DOE Bioenergy Technologies Office (BETO) 2023
Project Peer Review
DE-EE-0008250, WBS 3.5.1.501

# Multi-stream Integrated Biorefinery Enabled by Waste Processing

04/04/2023
Systems Development and Integration

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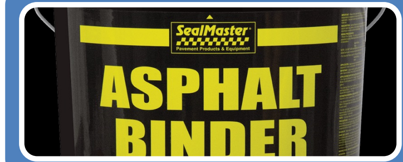
# Project Overview

- History: DE-FOA-0001689; Topic Area 2: High value products from waste/or other undervalued streams in an integrated biorefinery. The project has made significant progresses and is ready for BP2 verification.
- Goal: enable multi-stream integrated biorefinery (MIBR) by complex technical targets


100GPa elastic modulus and 2GPa tensile strength, ready for commercialization.



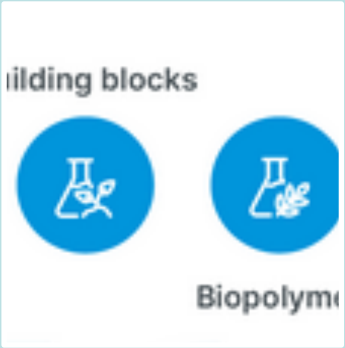

Increasing rutting temp by 10$^{o}$C (about 1 PG).


60% solubilized biorefinery waste, 25 g/L lipid titer,  and 30% conversion rate


**Integrating 2 out of the 3 aforementioned products to achieve MESP reduction by $0.5.**

# BETO Missions and Broader Energy/Environmental Challenges Addressed:

Improve biorefinery economics and sustainability



Produce high value bioproducts and manage biorefinery waste

Reduce carbon emission by complete biomass usage

Light-weighted material to reduce fuel and energy consumption in transportation sector


Asphalt binder modifier to improve infrastructure resilience to global climate changes

Biorefinery waste for lipid production will alleviate the feedstock limitations for biodiesel industry

:

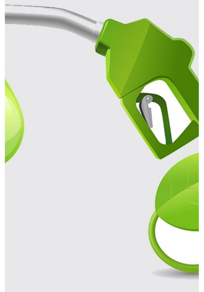
# Heilmeier Catechism Summary

## State of the art

- Lignin Partially burnt
- Limited value recovery, low overall carbon efficiency
- Lignin-carbon low quality

## Why?

- Bring down the biofuel price with diverse products
- Produce low-cost and high quality carbon fiber



($259 billion economic potential and 1.1 million jobs

($4.7 billion market with 11% annual growth

Structure-function relationship understanding

Biorefinery integration and scale up.

# Management

**MIBR Advancement**


Defined S.M.A.R.T. Go/No-Go milestones were set and implemented to ensure project progresses.

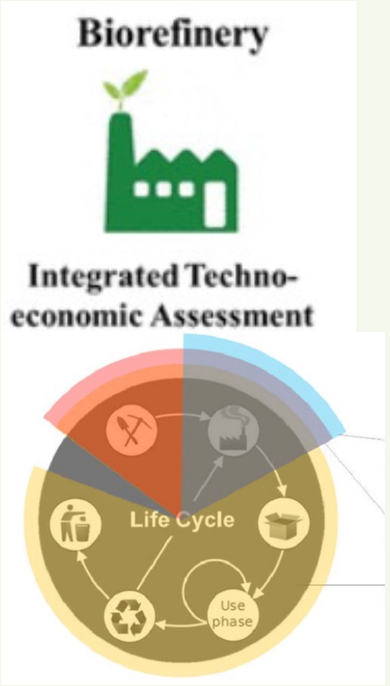
**MIBR Optimization**

Monthly Teleconferences

**Program manager meetings**

The technical milestones were designed in a way to ensure that the economic targets can be achieved. Full ASPEN model was built.

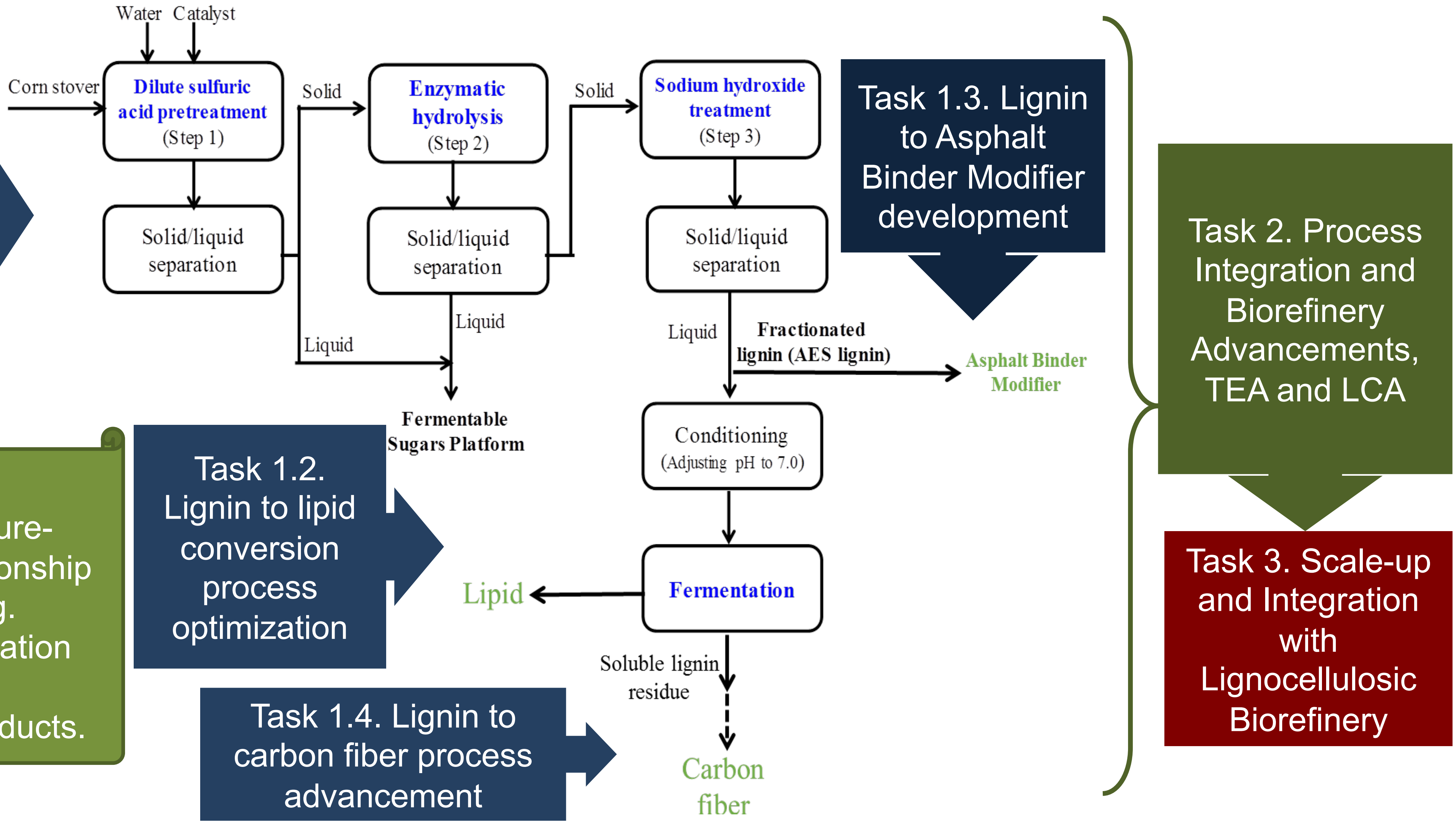
**MIBR Scaleup**




Down-selection to two product streams based on TEA and performance.

