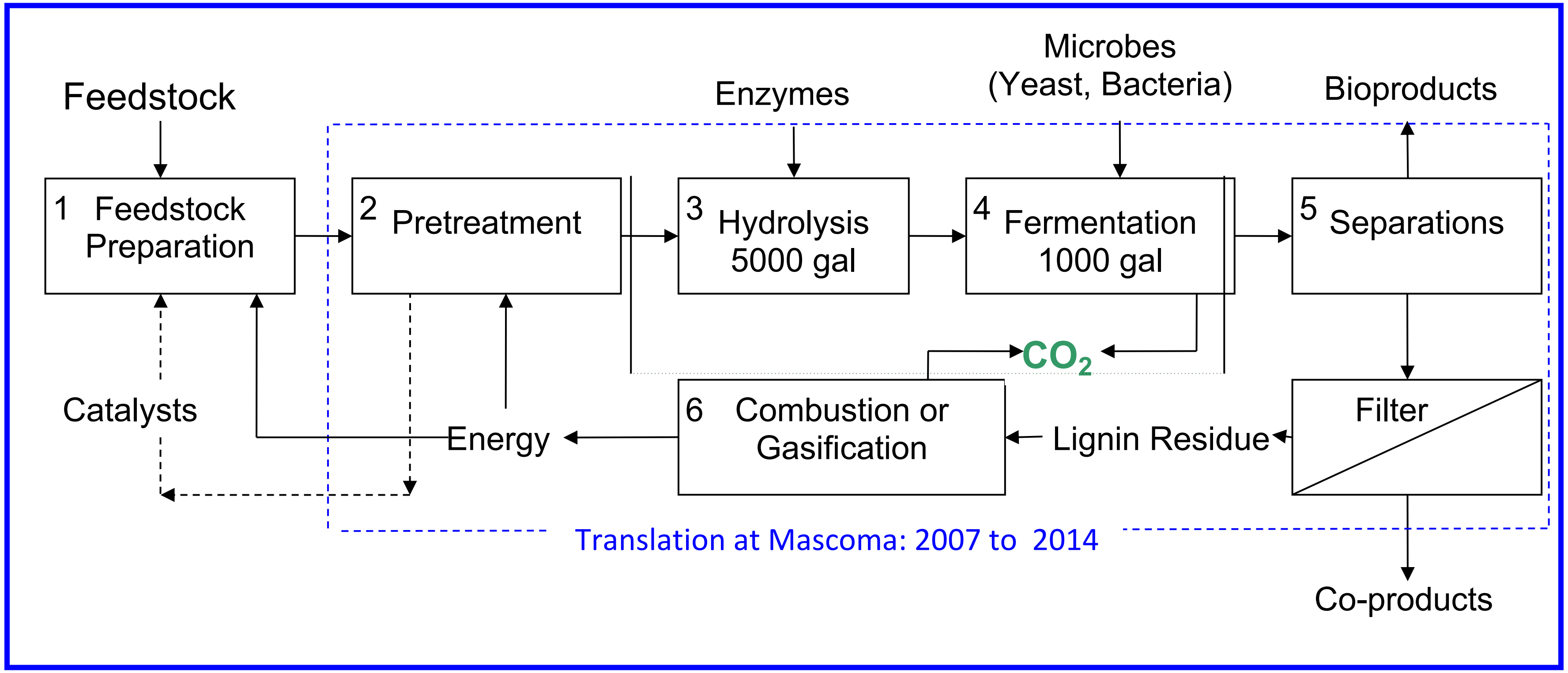
Feedstock	DLM Modeling	Characterization	TEA / LCA	Materials Data Base
John Aston, Lead David Thompson Jim Dooley Kingsly Ambrose	Arezoo Ardekani, Lead Carl Wassgren Kendra Erk Ria Corder	Eduardo Ximenes, Lead Kendra Erk Antonio Santos Antonio Cruz	Abigail Engelberth, Lead Nathan Mosier Thathiana Gallego Dale Monceaux	Carl Wassgren Lead Marcial Gonzalez Nathan Mosier John Aston
INL Purdue ABE Forest Concepts	Purdue ME MSE	LORRE ABE MSE INL Purdue, UF Sao Carlos	ANL Purdue ABE LORRE AdvanceBio	Purdue ME MSE LORRE INL Forest Concepts
completed	*95% completed*	*95 % completed*	*60 % / 25% completed*	*40 % completed*

<u>Graduate students and researchers:</u> Luana Assis Serra, Zachary Bebar, Carlos Canizaros, Xueli Chen, Fernanda da Cuhna, Diana Ramirez Gutierrez, Rishabh More, Akash Patil, Abhishek Paul, Bjorn Peng, Allison Ray

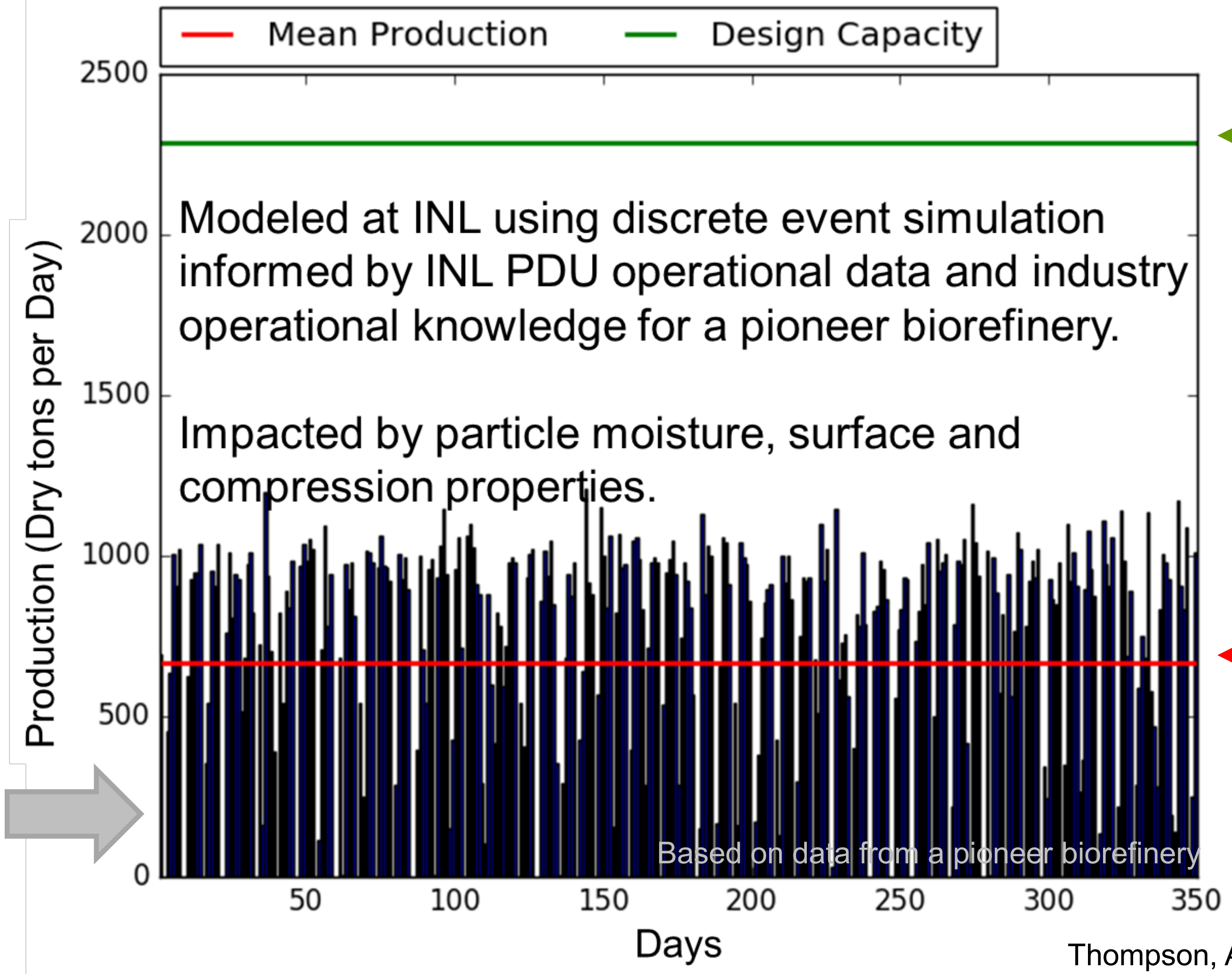
Project Overview

The 6 Steps for Conversion of Cellulose to Bioproducts



Ladisch, YM Kim, Mosier, 2006, 2010, 2017

Lesson learned: materials handling matters



Modeled at INL using discrete event simulation informed by INL PDU operational data and industry operational knowledge for a pioneer biorefinery.

Impacted by particle moisture, surface and compression properties.

Design capacity of a pioneer biorefinery

70% below the design capacity of a pioneer biorefinery

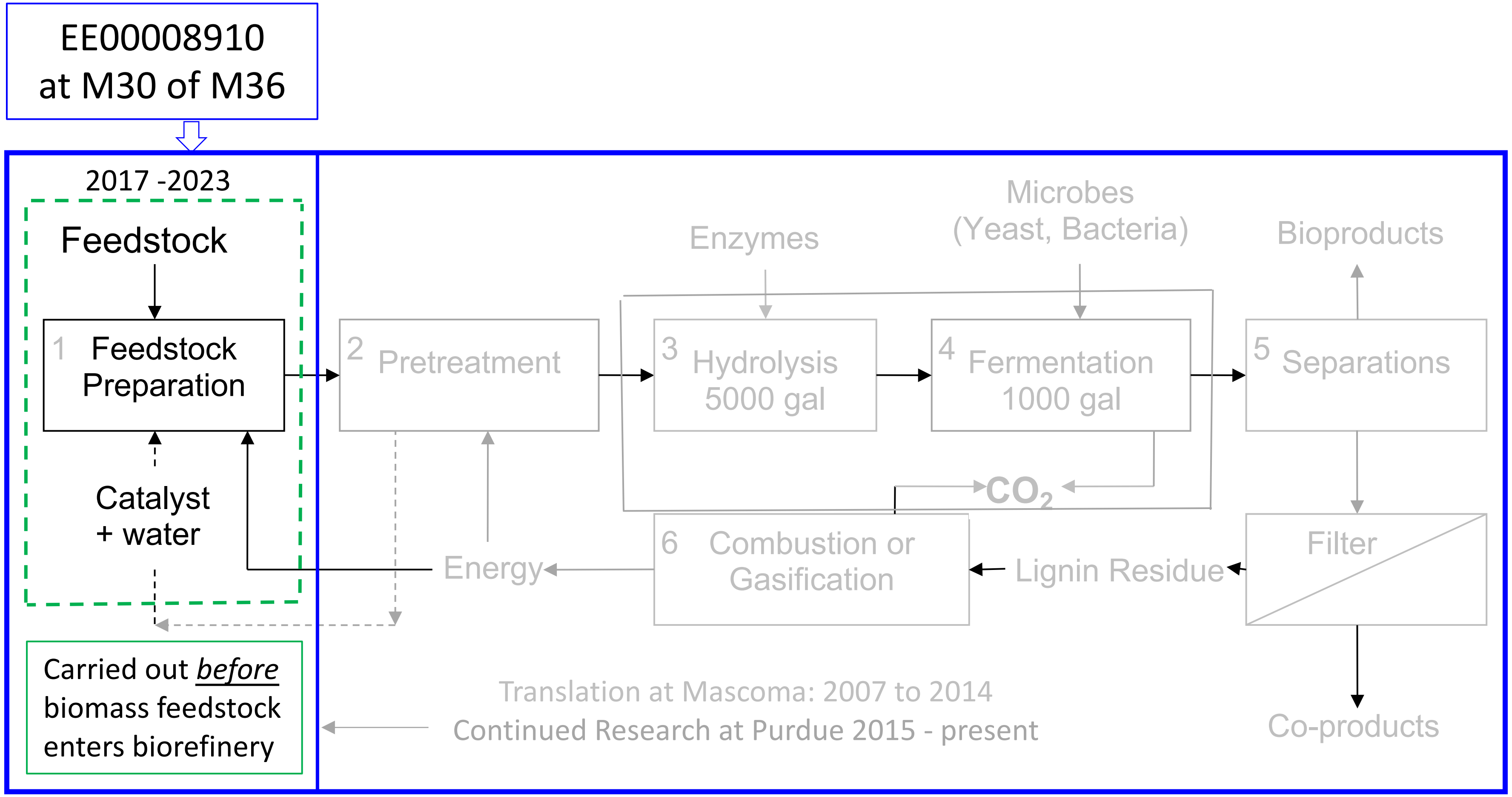
Attained capacity of a pioneer biorefinery

