DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Infinitely Recyclable and Biodegradable Films for Improved Food Packaging

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Plastics Deconstruction and Redesign

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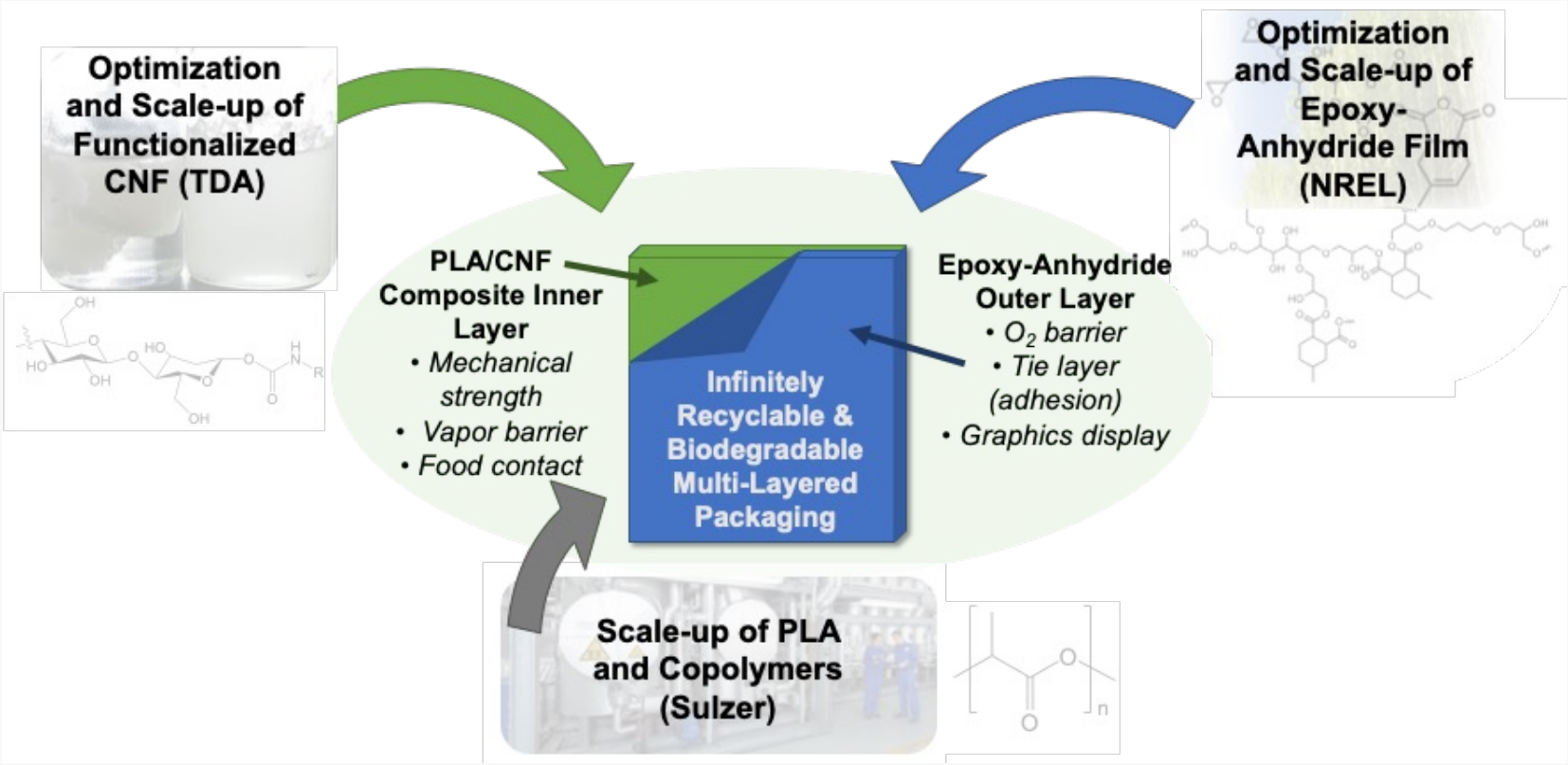
Project Overview

- Single use, multilayer films are very important materials, but generate an enormous amount of plastic waste. Sustainable alternatives need to be developed.

- In this project, we are transitioning from the traditional fossil fuel-based polyolefins to an ester-based paradigm that uses bio-derived materials to decarbonize the packaging industry.