# Approach – Process View

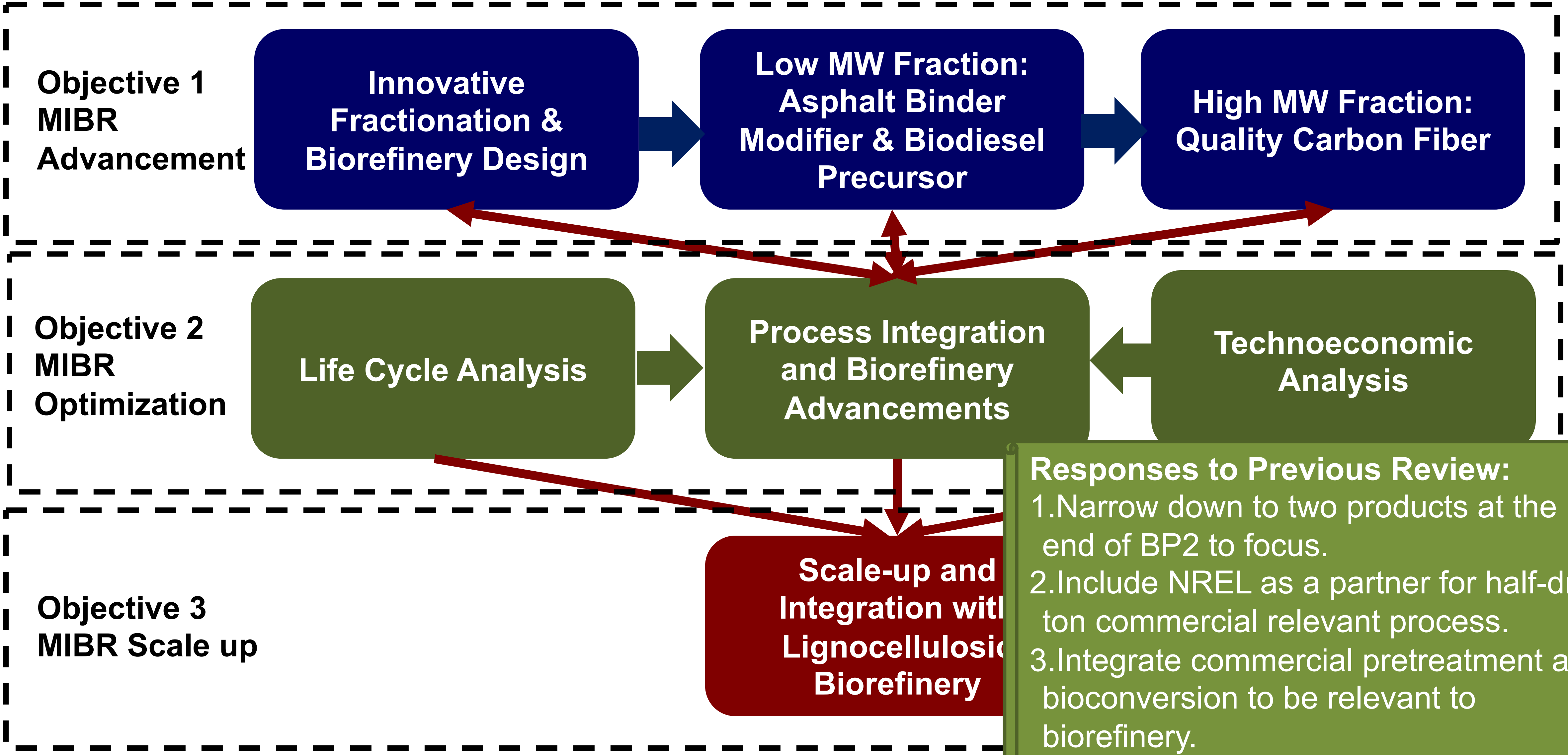
Task 1.1. Advance Pretreatment and fractionation technologies to enable three streams




**Challenges:**

1. Lack of structure-function relationship understanding.
2. System integration and scale up.
3. Too many products.

# Approach – Integration of Tasks




**Responses to Previous Review:**

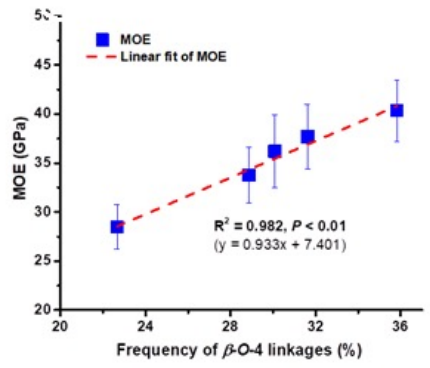
1. Narrow down to two products at the end of BP2 to focus.
2. Include NREL as a partner for half-dry ton commercial relevant process.
3. Integrate commercial pretreatment and bioconversion to be relevant to biorefinery.
4. Complete TEA to define GGE & MESP

# Technical Approaches

**DESIGN**

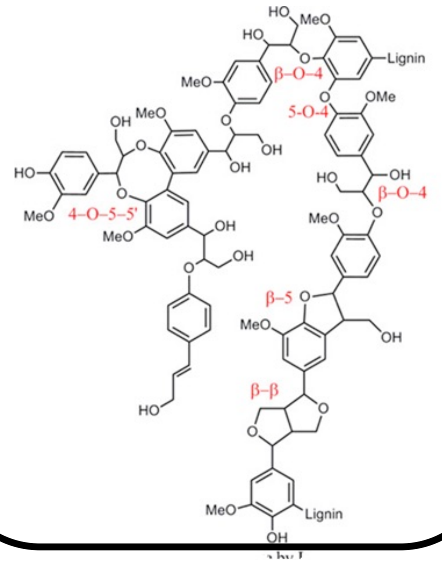
**Process Design**
**Microbial & Chemical Engineering**

**Feedstock Design**




**SCIENCE**

**Lignin Chemistry Structure-Property Relationship**




**PRODUCT**

**Carbon Fiber**

**Conversion to Lipid**

**Conversion to PHA**

**Nanoparticle**

**Pavement Material**

**Polymer Material**

Represented studies:

J.Li et al Matter 5 (10), 3513-3529

Z. Liu et al Nature communication 12 (1), 3912

Q. Li et al. *Green Chem.*, 19, 1628–1634

Z. Liu et al. *Green Chem.*, 21, 245-260

Q. Li et al., *iScience*, 23, 101405.

Q. Li et al., *J. Mat. Chem. A., 5, 12740-12746.*

S. Xie et al., *Adv. Sci.*, 6, 1801980.

# Progresses and Outcomes Summary

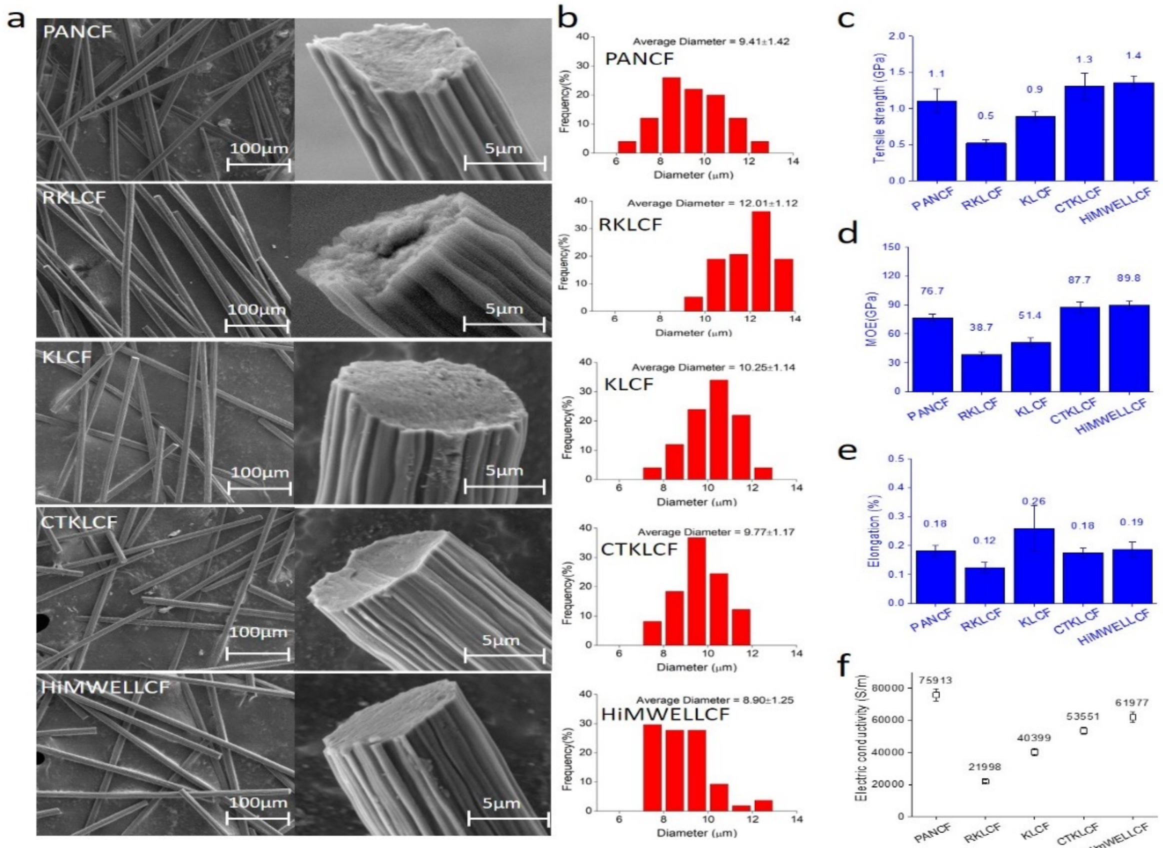
| Time Point | | Benchmark | | End of BP2 | | Current | End of the Project | |
|---|---|---|---|---|---|---|---|---|
| **Product** | **Metrics** | Milestones | Actual | Milestones | Actual | Actual | Milestones | Actual |
| **Carbon Fiber** | **MOE** | 20GPa | 21 Gpa | 50GPa | 75GPa | 90GPa | 100GPa | |
| | **Tensile** | 100MPa | ~200MPa | 1GPa | 1.1GPa | 1.4GPa | 2GPa | |
| **Asphalt Binder Modifier** | **Rutting Temp Incr.** | 7°C | 1PG 7°C | 10°C | 2PG 15°C | 2PG 15°C | 10°C | 2PG 15°C |
| | **Low temp** | Same | Same | Same | Same | Same | Same | Same |
| **Lipid for Biodiesel** | **Titer** | 10g/L | 10g/L | 15g/L | 12g/L | N.A. | N.A. | |
| | **Conversion** | 30% | 30% | 30% | 30% | N.A. | N.A. | |
| **Economic Outcome** | **MESP[1]** | N.A. | | N.A. | | $1.88* | N.A. | |
| | **~$/GGE[2]** | N.A. | | N.A. | ~$3 | $2.56* | ~$3/GGE | |