Due to materials handling (solids)

Thompson, Aston et al., 2018, 2020; Monceaux, 2022

Project Overview

The 6 Steps for Conversion of Cellulose to Bioproducts



Ladisch, Thompson, et al, 2006, 2011, 2017, 2022

Statement of Project Objectives and Specific Aims: EE0008910

Purdue University, INL, ANL, Forest Concepts, AdvanceBio. Project at M30 of M36

Objectives:

Model the formation of an aqueous slurry that may be pumped and processed at high solids loadings i.e., a liquefied form of corn stover, and

relate to chemical and physical characteristics of the biomass material.

The research plan is address research gaps related to the biomass component variability and feedstock conversion interface.

Specific Aims (Technical Objectives)

Investigate characteristics associated with tissue components of cob, stalk, husk, and leaves from corn stover and formation into pellets

Determine how these change during preprocessing into pellets and make high loadings possible before pretreatment

Capture knowledge in dimensionless chemical engineering parameters & mathematical modeling of rheology of flowable slurries of corn stover fractions - before pretreatment – at up to 300 g/L

Formation of highly concentrated, fluid slurries from corn stover would enable transportation of stover as a pumped fluid rather than as a solid material that must be conveyed, resulting in significant savings in pretreatment costs and enhanced operability.

Verification 09032020

Task 1: Verify Overall Approach and Workflow

Tasks from SOPO

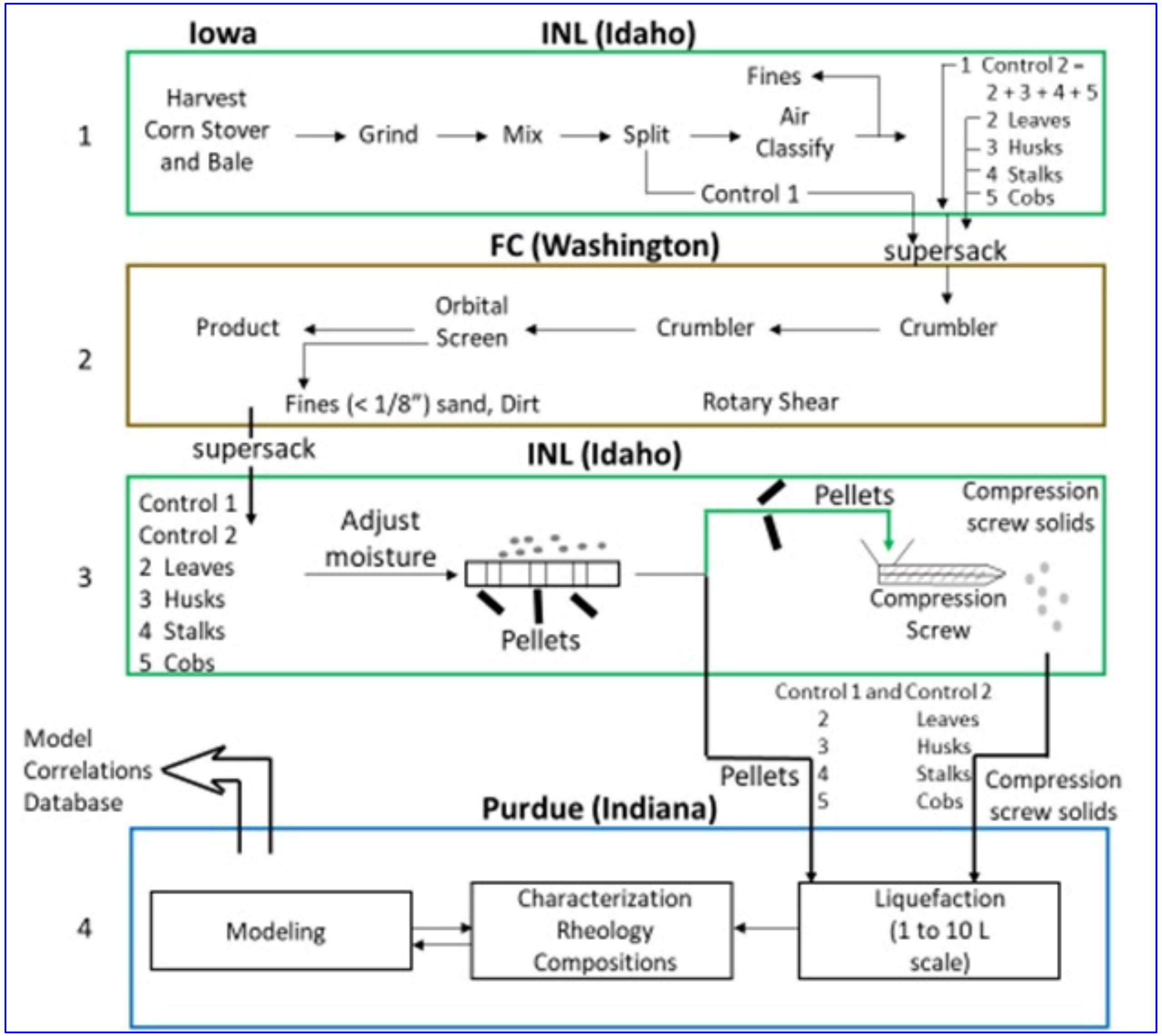
Task 1: Verification (completed)
Task 2: classification of corn stover components and preparation of pellets (completed)
Task 3: computational modeling – Immersed Boundary Method (IB) for biomass slurries (95% completed)
Task 4: slurry-forming experiments with fed batch reactors, characterization, data fitted to models (90%)
Task 5: techno-economic assessment (TEA) (60%)
Task 6: life-cycle analysis (LCA) preprocessing step (25%)
Task 7: characterization of optimized materials; dimensionless correlations - materials data base (40%)
Task 8: communications, reporting, project coordination

Key elements of the technical scope: (1) verification, (2) corn stover preparation and pelleting, (3) modeling, (4) slurry formation; (5) material characterization; and (6) calculate operational (OpEx) / cap (CapEx) expenses.