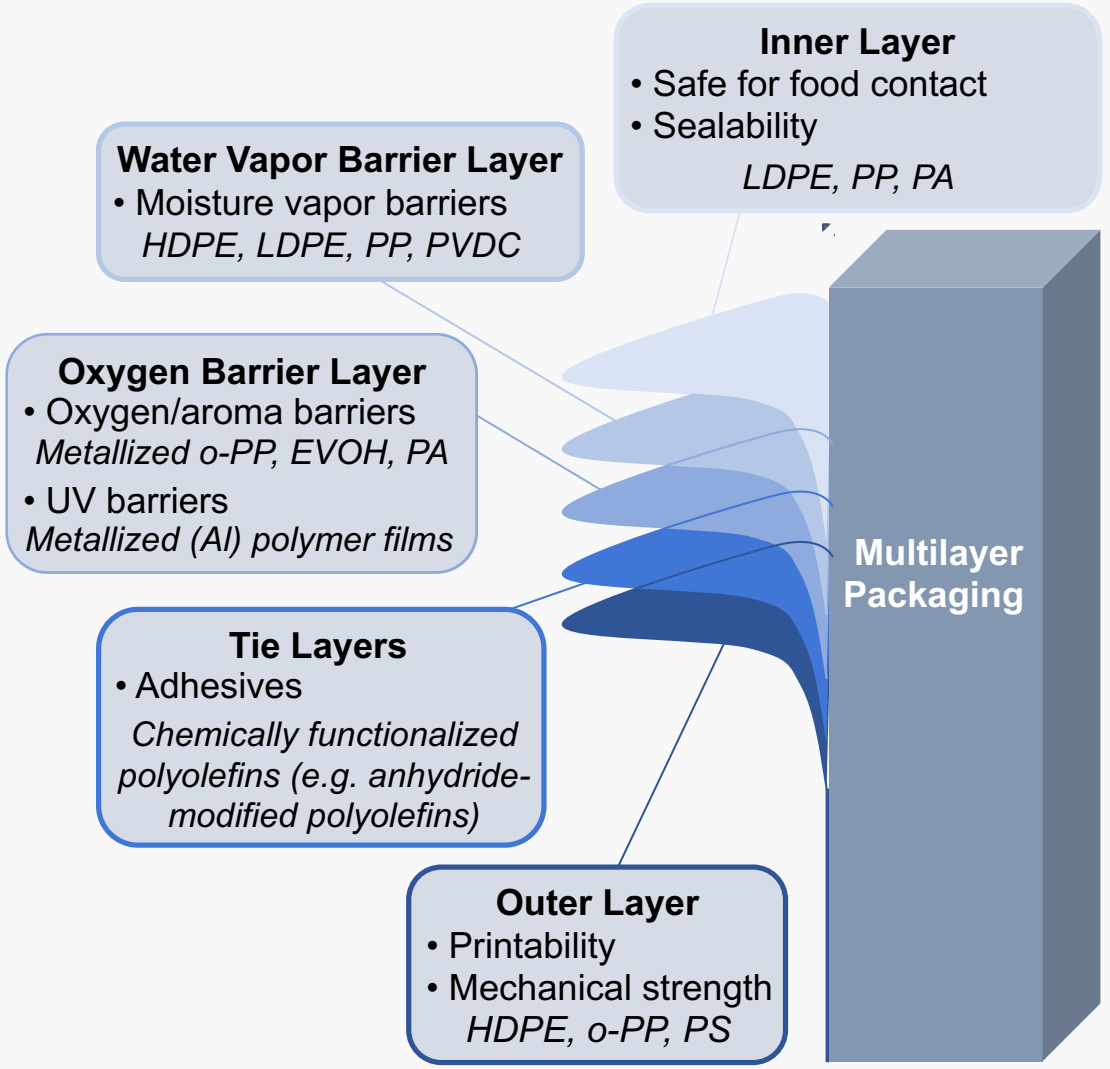
- This effort will develop new, sustainable multilayer films made of a biodegradable, biomass-derived nanocomposite and inherently recyclable epoxy-anhydride polymer.



1 - Approach

- We will develop two materials that will be incorporated into a multi layer film.
  - The PLA/cellulose nanocomposite will act as an inner layer that is safe for food contact, provides mechanical strength, and acts as a vapor barrier.
  - The epoxy-anhydride layers will act as an oxygen barrier and will be designed for printability to allow graphics display.

- **Overall approach: develop recyclable, biodegradable polymers that have complimentary properties to make a multilayer film.**
  - In line with BETO goals to reduce plastic waste, develop a circular plastics economy, and advance US manufacturing of sustainable materials.