*** $1.88 MESP and $2.56/ GGE when carbon fiber is sold at $20 per Kg.**

# Progress and Outcomes: Technical

## Structure-Property Relationship

## Performance Improvement to Milestones




## HiMWELL Lignin

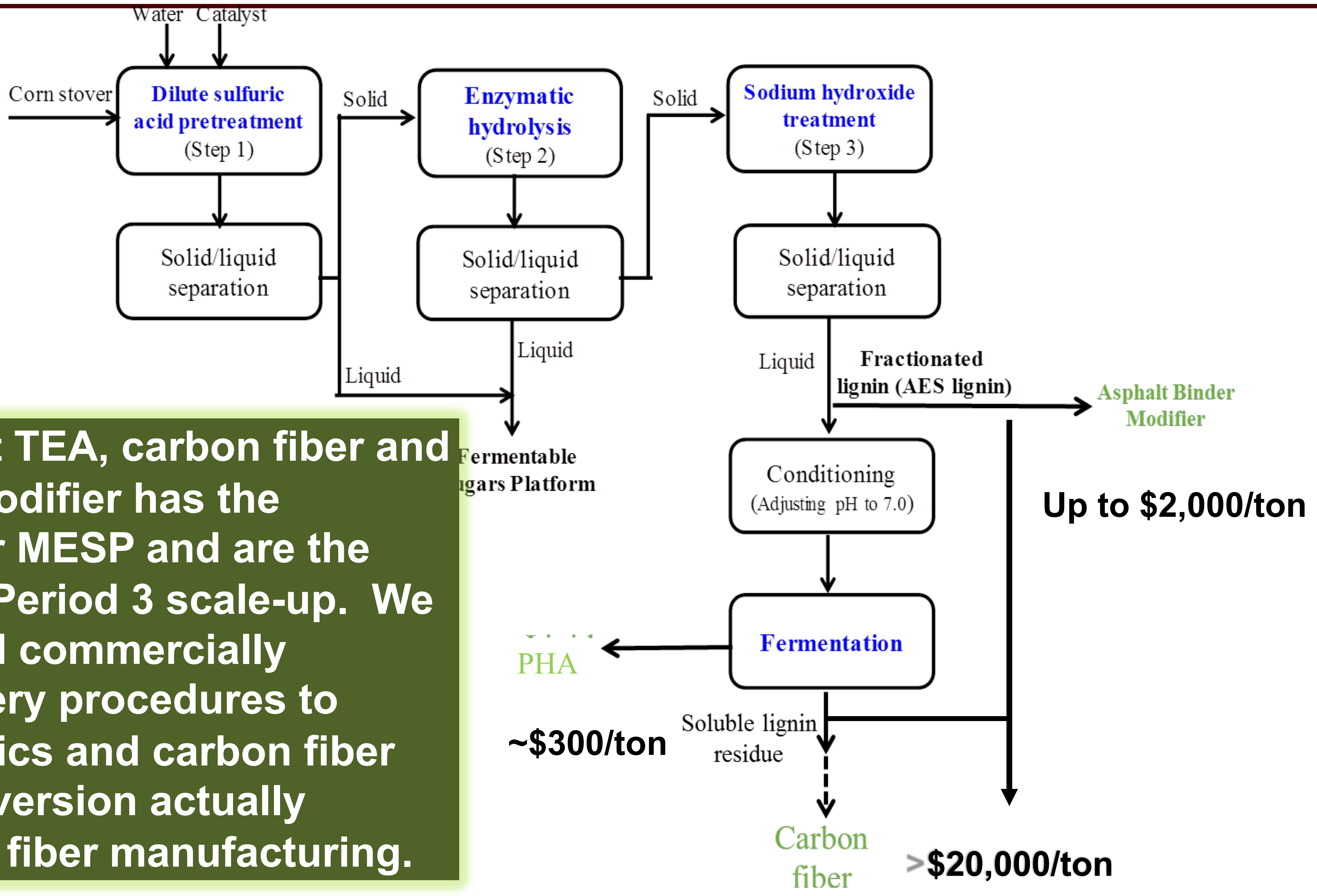
- More uniform
- High molecular weight
- Modified –OH group with cross-linkage