Project currently at month 30 of 36 month schedule

Workflow

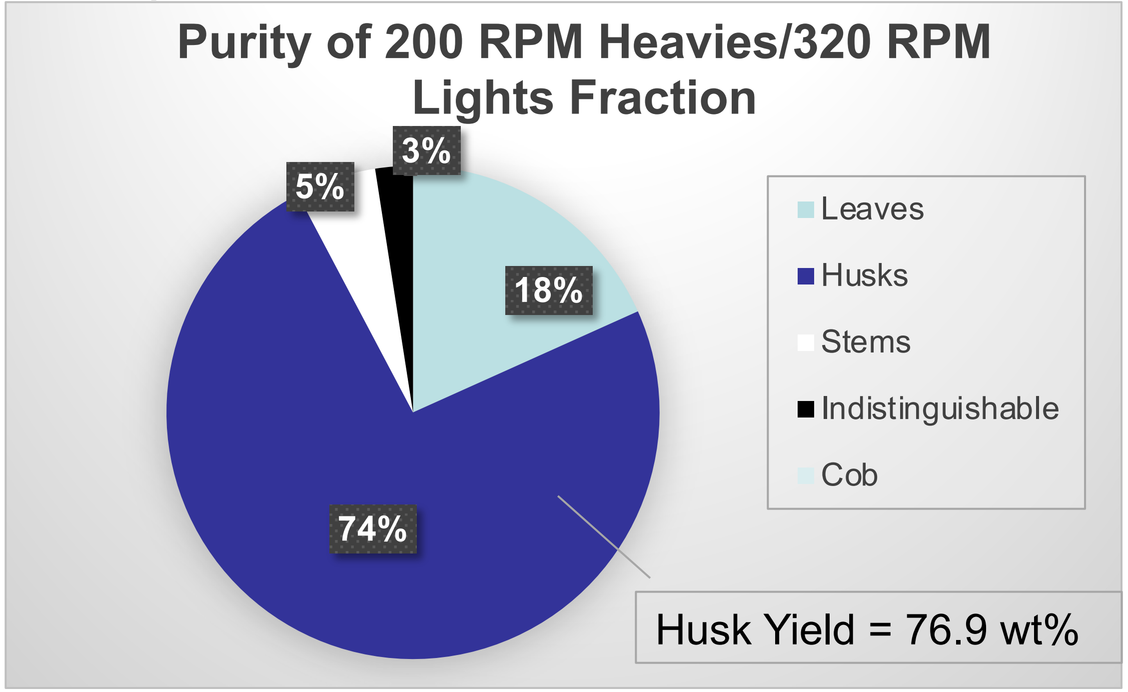
Task 1 is completed

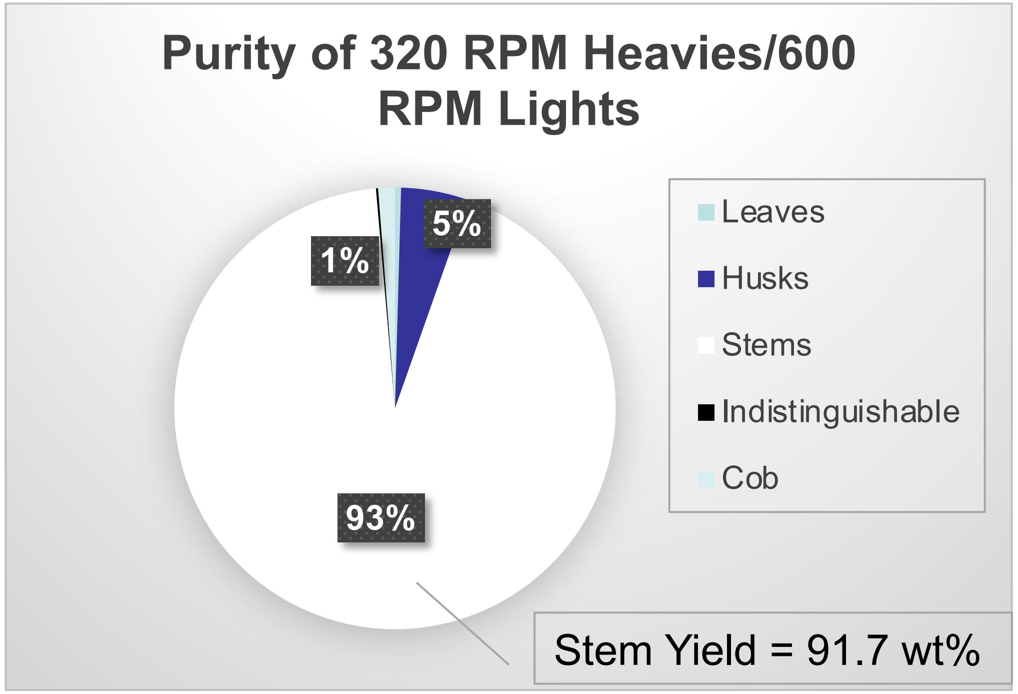


Task 2: Corn stover separated into Anatomical Fractions via Air Classification 75 wt% Target for Purity & Yield

Task 2 is completed

Example:





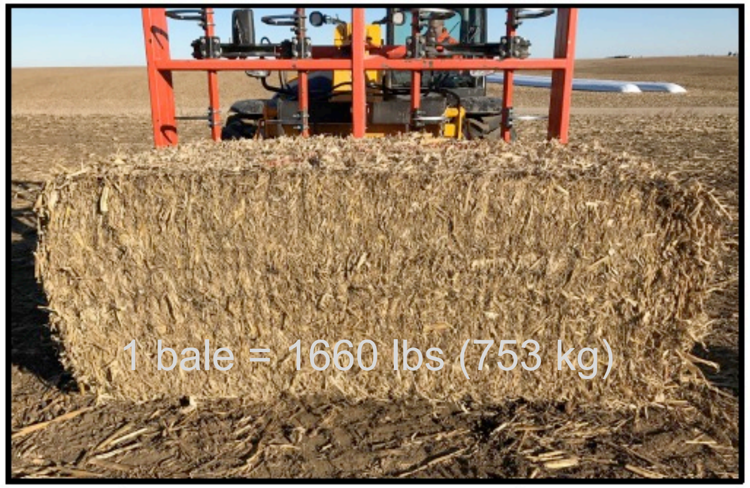
Aston, Thompson, Dooley, 2021.2022

Data collected from the fractionation of a single bale (1660 lbs).
Separate project showed bale-to-bale variability of ± 10 wt% per fraction, especially for leaf and husk fractions.
Lower rpm of fan corresponds to a lower airflow and therefore separates out light fractions.

Task 2: Bale to Anatomical Fractions at INL

Task 2 is completed

Air Fractionation
- Fan rpm generates air stream
- Fan rpm at 200 to 600 rpm
- Bale to bale variability ± 10%
- 1660 lbs cornstover processed



Fractionation impacted by
- harvesting method
- moisture content
- air speed (airflow)

Separation into 4 fractions

Aston, Thompson, Dooley, 2021.2022


Cob


Stalk


Husk


Leaf

Impact: Distinct fractions obtained at meaningful scale

Task 3: Modeling of Shear Stress for High Concentration Slurries

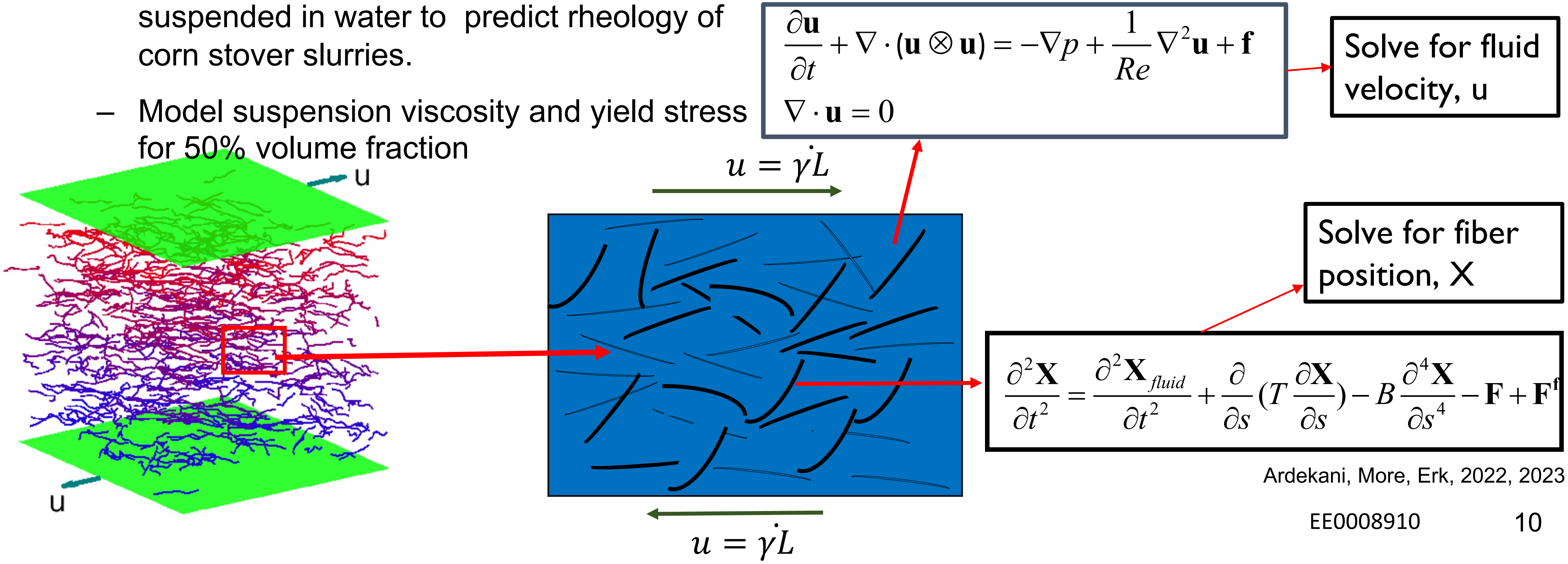
Task 3: 95% completed

Objectives and Specific Aims

- Numerically compare the shear stress at start up with experimental results for corn stover slurries
- Compare steady state shear stress with experiment for corn-stover slurries

Approach

- Develop computational model for fiber suspended in water to predict rheology of corn stover slurries.
- Model suspension viscosity and yield stress for 50% volume fraction



$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = -\nabla p + \frac{1}{Re}\nabla^2 \mathbf{u} + \mathbf{f}$$

$$\nabla \cdot \mathbf{u} = 0$$

Solve for fluid velocity, u

$$\frac{\partial^2 \mathbf{X}}{\partial t^2} = \frac{\partial^2 \mathbf{X}_{fluid}}{\partial t^2} + \frac{\partial}{\partial s}\left(T \frac{\partial \mathbf{X}}{\partial s}\right) - B \frac{\partial^4 \mathbf{X}}{\partial s^4} - \mathbf{F} + \mathbf{F}^{f}$$

Solve for fiber position, X

Ardekani, More, Erk, 2022, 2023

Task 3: Model gives good fit to experimental measurements

Task 3: 95% completed

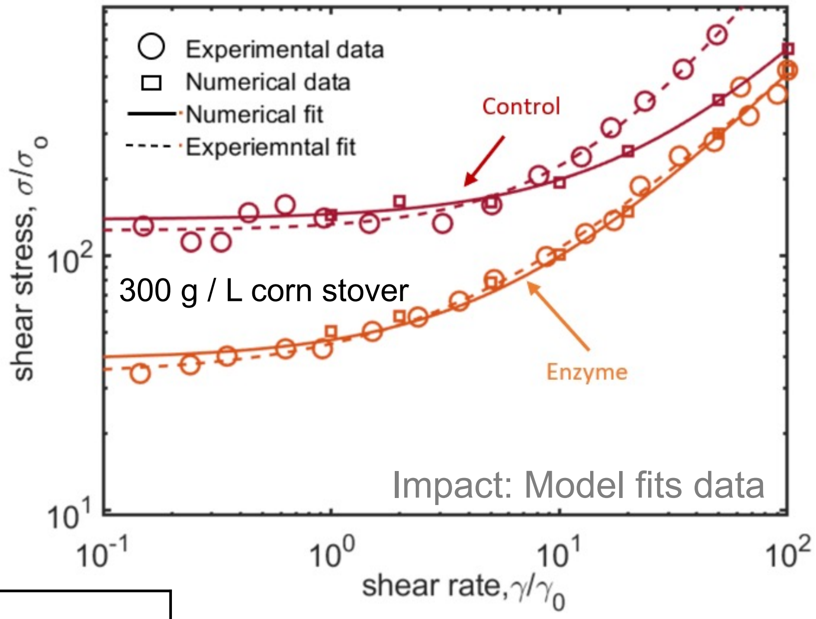
Example: comparison of steady state shear stress for corn stover slurries

Dashed line shows experimental fit
Solid lines show numerical fit of Herschel-Bulkley Model:

$$\sigma/\sigma_o = \tau_y + b * (\gamma/\gamma_o)^c$$

where τ_y, b and c are fitting parameters
τ_y denotes yield stress of suspension.

Control: no enzyme, agitated at 50^0 C
Enzyme: 1FPU (filter paper unit) / g enzyme in agitated reactor (mechanically sheared) at 50^0 C



Impact: Model fits data

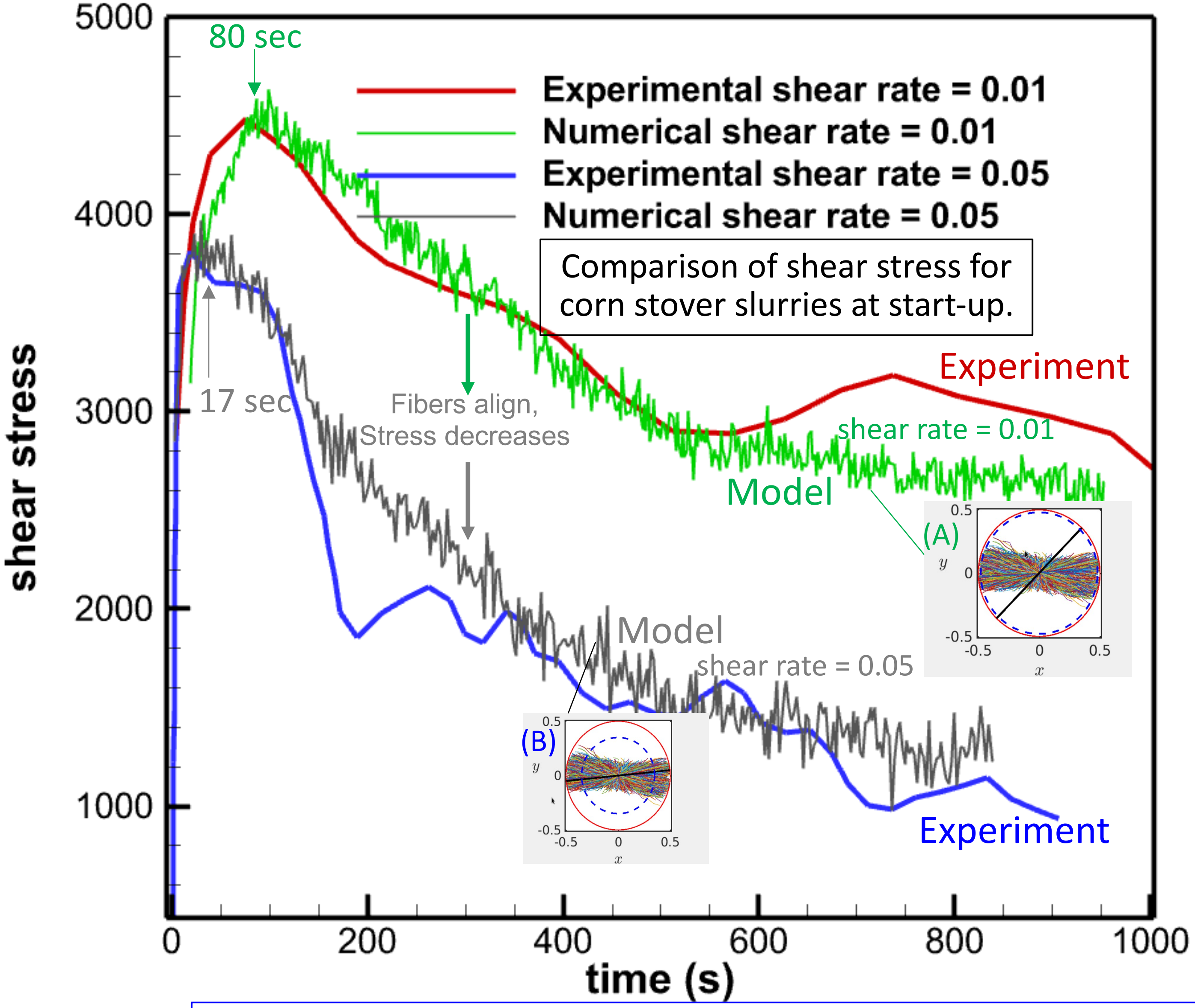
Table . Comparison of Herschel – Bulkley model parameter				
Treatment	**Parameter**	**Numerical**	**Experimental**	**% error**
Control	τ_y	138	125	10.4%
	L^2 - Norm	419.56	498	15.75%
Enzyme	τ_y	39	34	14%
	L^2 - Norm	378	421	10.21%

$$L^2 - Norm = \sqrt{\sum_{K=1}^{N} \left|\frac{\sigma}{\sigma_0}\right|^2}$$

Ardekani, Erk, Szeto, More, dos Santos 2022, 2023

Task 3: Modeling of Shear Stress for High Concentration Slurries

Task 3: 95% completed



Comparison of shear stress for corn stover slurries at start-up.

Model predicts - and data show – times when shear stress maxima occur during start-up of mixing of corn stover slurry (17 and 80 sec)

Model: randomly places fiber in domain, and then calculates time dependent shear stress.

As fibers align, shear stress decreases.
As shear rate increases, stress decreases.

Dimensionless shear rate	Experimental value (dimensionless)		Numerical (dimensionless)	
	Max. stress	Time at max stress	Max. stress	Time at max stress(s)
0.01	4470	79.6	4650	89
0.05	3380	17.7	3850	24

Erk, Corder, Ardekani, 2022

Impact: IBM model predicts rheology based on biophysical properties of particles: shows why fed batch is needed

Task 4: Characterization of Corn Stover Fractions

Task 4: 95 % completed

Objectives

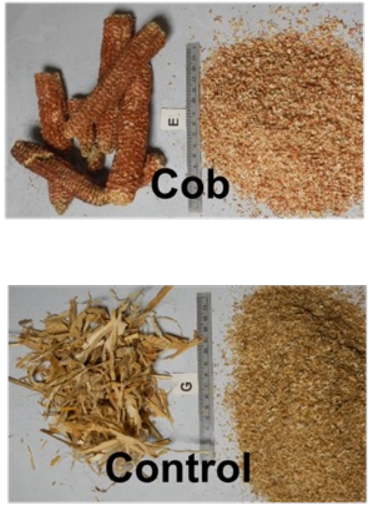
Determine particulate physical properties, compositional analysis, rheological measurements with integration of data obtained into a corn stover particulate database for particles prepared by hammer-milling and rotary shearing, and formed into pellets during course of this project.

Specific Aims

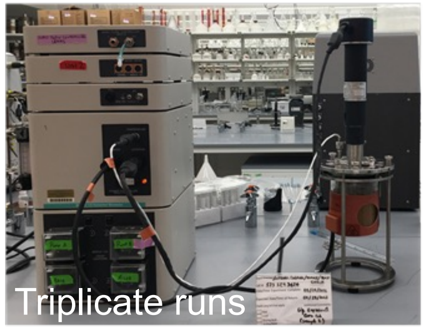
Corn stover

Leaf
Husk
Stem
Cob
Unfractionated
Screened 2mm

Fractioning → **Pellets Characterization** → **Liquefaction** → **Slurry Characterization**



Bioreactor 180 rpm & 50 °C



Cob (E sample) – Ctec-2 and Celluclast 1.5L – 3 FPU/g

Slurry** (pumpable) yield stress < 600 Pa

(1) Physical Properties (2) Compositions (3) Rheology

Aston, Cruz, Gutierrez, Chen, Ray, da Cuhna, 2021 to 2023

Task 4: Characterization of physical properties

2-mm particle size of different fractions prepared by Forest Concepts' rotary shear technology

100% completed

Leaf

Husk

Stem

Cob

Unfractionated
Screened 2 mm

Unfractionated
Control

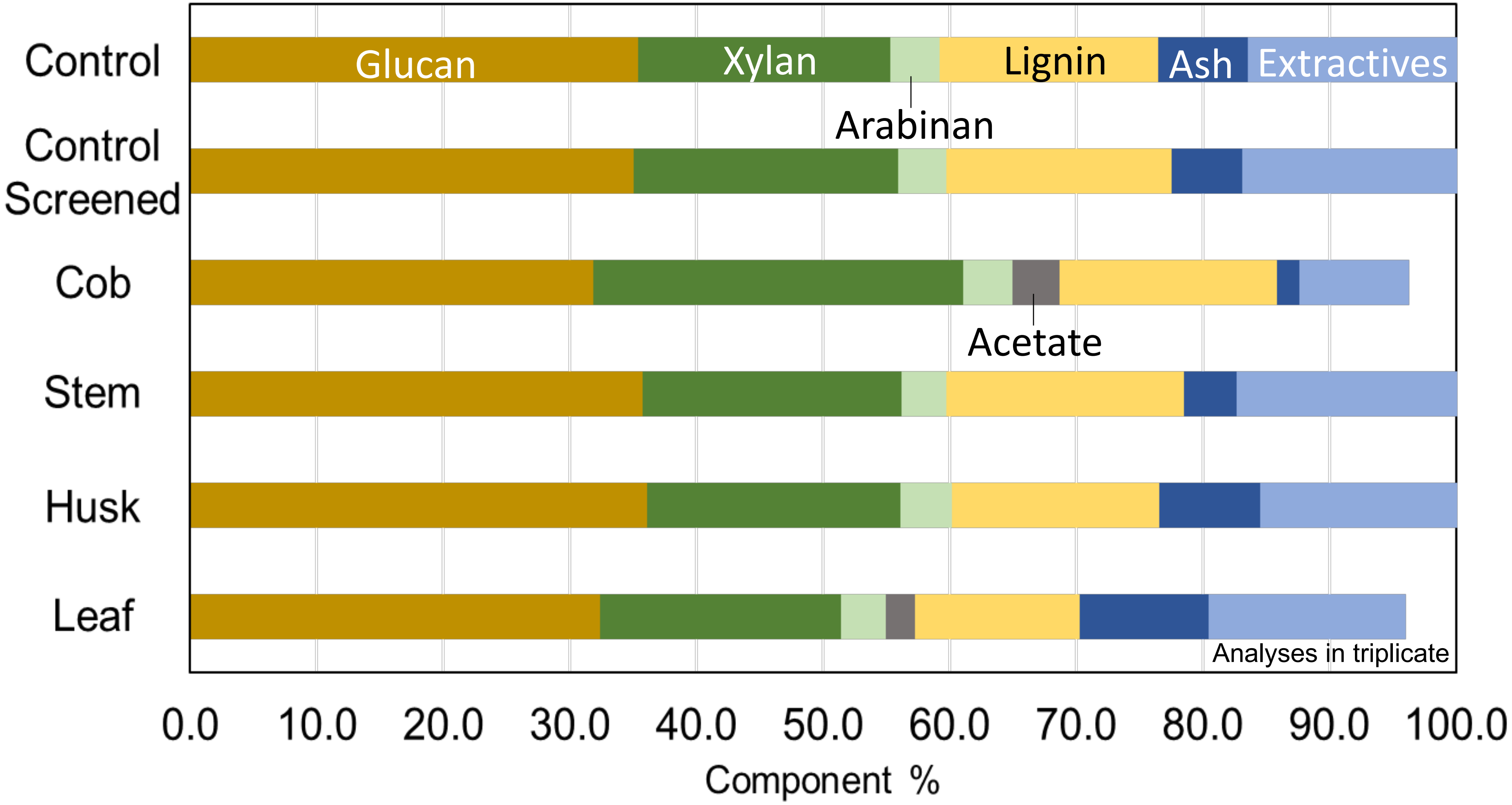
	Moisture	Particle Size		Bulk Density		Yield			Comminution Energy	
Material	MC (%wb)	Initial Xgm (mm)	Accepts Xgm (mm)	Loose (kg/m³)	Tapped (kg/m³)	% Accepts	% Fines	% Recirc	Specific E [kWh/odt] (MJ/odMg)	TEA Design E (kWh/odt)
A - Leaf	10.5	12.0	1.33	97	124	96.7	3.3	65	5.5 (22.0)	7.3
B - Husk	8.0	6.60	1.35	91	116	93.1	6.9	42	7.1 (28.3)	9.5
C - Stem / Husk	7.7	8.93	1.38	107	134	95.4	4.6	47	5.0 (19.7)	6.7
D - Stem	7.3	13.8	1.55	134	166	98.3	1.7	52	7.3 (29.2)	9.7
E - Cob	9.5	90.4	1.78	224	279	99.6	0.4	63	11.1 (44.1)	14.8
F - Unfractionated / Screened	7.5	8.08	1.58	107	139	98.2	1.8	51	4.2 (16.6)	5.6
G - Unfractionated Control	7.8	8.26	1.46	112	142	93.9	6.1	46	6.1 (24.1)	8.1