## High Quality CF

- Tensile Strength: 1.4 GPa
- Elastic Modulus: ~90 GPa

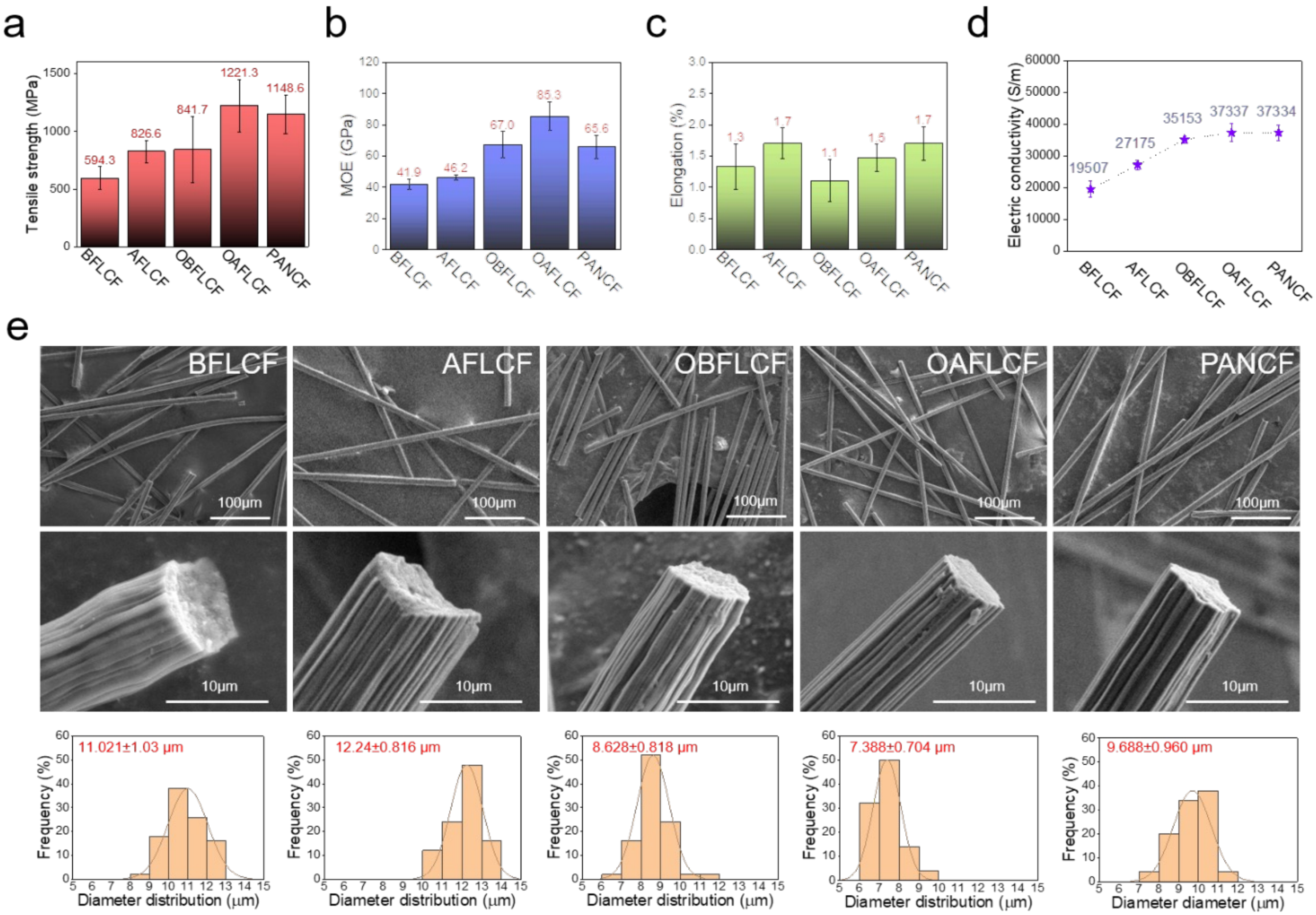
Li et al., Matter 5 (10), 3513-3529

# Selection of Value-adding  Products to Maximize Impact

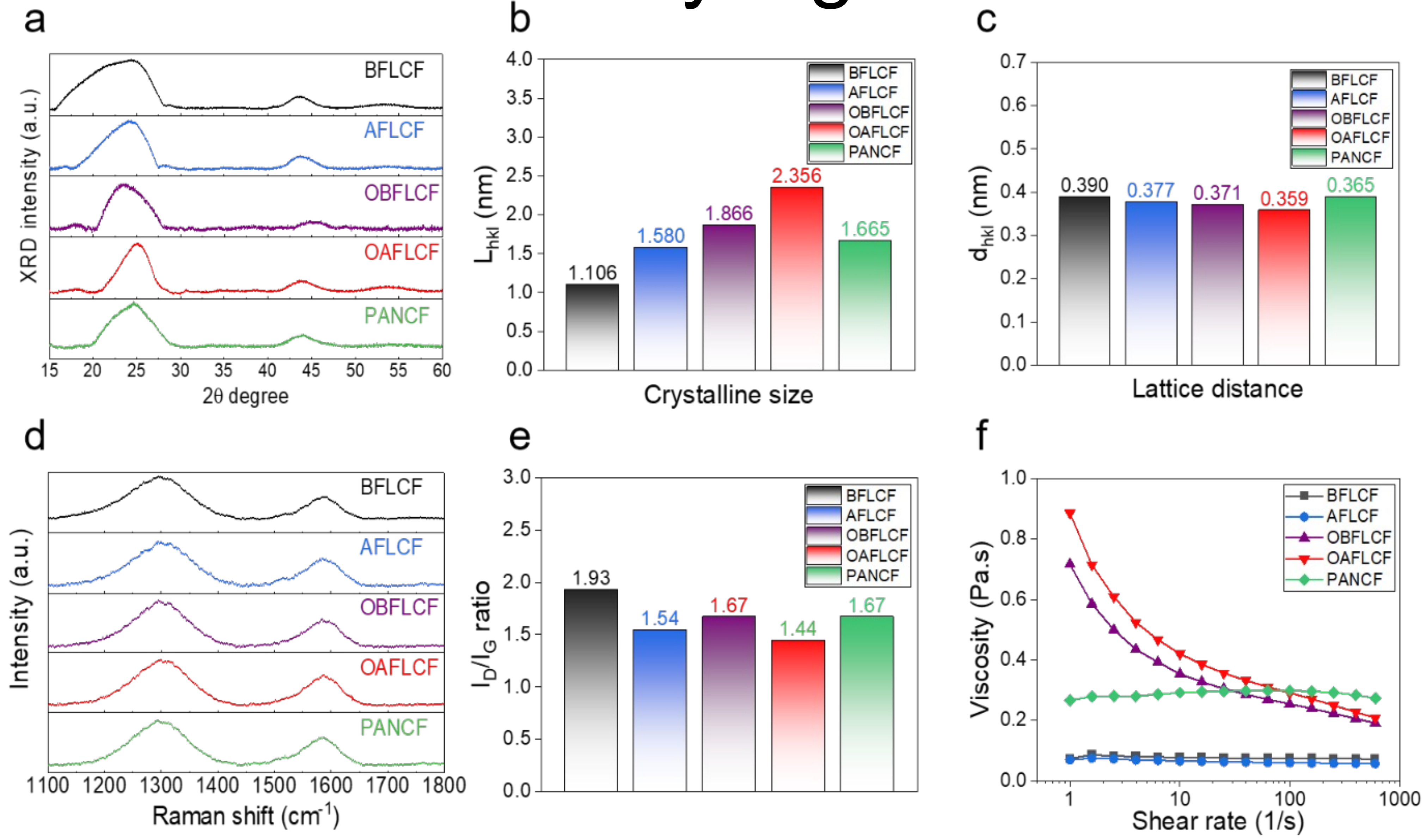


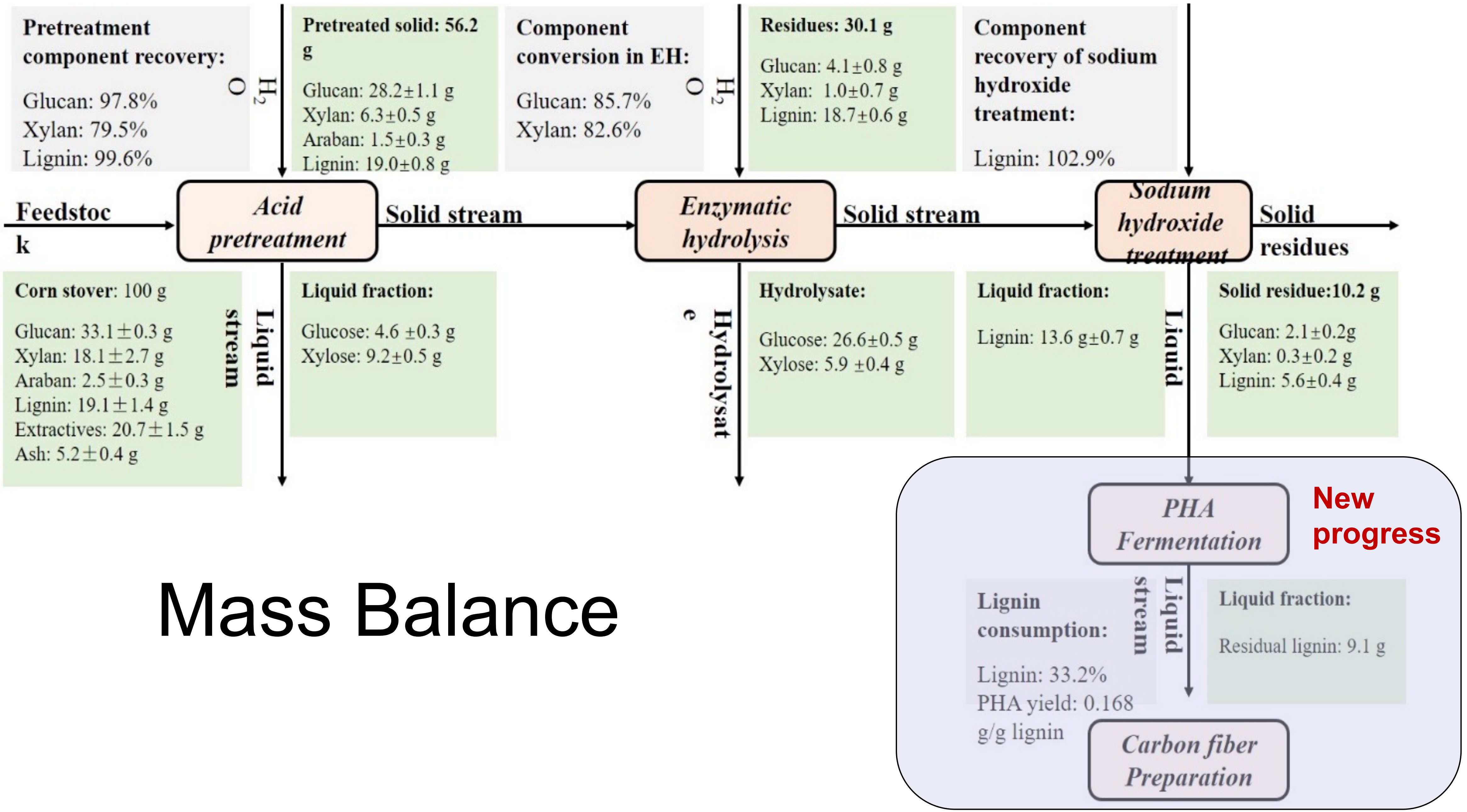

**Based on current TEA, carbon fiber and asphalt binder modifier has the potential to lower MESP and are the focus of Budget Period 3 scale-up.  We further integrated commercially relevant biorefinery procedures to produce bioplastics and carbon fiber together. Bioconversion actually improves carbon fiber manufacturing.**

# After Fermentation Lignin for High Quality Carbon Fiber



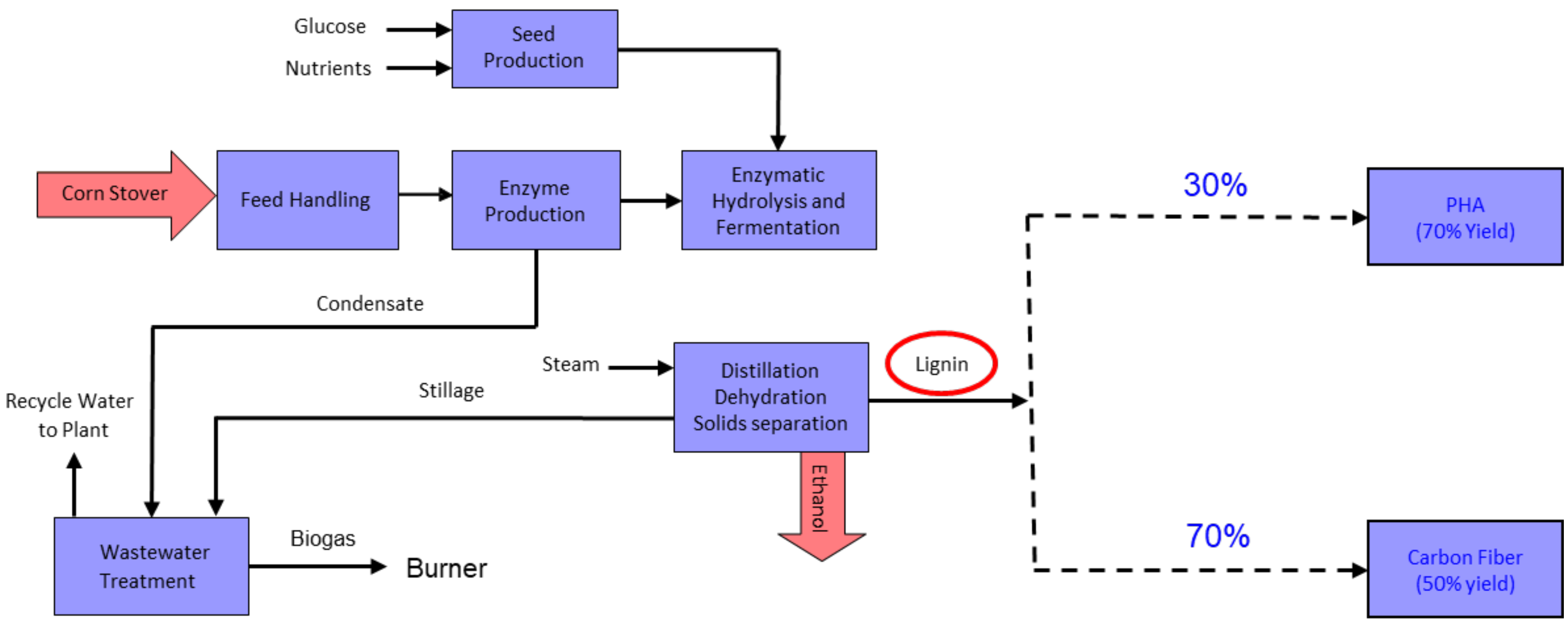
# Mechanism for Quality Lignin Carbon Fiber