Analysis in triplicate

Aston, Dooley, Thompson, 2022

Task 4: Characterization of compositions of corn stover fractions

Task 4: 95% completed

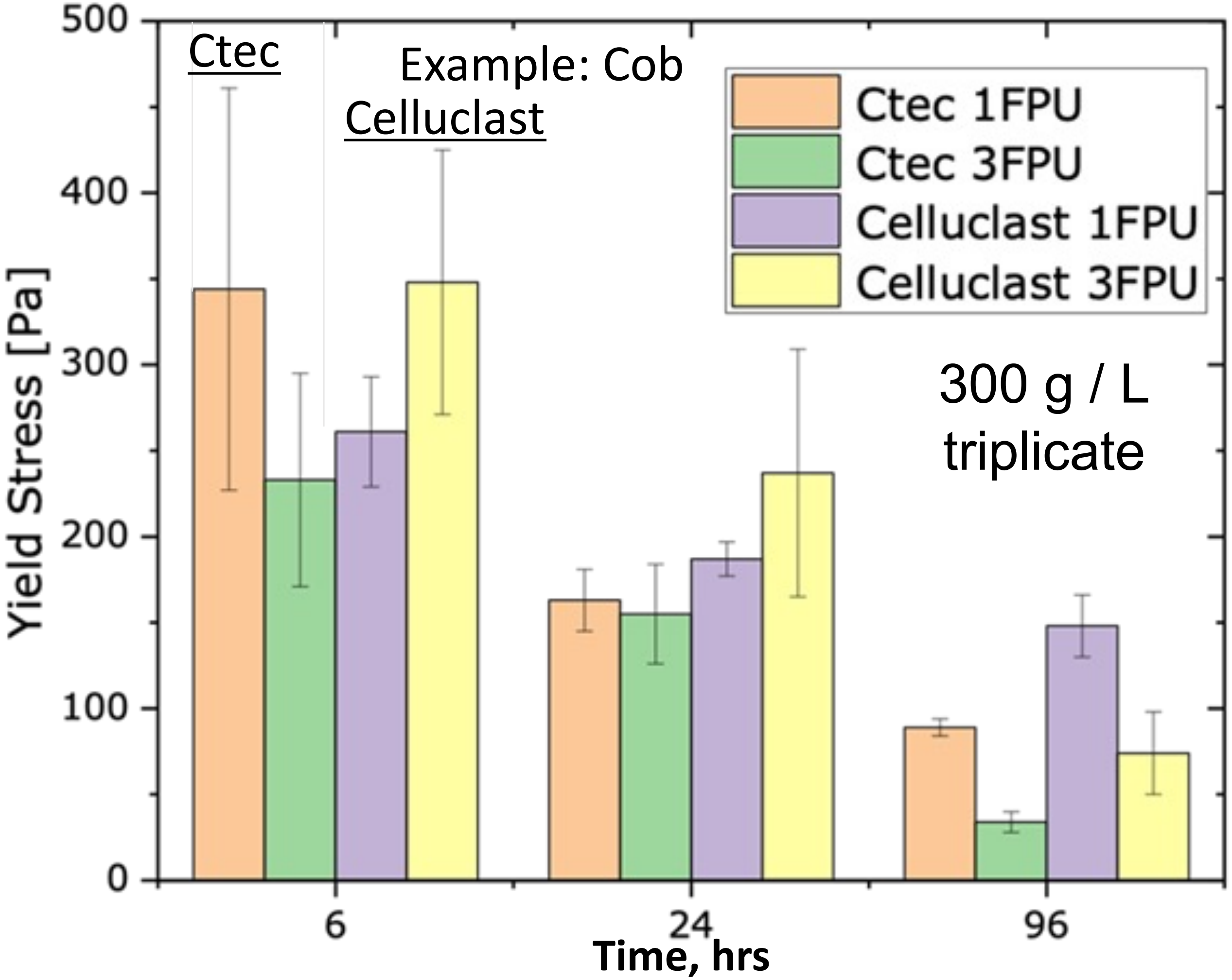


Impact: IBM model predicts rheology based on biophysical properties of particles

Gutierrez, Chen, Ximenes, Mosier, 2022

Task 4: Characterization of rheology for different fractions

Task 4: 95% completed



Water Absorption Test

R = ratio of absorbed water to solid mass

Sample	t = 10 min	8 hr
2.2 mm – not fractionated	1.1	4.2
Stem	1.1	4.8
Cob	1.1	4.8
Not Fractionated	1.1	6.2
Leaves	1.1	6.6

If R > 5; Liquefaction inhibited,
with Yield Stresses > 600
Goal: Yield Stress < 200 to 600

Measurements in triplicate Gutierrez, Szeto, Cruz, Erk, Ximenes, 2022

Impact: Water absorption is inversely related to slurry formation at 300 g/L; provides metric for biomass acceptance criteria at plant gate

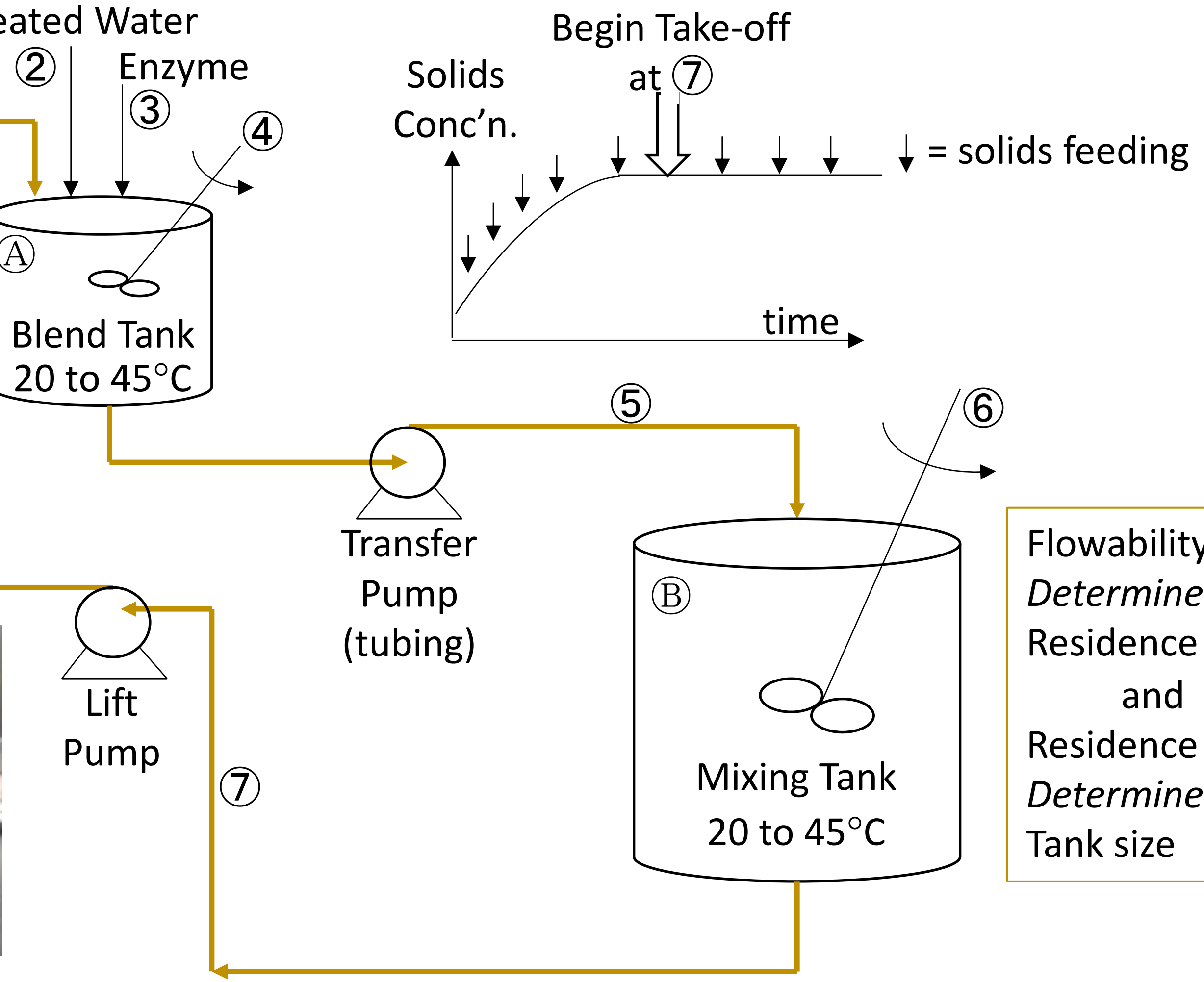
Task 4, 5: Techno-economic Assessment (TEA)

Process flow before pretreatment

60% completed

Tank	Description
A	design for max yield stress (small volume, small motor fed-batch, short time)
B	large volume, long time, constant yield stress

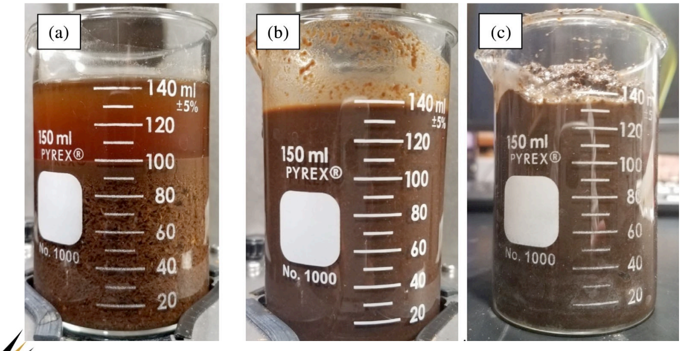
Pellets or aggregates ①
(no pretreatment)



⑦
take-off for characterization

Corn stover solids

(a) 10 % w/v
(b) 20 %
(c) 30 %



Flowability
Determines
Residence Time
and
Residence Time
Determines
Tank size

dos Santos, Overton, Kim, Ximenes, Cruz, Mosier, et al, 2021

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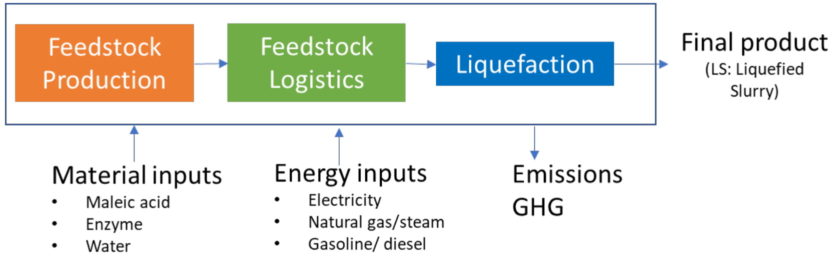
Task 6: Life Cycle Analysis (LCA) Underway, Q9 to Q12, M25 to M36

Task 6: 60% completed

Leveraging material from GREET- LCA modeling tool

TEA
Results



System boundary for Life-cycle analysis (LCA)

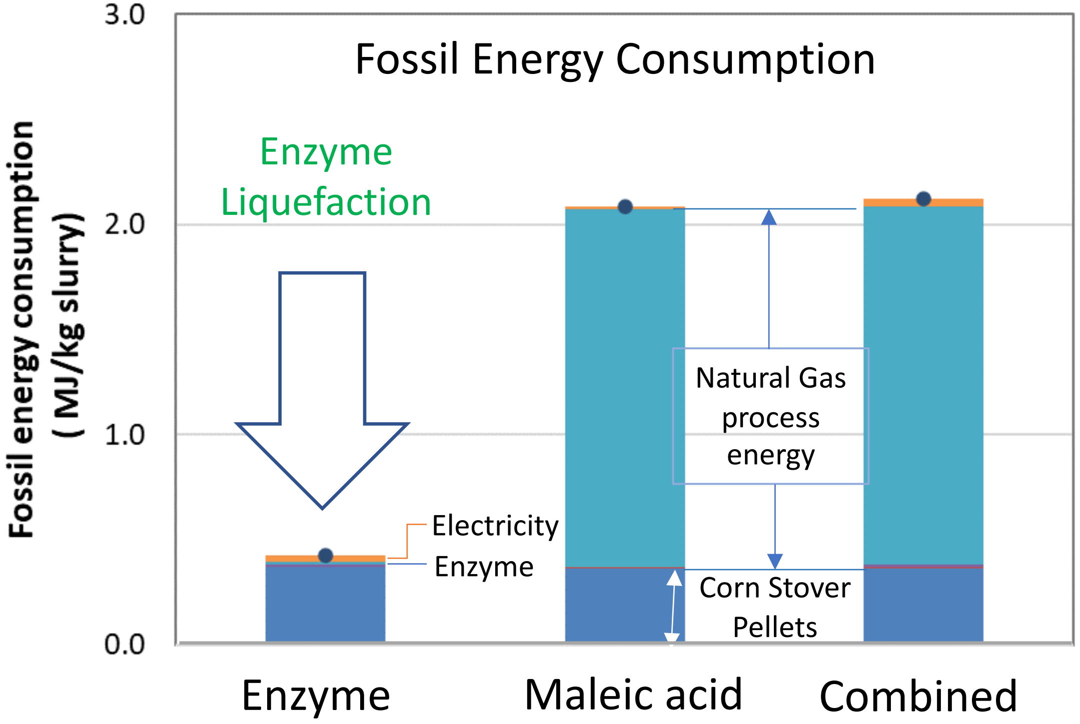
Use material and energy balance starting from corn stover, for a slurry solids loadings of 300 g/L to assess emission energy burdens, and cost prior to the slurry entering a pretreatment step. This TEA/LCA will be focused on the pre-processing steps.

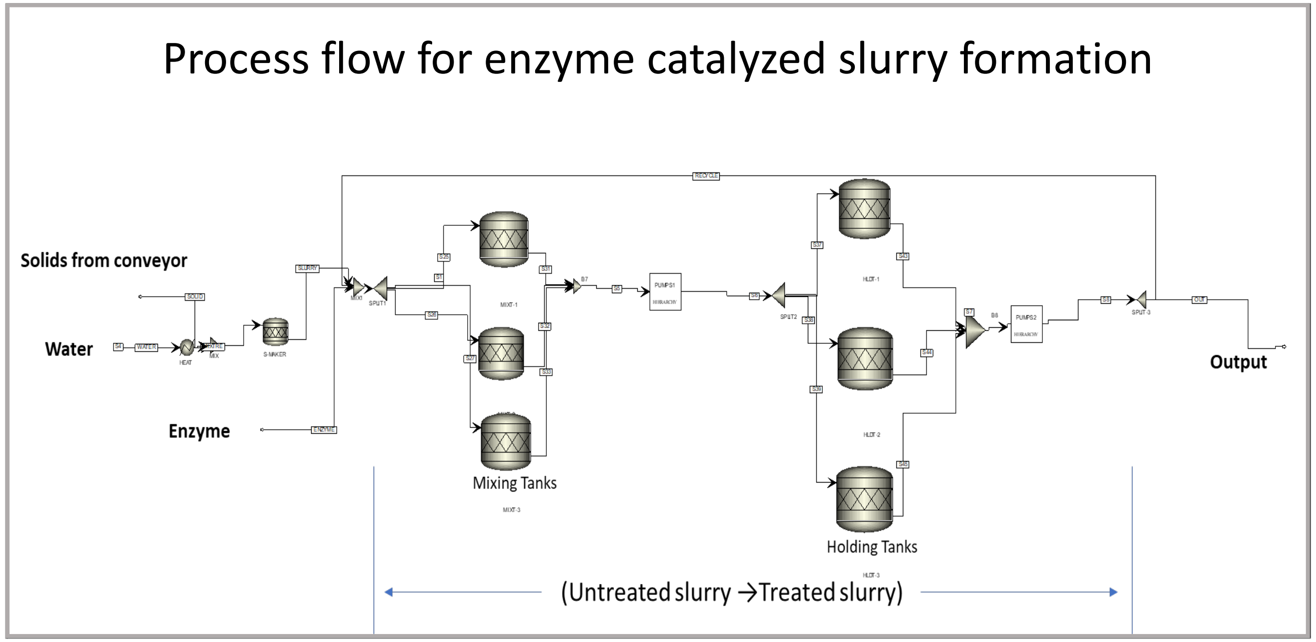
Gallego, Engelberth, Monceaux 2023

Task 6: Technical Assessment and Life Cycle Analysis

60% completed

Framework from DOE 0008256





ASPEN^{TM} process simulation and modeling software

Corn Stover Pellets → Liquefaction → Enzyme Hydrolysis → Fermentation → Bioproducts

$0.027 / lb slurry = target cost for ethanol at $2.22 /gal.

Patil, Engelberth, Maulik, Ximenes, Mosier, Gallego, Monceaux, 2022

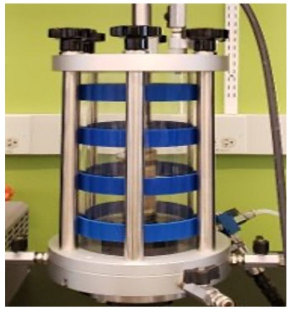
Task 7: Materials Properties Database

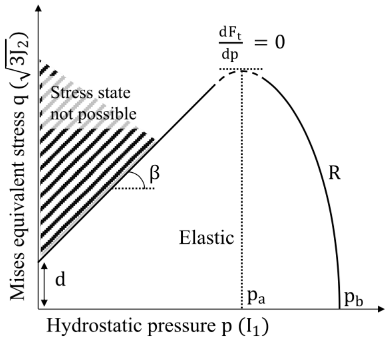
40% completed

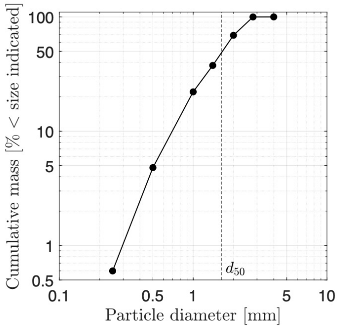
receive pelleted material

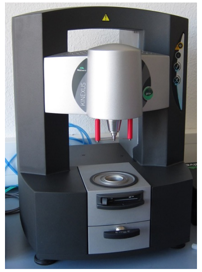
↓

de-aggregate pellets and treat to reach desired moisture content









store data in a database

Method	Correlation
Tri-axial Tester composition by NREL LAP's	Modified Drucker-Prager Cap (mDPC) Tabulated Datasets
Particle Level Measurements (by sieving) densities, size, shape	Particle size distributions Density Correlations Tabulated Data
Rheology Fed-batch bioreactors runs to prepare slurries	IBM model Rheology correlations (Ardekani, Erk, this work) Graphical Comparisons

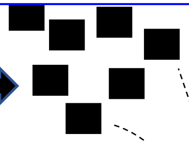
All measurements in triplicate

Wassgren, Paul, Gonzalez, Mosier, 2022, 2023

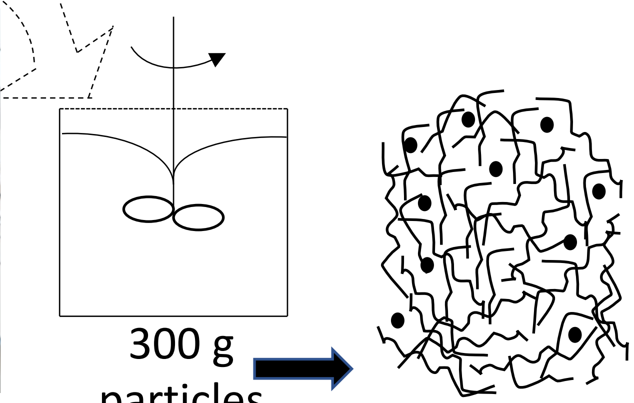
Summary and Overall Impacts: Mechanism, model, method for slurry formation of corn stover fractions