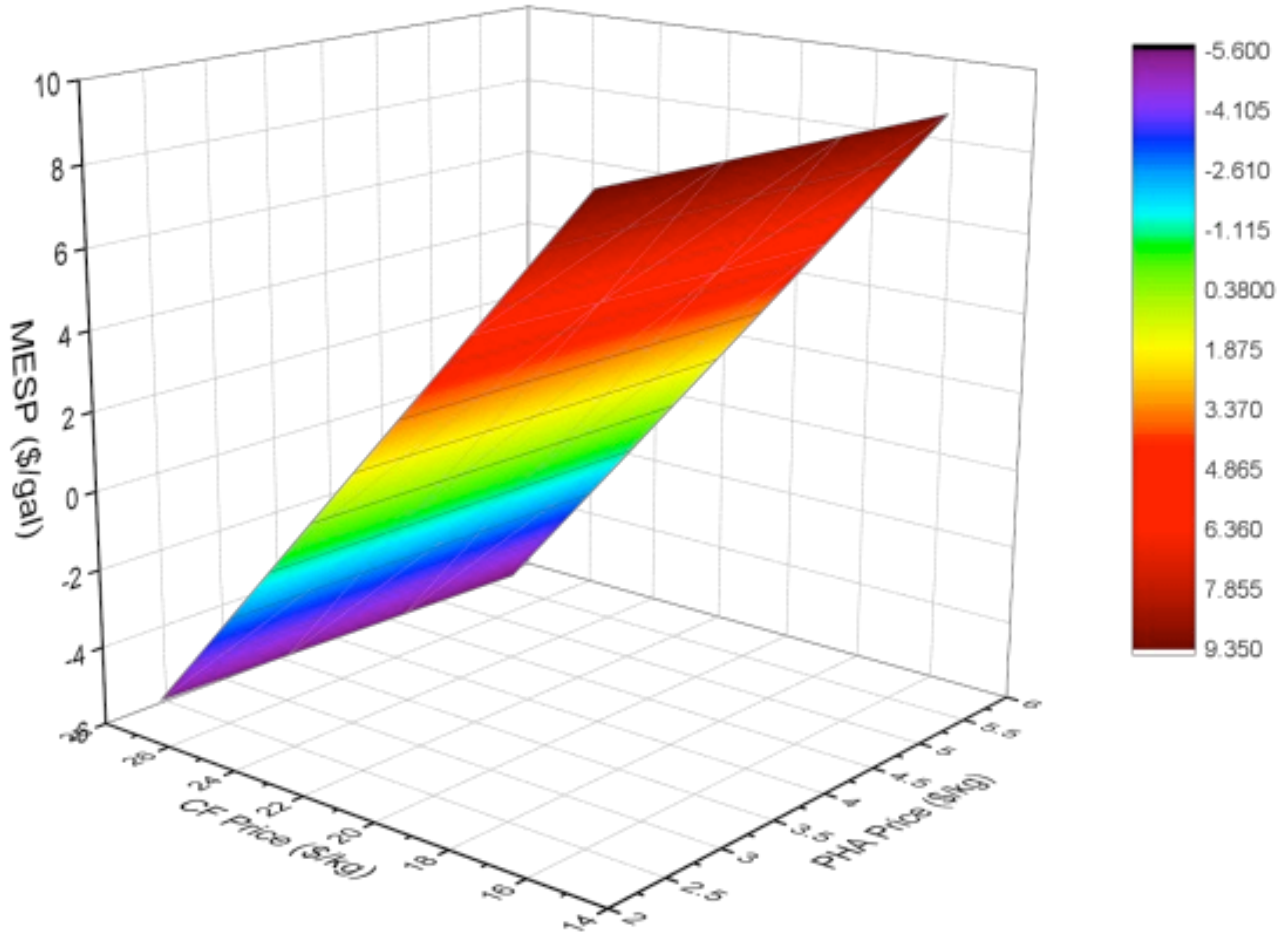



# Mass Balance

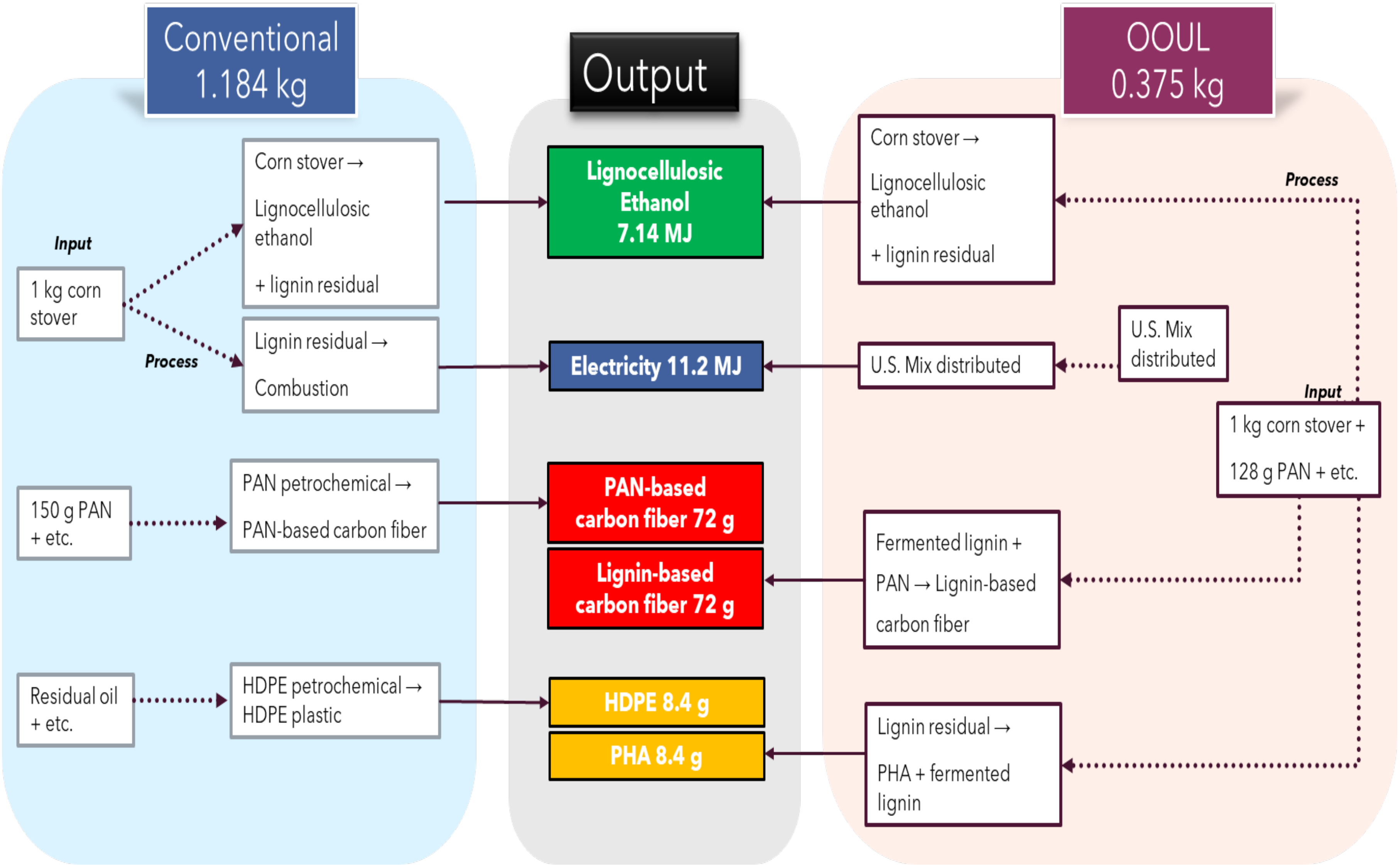
# Scenario for lignin upgrading in the Ethanol Biorefinery: Coproduction of PHA and Carbon Fiber



# Effect of PHA selling price and Carbon Fiber selling price on MESP



# Summary of estimated CO2 emission



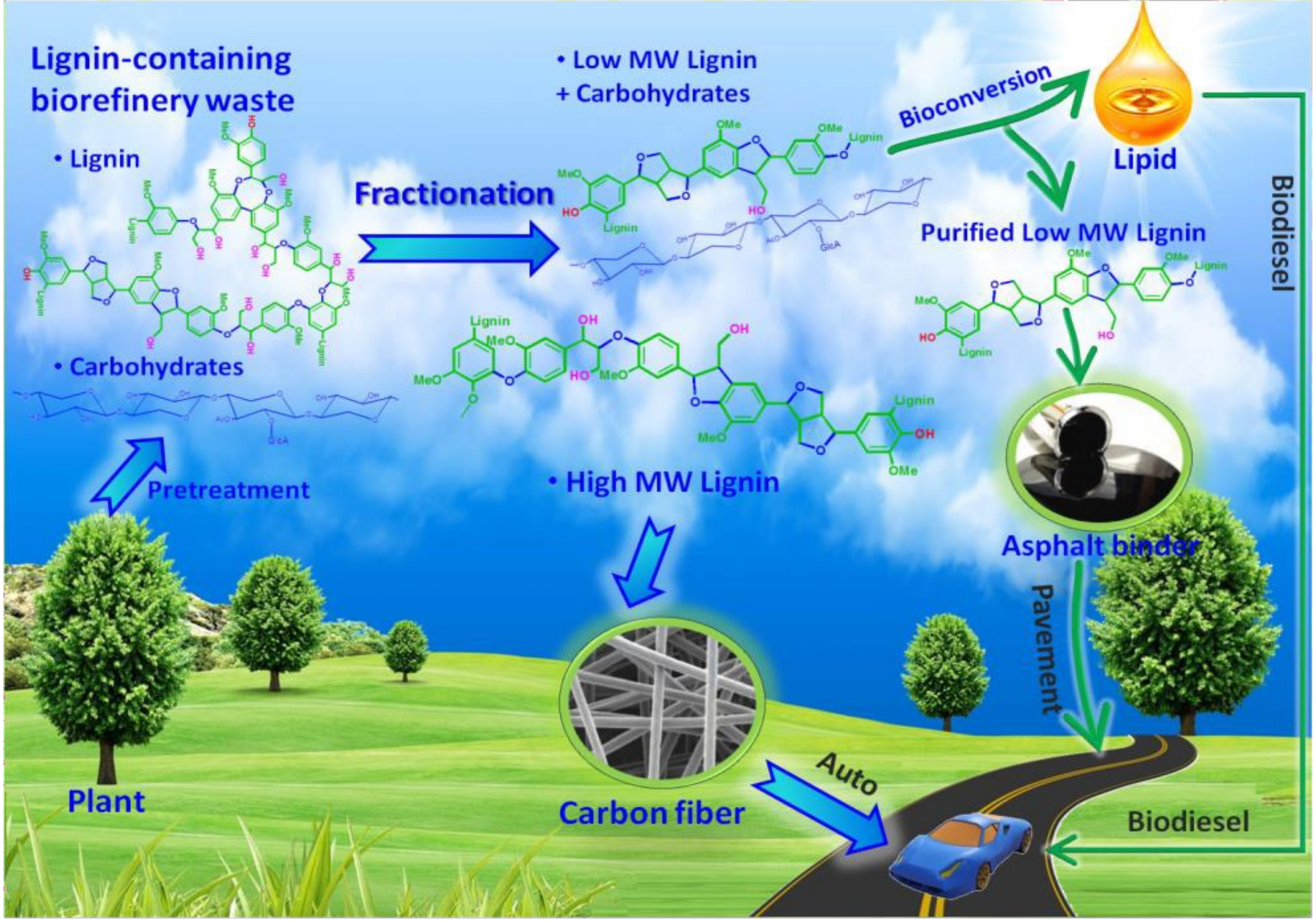

| Scenario | CO2 emission |
|---|---|
| Conventional | 1.184 kg |
| MIBR | 0.375 kg |

# Broad Scientific Impact and Transformative Industrial Impact

- Transformative Industrial Impact
  1. Develop two out of three product streams to bring down the MESP to below $3/GGE range.
  2. Constantly engage biorefinery companies like ICM, ADM, and POET.
  3. Constantly engage carbon fiber industry, national biodiesel association, and investors.
  4. TEA has shown significant potential of the platform to transform biorefinery economics.
- Broad Energy and Environmental Impacts– Well Addressing BETO Missions
  1. Improve biorefinery sustainability and cost-effectiveness with value-added products from waste.
  2. Provide low-cost carbon fiber to improve energy efficiency for US energy sector, with applications on wind turbine, automobile and others.
  3. Alleviate the feedstock shortage at biodiesel industry.
  4. Enhance asphalt high temperature performance to improve infrastructure resilience to climate changes.
- Broad Scientific Impacts
  1. 31 publications.
  2. Two PCT patent applications and one provisional patent application.
  3. Numerous scientific presentations and special events to engage companies.

**BETO Missions:**

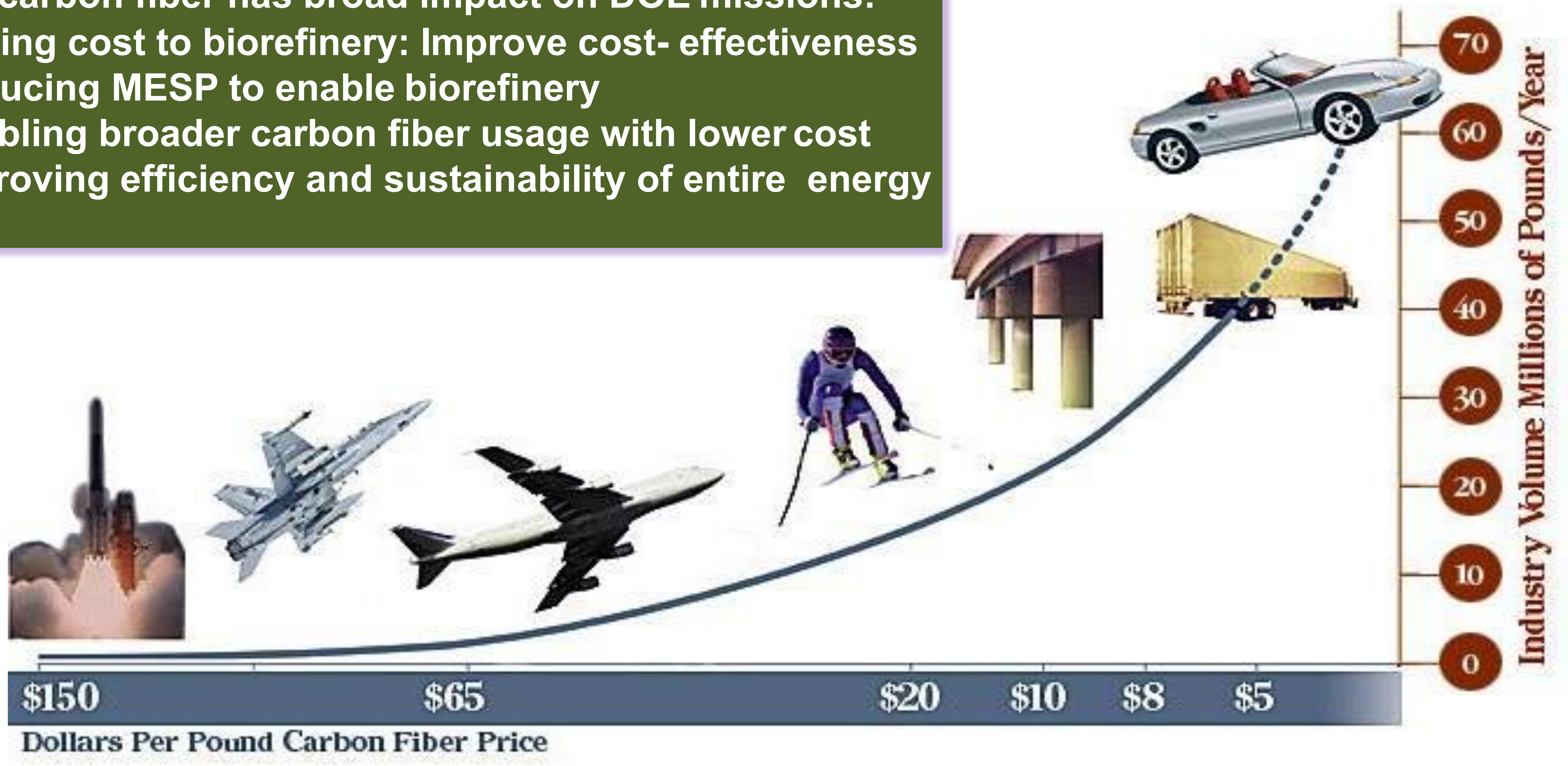
- Improve biorefinery economics and sustainability
- Produce high value bioproducts and manage biorefinery waste
- Reduce carbon emission by complete biomass usage



# Impact: Lignin as a Promising Substitute for Carbon Fiber Precursor

**Lignin carbon fiber has broad impact on DOE missions:**

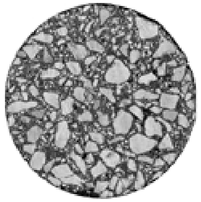
1) Adding cost to biorefinery: Improve cost- effectiveness
2) Reducing MESP to enable biorefinery
3) Enabling broader carbon fiber usage with lower cost
4) Improving efficiency and sustainability of entire energy sector

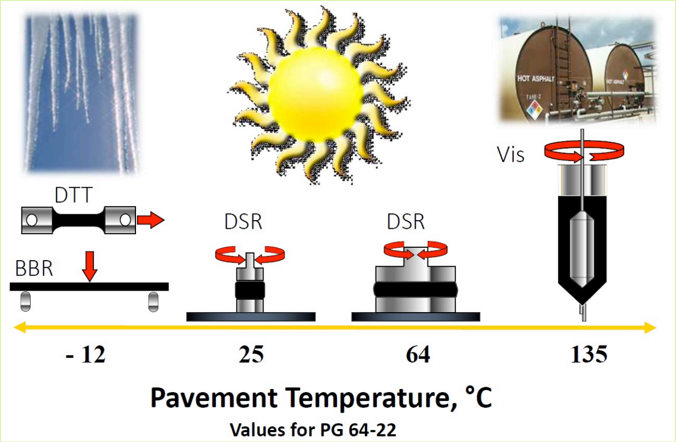


# Impact: Asphalt Binder Modifier to Enhance Infrastructure Resilience to Climate Change

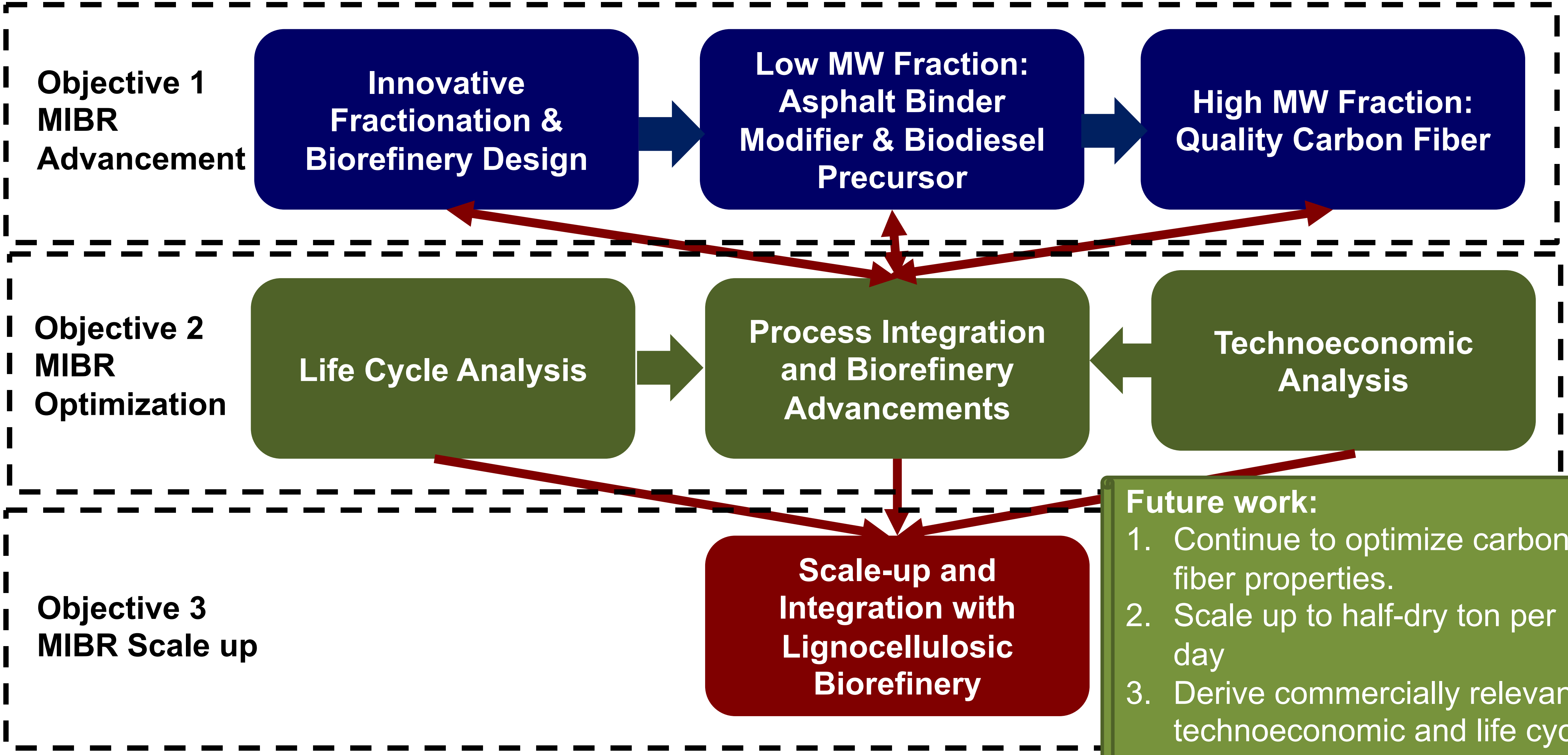
- Asphalt pavement facts:
  - 2.5 million miles of asphalt paved road in US.
  - 3,500 asphalt mix plants in US, producing about 350 million tons of asphalt mixes per year: $21 billion.
  - 17.5 million tons of asphalt binders
    - Binder: $600/ton
    - Market: $10.5 billion

- Asphalt binder functions as a glue in asphalt mixtures. Its quality have big influence on pavement perform.