Overall about 85 to 90% completed

300 g cornstover (pellets) →

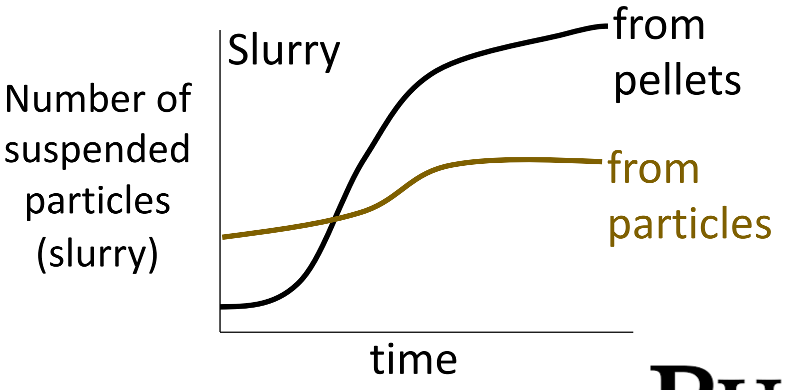


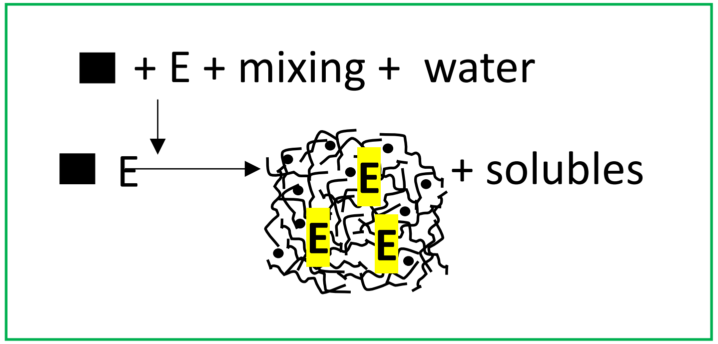
Professors Rosi and Antonio Cruz, 2022



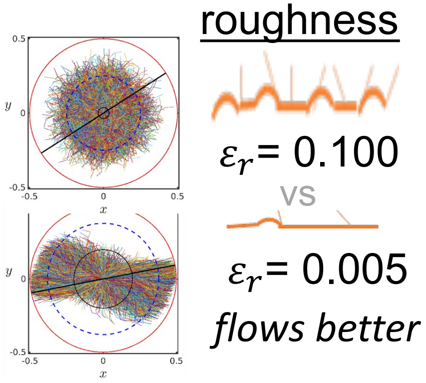
300 g particles →

Gutierrez, Assis Serra, 2022





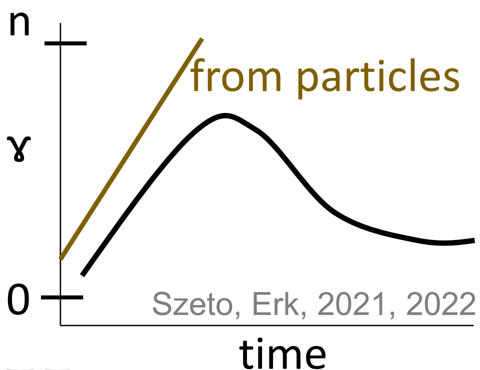
Ximenes, Ladisch, 2019



More, Ardekani, 2022

$$E + P \rightleftharpoons E + PE \rightarrow 10{,}000\ CE + \text{solubles}$$

One pellet ⇒ 10,000 particles ⇒ Slurry



Szeto, Erk, 2021, 2022

Goal is to decrease yield stress < 200 for slurries at 300 g corn stover / L

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Overall Project Conclusions and Impacts

Corn stover may be fractionated into readily liquefied materials.

Corn stover (unfractionated form) readily forms slurries at enzyme loadings of 1 to 3 FPU/g.

Acceptance criteria for corn stover may be based on laboratory measured water absorption

Pellets are needed and fed batch addition required to achieve high loadings

Some tissue fractions form slurries more readily than others (*work in progress*)
Water absorption is a key indicator

Life cycle analysis shows enzyme catalyzed liquefaction has acceptable energy requirement

Impacts:

Slurry formation with fractionated corn stover, achieved before pretreatment, has potential to avoid solids handling challenges experienced in pioneer biorefineries.

Model developed that explains how an aqueous slurry that may be pumped and processed at high solids loadings;

Model, validated with experimental measurements, addresses research gaps at feedstock conversion interface.

Quad Chart Overview

Timeline

- *Project start date: (BP 2); October 1, 2019*
- *Project end date: Sept. 30, 2023*

(approval letter Mar. 21, 2021)

	FY22 Costed	Total Award
DOE Funding	450,934	*1,378,384*
Project Cost Share	77,324	*346,366*

TRL at Project Start: TRL 3

TRL at Project End: TRL 4

Project Goal

Model formation of an aqueous slurry that may be pumped and processed at high solids loadings; address research gaps at feedstock conversion interface.

End of Project Milestone

Written report with mathematical model, bulk property database, and dimensionless parameters for high loading slurries of corn stover fractions

Funding Mechanism

DE-FOA-0002029 AOI 2a. 109-58 Energy Policy Act (2005) cooperative agreement CEDA 81.087.

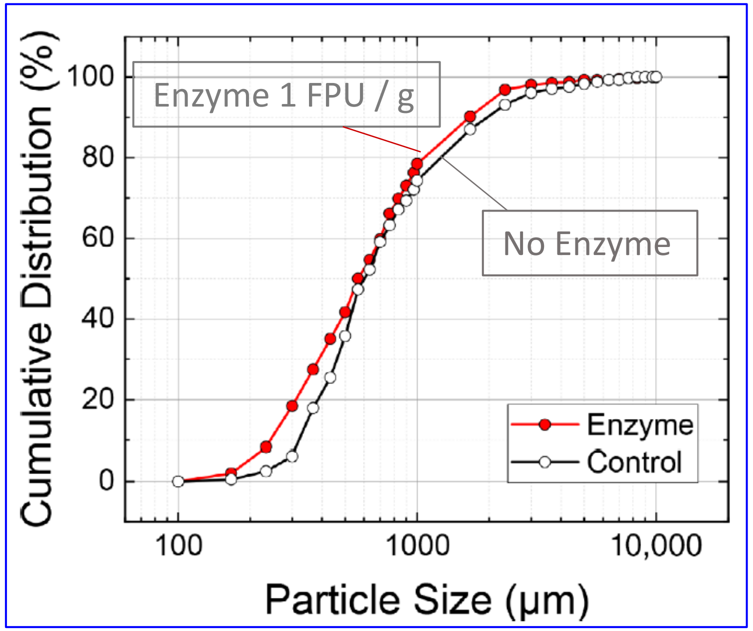
Project Partners

Partner 1	INL
Partner 2	ANL
Partner 3	Forest Concepts
Partner 4	AdvanceBio

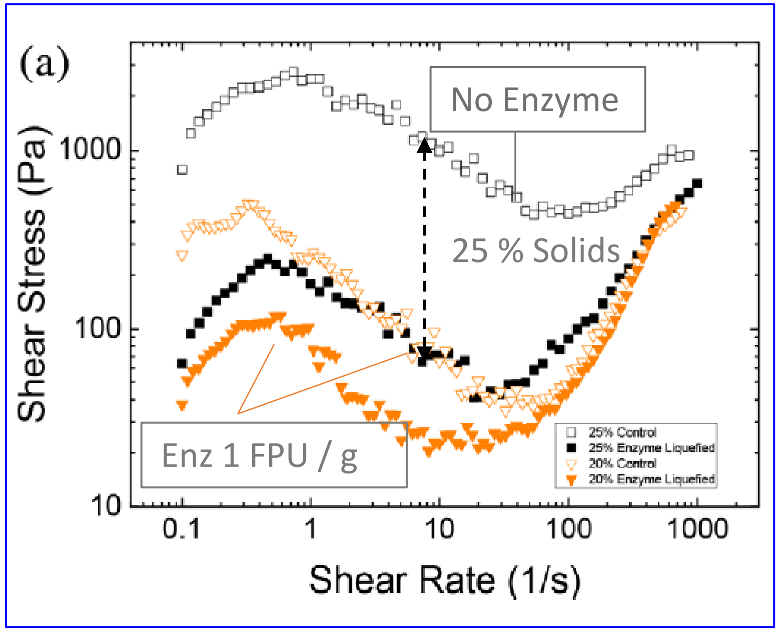
Additional Slides

Rheology shows enzyme reduces shear stress and viscosity > 10 x

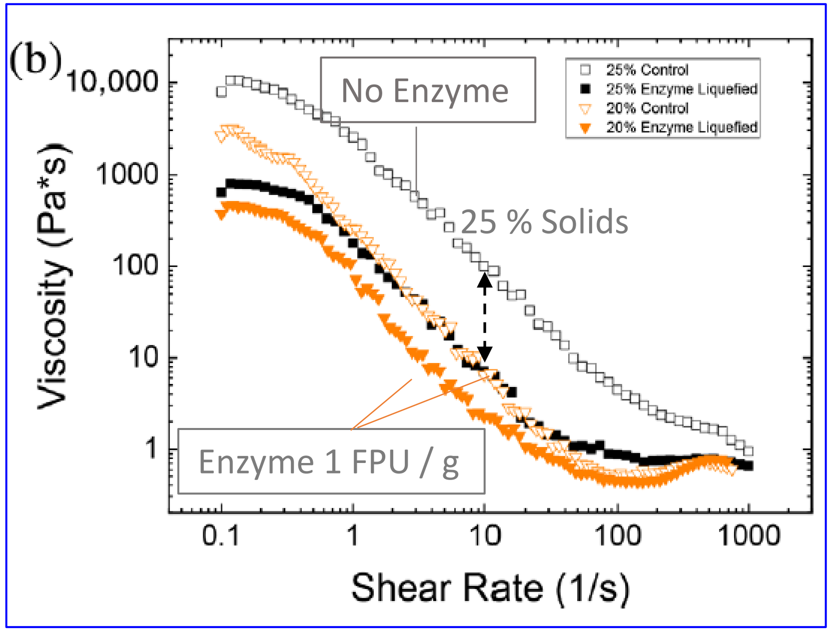
Particle Size Distribution Similar



+ enzyme = 20x lower shear stress



+ enzyme = 10x lower viscosity



Change in particle surface roughness may be a factor

Computational modeling by immersed boundary method (IBM) shows that viscosity increases as large fiber volume to total fiber volume increases.

More, Ardekani et al, 2020; Szeto, Erk et al, 2021

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LABORATORY OF RENEWABLE RESOURCES ENGINEERING

EE0008910

Supporting Publications

from EE0008256

1. Patil, A., A. S. Engelberth, M. R. Ladisch, “Effect of biomass liquefaction on glucose and xylose prices predicted by National Renewable Energy Laboratory biochemical sugar model,” Biofuels, Bioproducts and Biorefining, 17(1), 1-290 (2023).

2. Serra, L. A., R. G. da Silva Cruz, D. M. R. Gutierrez, A. J. G. Cruz, C. A. T. Canizares, X. Chen, N. Mosier, D. Thompson, J. Aston, J. Dooley, P. Sharma, J. L. De Marco, J. R. M. de Almeida, K. Erk, E. Ximenes, M. R. Ladisch, “Screening method for Enzyme-based liquefaction of corn stover pellets at high solids, Bioresour. Technol., 363, 1-10, doi: 10.1016/j.biortech.2022.127999 (2022).

3. Bordignon, S. E., E. Ximenes, O. M. Perrone, C. da Cost Carriera Nunes, D. Kim, M. Boscolo, E. Gomes, E. X. F. Filho, R. da Silva, and M. R. Ladisch, “Combined Sugarcane Pretreatment for the Generation of Ethanol and Value-Added Products,” Front. Energy Res., 10, 1-2, doi:10.3389/feng.2022.834966 (2022).

4. Ximenes, E., C.S. Farinas, A.C. Badino, M.R. Ladisch, “Moving from residual lignocellulosic biomass into high-value products: Outcomes from a long-term international cooperation,” Biofuels, Bioproducts, Biorefining, DOI: 10.1002/bbb.2179, 15(2), 563-573 (2021).

5. Buffo, M. M., A. L. Z. Ferreira, R. MRG Almeida, C. S. Farinas, A. C. Badino, E. A. Ximenes, M. R. Ladisch, Cellulolytic enzymes production guided by morphology engineering, EMT, 149, 1-29 (2021).

6. Ruiz, H. A., M. Galbe, G. Garrote, D. M. R-Gutierrez, E. Ximenes, S-N. Sun, D. Lachos-Perez, R. M. Rodríguez-Jasso, R-C. Sun, B. Yang, M. R. Ladisch, “Severity factor kinetic model as a strategic parameter of hydrothermal processing (steam explosion and liquid hot water) for biomass fractionation under biorefinery concept,” Bioresource Technology, 342, 1-14 (2021).

7. dos Santos, A. C. F., J. C. Overton, R. Szeto, M. H. Patel, D. M. R. Gutierrez, A. M. M. Moreno, K. A. Erk, J. E. Aston, D. N. Thompson, J. H. Dooley, P. Sharma, N. S. Mosier, E. Ximenes, M. R. Ladisch, “New strategy for liquefying corn stover pellets,” Bioresource Technology, 341, 1-7 doi.org/10.1016/j.biortech.2021.125773 (2021).

8. Szeto, R., J. C. Overton, A. C. F. dos Santos, C. Eby, N. S. Mosier, E. Ximenes, M. R. Ladisch, K. A. Erk, “Rheology of enzyme liquefied corn stover slurries: The effect of solids concentration on yielding and flow behavior,” Biotechnol. Prog., 37(6):e3216, doi:10.1002/btpr.3216 (2021).

9. Almeida, R. M.R.G., W. R. O. Pimentel, M. S. R. Santos-Rocha, M. M. Buffo, C. S. Farinas, E. A. Ximenes, M. R. Ladisch, “Protective effects of non-catalytic proteins on endoglucanase activity at air and lignin interfaces,” Biotech. Prog., doi.org/10.1002/btpr.3134 (2021).

10. Almeida, R. MRG and M. R. Ladisch, “Enzyme Interactions on Lignocellulosic Biomass Structure,” (Chapter 3) in Recent Advances in Bioconversion of Lignocellulose to Biofuels and Value-Added Chemicals within the Biorefinery Concept, Elsevier, 33-59 (2020).

11. dos Santos, A. C.F., E. Ximenes, D. Thompson, A. E. Ray, R. Szeto, K. Erk, B. S. Dien, M. R. Ladisch, “Effect of Using a Nitrogen Atmosphere on Enzyme Hydrolysis at High Corn Stover Loadings in an Agitated Reactor,” Biotechol. Progress. 2020;e3059. https://doi.org/10.1002/btpr.3059 (2020).

12. Freitas dos Santos, A-C., E. Ximenes, Y. Kim, and M. R. Ladisch, “Lignin-Enzyme Interactions in the Hydrolysis of Lignocellulosic Biomass,” Trends in Biotechnology (doi.org/10.1016/tibtech.2018.10.010, 37(5), 518-531 (2019).

13. Ázar, R. I. S., T. Morgan, M. H-P. Barbosa, V. M. Guimarães, E. Ximenes, M. Ladisch, “Impact of Protein Blocking on Enzymatic Saccharification of Bagasse from Sugarcane Clones,” Biotechnology and Bioengineering (published on-line, 2019; doi: 10.1002/bit.26962), 116, 1584-1593 (2019).

14. Vasconcellos, V. M., C. S. Farinas, E. Ximenes, P. Slininger, M. R. Ladisch, “Adaptive Laboratory Evolution of Nanocellulase Producing Bacterium,” Biotechnol. Bioeng., 116(8), 1923-1933 (2019).

Also, Presentations at Society of Industrial Microbiology, AIChE, Society of Rheology, ASME; Purdue organized meeting of industry, government, universities , 2022

PURDUE AGRICULTURAL & BIOLOGICAL ENGINEERING

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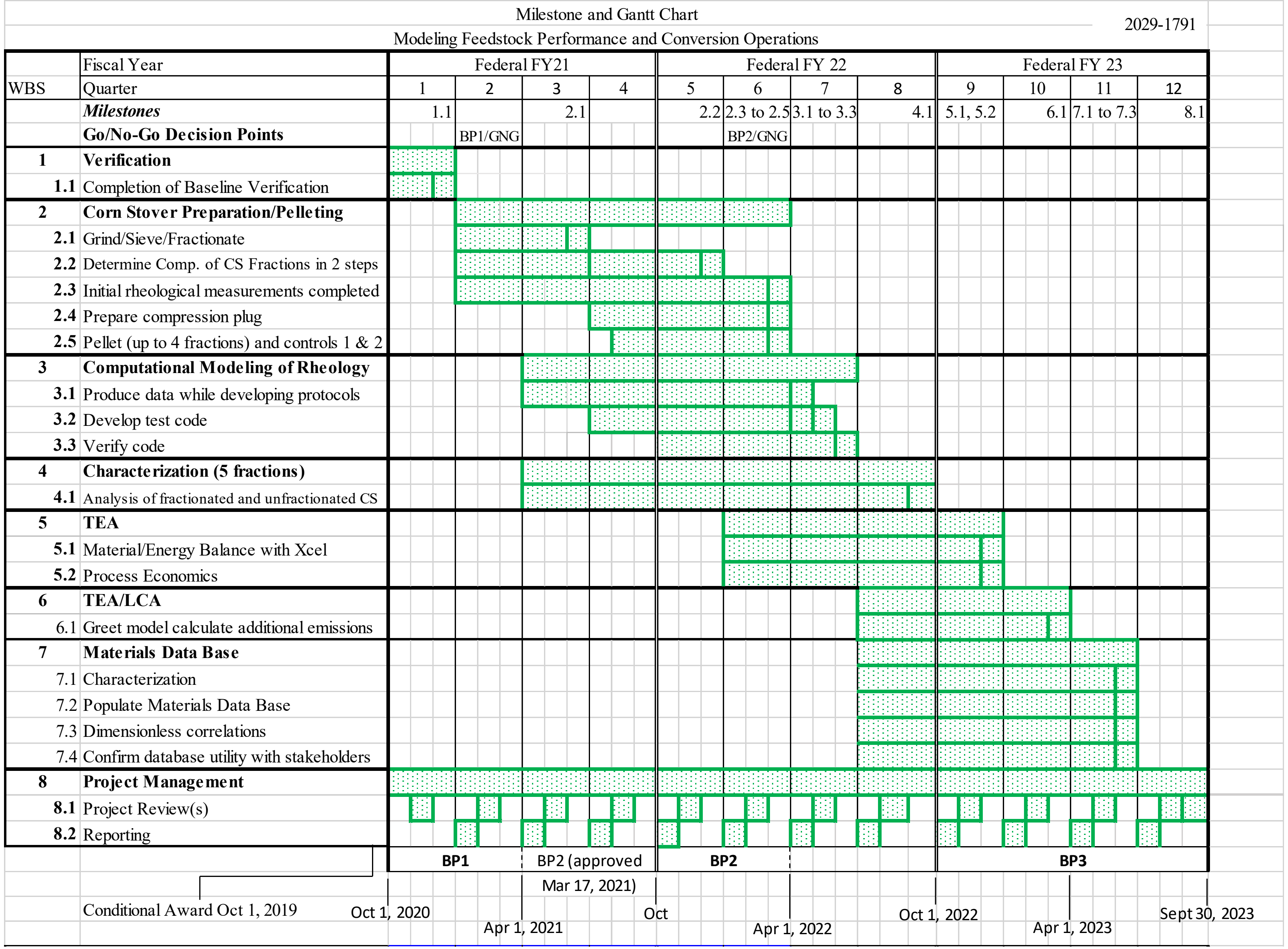
Publications, Patents, Presentations, Awards, and Commercialization

There are none yet for EE0008910 as of Feb 20, 2023

Revised Timeline: Nov, 2020; Jan, 2021; Mar 2022

File (sent on Mar 28, 2022): Milestone Chart_CC-7-18-19 rev 5 Nov 19 19 AW1 rev-Final cc 2-24-22



Milestone and Gantt Chart

Modeling Feedstock Performance and Conversion Operations

2029-1791

	Fiscal Year	Federal FY21				Federal FY 22				Federal FY 23			
WBS	Quarter	1	2	3	4	5	6	7	8	9	10	11	12
	Milestones	1.1		2.1		2.2	2.3 to 2.5	3.1 to 3.3	4.1	5.1, 5.2	6.1	7.1 to 7.3	8.1
	Go/No-Go Decision Points		BP1/GNG				BP2/GNG						
1	**Verification**	🟩											
1.1	Completion of Baseline Verification	🟩											
2	**Corn Stover Preparation/Pelleting**		🟩	🟩	🟩	🟩	🟩						
2.1	Grind/Sieve/Fractionate		🟩	🟩									
2.2	Determine Comp. of CS Fractions in 2 steps		🟩	🟩	🟩	🟩							
2.3	Initial rheological measurements completed		🟩	🟩	🟩	🟩	🟩						
2.4	Prepare compression plug				🟩	🟩	🟩						
2.5	Pellet (up to 4 fractions) and controls 1 & 2				🟩	🟩	🟩						
3	**Computational Modeling of Rheology**			🟩	🟩	🟩	🟩	🟩					
3.1	Produce data while developing protocols			🟩	🟩	🟩	🟩	🟩					
3.2	Develop test code				🟩	🟩	🟩	🟩					
3.3	Verify code					🟩	🟩	🟩					
4	**Characterization (5 fractions)**			🟩	🟩	🟩	🟩	🟩	🟩				
4.1	Analysis of fractionated and unfractionated CS			🟩	🟩	🟩	🟩	🟩	🟩				
5	**TEA**						🟩	🟩	🟩	🟩			
5.1	Material/Energy Balance with Xcel						🟩	🟩	🟩	🟩			
5.2	Process Economics						🟩	🟩	🟩	🟩			
6	**TEA/LCA**								🟩	🟩	🟩		
6.1	Greet model calculate additional emissions								🟩	🟩	🟩		
7	**Materials Data Base**								🟩	🟩	🟩	🟩	
7.1	Characterization								🟩	🟩	🟩	🟩	
7.2	Populate Materials Data Base								🟩	🟩	🟩	🟩	
7.3	Dimensionless correlations								🟩	🟩	🟩	🟩	
7.4	Confirm database utility with stakeholders								🟩	🟩	🟩	🟩	
8	**Project Management**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
8.1	Project Review(s)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
8.2	Reporting		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

BP1 | BP2 (approved Mar 17, 2021) | **BP2** | **BP3**

Conditional Award Oct 1, 2019

Oct 1, 2020

Apr 1, 2021

Oct

Apr 1, 2022

Oct 1, 2022

Apr 1, 2023

Sept 30, 2023