# Future Work




**Future work:**
1. Continue to optimize carbon fiber properties.
2. Scale up to half-dry ton per day
3. Derive commercially relevant technoeconomic and life cycle impact

# Summary

*The project will leapfrog the technologies to enable multi-stream integrated biorefinery (MIBR).*

1. Overview – The develop and integrate multiple value-added bioproduct streams to enable multi-stream integrated biorefinery (MIBR) to reduce MESP and improve sustainability and cost-effectiveness of lignocellulosic biorefinery.
2. Management
   - S.M.A.R.T Milestones, and Go/No-Go milestones at the end of each BP.
   - Constant engagement with commercial partners.
   - TEA and LCA guide the process advancement for commercial relevance.
   - Two PCT patents filed.
3. Approach
   - Rigorous management approach to enforce milestones.
   - MIBR Development by Optimizing and Advancing Each Product Process
   - MIBR Integration and Optimization
   - MIBR Scale-up, TEA and LCA to guide the technology advancements and commercialization.
4. Impact
   - The project is directly addressing MYPP goals.
   - Aspen Plus model significant potential of carbon fiber to reduce MESP
   - The low-cost carbon fiber could improve the efficiency of energy sector substantially.
   - The asphalt binder modifier can enhance the infrastructure resilience to global climate changes.
5. Technical Accomplishments/Progress/Results
   - The project has met all BP2 milestones.
   - The project has delivered solutions to reduce MESP significantly
   - The project has led to profound scientific discoveries, guiding future process development
   - We will continue the scale up of two out of three streams according to the Go/No-Go milestones.

# Quad Chart Overview

## Timeline

- Project start date: 09/01/2018
- Project end date: 11/30/2023

| | FY22 Costed | Total Award |
|---|---|---|
| **DOE Funding** | $985,364 | $2,236,211 |
| **Project Cost Share** | $460,631 | $559,056 |

## Project Partners*

- University of Tennessee, Knoxville/Oak Ridge National Lab
- Washington State University
- Texas Transportation Institute

## Project Goal

The project will leapfrog the technologies to enable multi-stream integrated biorefinery (MIBR), which will improve the economics and sustainability of lignocellulosic biorefinery and reduces MESP and $/GGE.

## End of Project Milestone

At the end of the project, we will deliver integrated biorefinery to produce carbon fiber at MOE of 100GPa and tensile strength of 2GPa, along with asphalt binder modifier with 1PG increase of high temperature performance without compromising low temperature performance. We will select two product streams out of three streams in BP2. Currently, we set to select asphalt binder modifier and carbon fiber as next step focus.

## Funding Mechanism

DE-FOA-0001689; Topic Area 2: High value products from waste/or other undervalued streams in an integrated biorefinery.

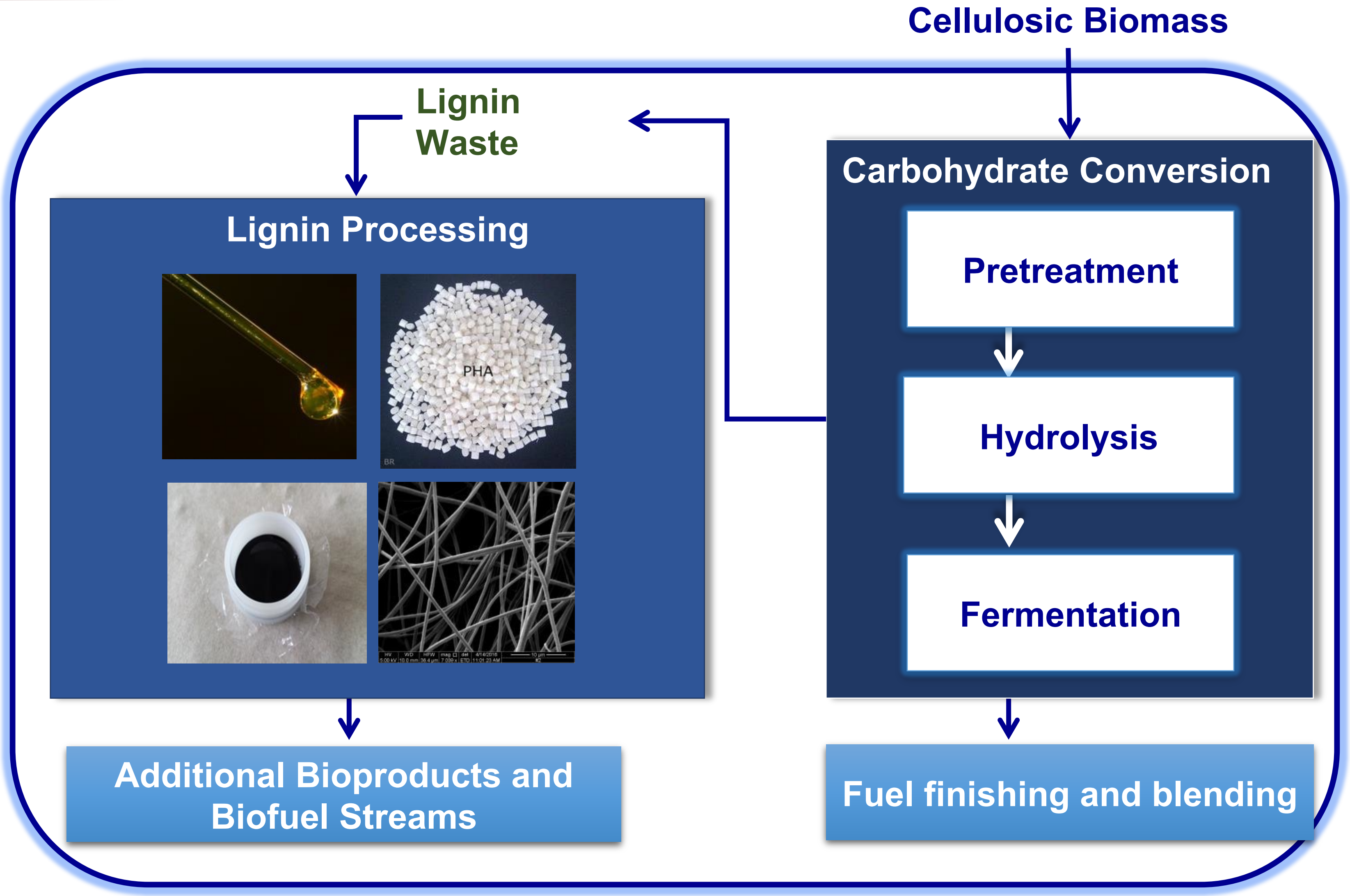
2018.

# Additional slides

# Impact: Lignin Utilization to Enable Economic and Sustainable Multi-stream Biorefinery

**BETO Missions:**

- Improve biorefinery economics and sustainability
- Produce high value bioproducts and manage biorefinery waste
- Reduce carbon emission by complete biomass usage




Xie, et al. Industrial Biotechnology 12 (3), 161-167

# Management Approach – Go/No-Go Milestones

| Time Point | | Benchmark | End of BP2 | End of the Project |
|---|---|---|---|---|
| **Product** | **Metrics** | Milestones | Milestones | Milestones |
| **Carbon Fiber** | **MOE** | 20GPa | 50GPa | 100GPa |
| | **Tensile** | 100MPa | 1GPa | 2GPa |
| **Asphalt Binder Modifier** | **Rutting Temp Incr.** | 7°C | 10°C | 10°C |
| | **Low temp** | Same | Same | Same |
| **Lipid for Biodiesel** | **Titer** | 10g/L | 15g/L | 25g/L |
| | **Conversion** | 30% | 30% | 40% |
| **Economic Outcome** | **MESP[1]** | N.A. | N.A. | N.A. |
| | **~$/GGE[2]** | N.A. | N.A. | ~$3/GGE |

Technical Advancements Derive Economic Output and TEA guide Tech Development

1. Minimal Ethanol Selling Price
2. Gasoline Gallon Equivalent

- **Defined S.M.A.R.T. Go/No-Go milestones were set and implemented to ensure project progresses.**
- **The technical milestones were designed in a way to ensure that the economic targets can be achieved. Full ASPEN model was built.**
- **Down-selection to two product streams based on TEA and performance.**

# Acknowledgement


**Project Management:**

Joshua Messner　Marykate O'Brien　Jay Fitzgerald
Kelly Nguyen

**CoPIs:**

Dr. Art Ragauskas
Dr. Fujie Zhou
Dr. Brandon Emme
Dr. Bin Yang
Dr. Bruce McCarl

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The project has led to 28 publications with a total impact factor at 190.

# Patent and Commercialization

- **The project has led to three patent applications.**

1. J.S. Yuan, et al., “Conversion of lignin into bioplastics and lipid fuels”, PCT/US2016/024579, WO 2016154631 A1 – The PCT patent is at US and EU application stage.
2. J.S. Yuan et al., “Lignin fractionation and fabrication for quality carbon fiber”, PCT/US2019/019620 – This is a PCT application.
3. J.S. Yuan et al,. “Lignin molecular design to transform green manufacturing.” Provisional

- **Commercialization efforts -- We have actively engaged with two industries.**

1. For lignocellulosic biorefineries, we have worked closely with ICM inc. We also had dialogue with POET for lignin utilization.
2. For carbon fiber industry and pavement industry, we are engaging with Venture Capital and start ups for commercialization.