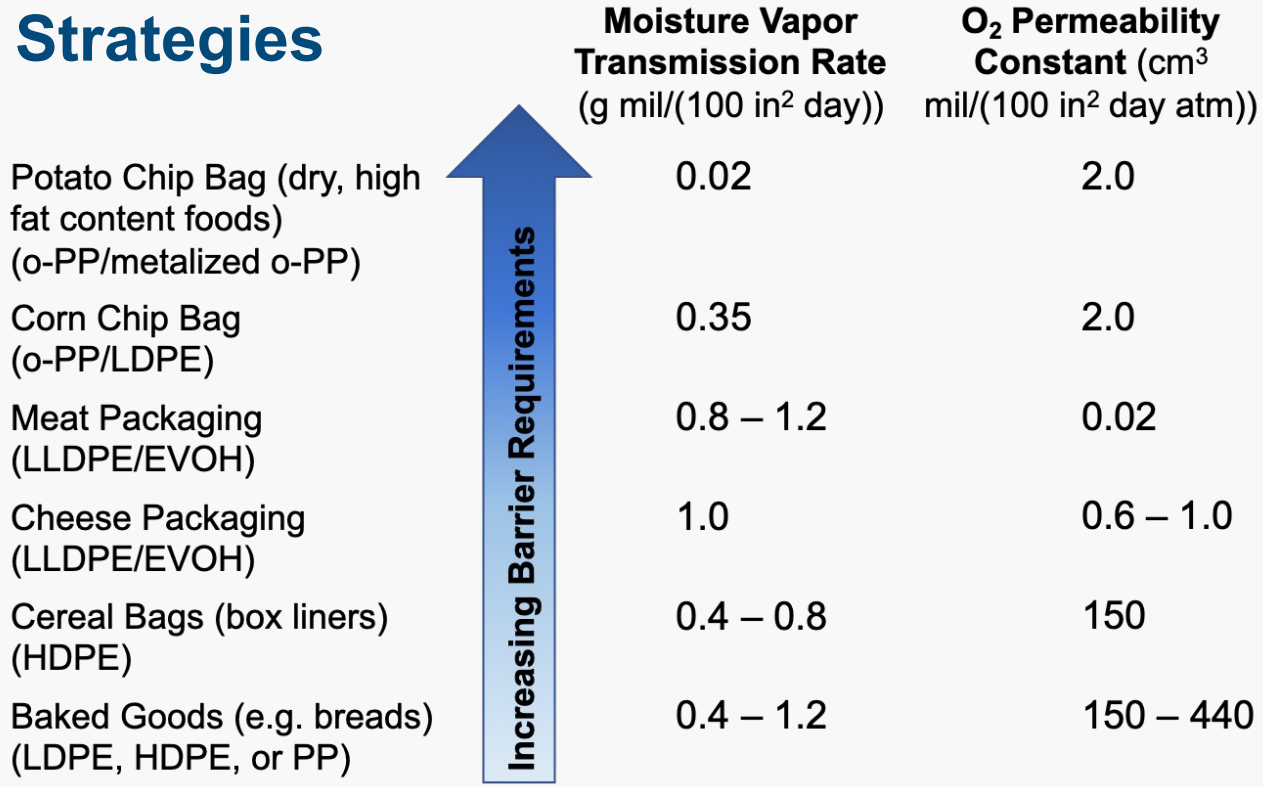


Polymer abbreviations: ethylene vinyl alcohol (EVOH), oriented polypropylene (o-PP), polyamide (PA), polyethylene terephthalate (PET), high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinylidene chloride (PVDC)

1 - Approach

Primary Challenges and Mitigation Strategies

- Reaching very low permeabilities for both vapor and oxygen is challenging.
  - Different applications have very different barrier property requirements.
  - Targeting an LLDPE/EVOH replacement, and if we exceed our goals can apply the material to additional markets.
- The film requires FDA approval for use in food-contacting applications.
  - PLA will be the food contacting layer, and is already approved for this use. Only the cellulosic additive will need FDA approval as a food contact substance (FCS).
  - TDA has extensive regulatory approval experience (including FDA).
  - We will engage with the FDA through a "prenotification consultation," which allows us to discuss our planned filing and ensure we collect the required data.



	Moisture Vapor Transmission Rate (g mil/(100 in^2 day))	**O_2 Permeability Constant** (cm^3 mil/(100 in^2 day atm))
Potato Chip Bag (dry, high fat content foods) (o-PP/metalized o-PP)	0.02	2.0
Corn Chip Bag (o-PP/LDPE)	0.35	2.0
Meat Packaging (LLDPE/EVOH)	0.8 – 1.2	0.02
Cheese Packaging (LLDPE/EVOH)	1.0	0.6 – 1.0
Cereal Bags (box liners) (HDPE)	0.4 – 0.8	150
Baked Goods (e.g. breads) (LDPE, HDPE, or PP)	0.4 – 1.2	150 – 440

1 - Approach

Go/No-Go Decision Points

- **Go/No-Go #1: Initial Verification**
  - The DOE verification team will validate the project baseline capabilities, metrics, and technical plan.
- **Go/No-Go #2: Individual Layers Meet Target Properties**
  - Optimized PLA composite shows at least 25% reduction in water permeability
  - Optimized epoxy-anhydride polymer has an O_2 permeability of less than 2.6 cm^3 mil /(100 in^2 day atm)
    - Replacement for polyamides (a common oxygen and aroma barrier layer material)
  - Preliminary LCA indicates that production and recycling/composting results in lower GHG emissions than the current state-of-the-art
- **Go/No-Go #3: Multilayer Film Meets Target Properties and Cost Targets**
  - Optimized multilayer film is produced at the kg scale and meets barrier property targets.
  - Recyclability studies show >50% recycled monomers (>95% purity) and/or compostability studies show >50% degradation.
  - TEA/LCA shows the material can be produced at a cost equal to or less than the state of the art films ($3.80/kg) and with lower GHG emissions.

1 - Approach

Risk Analysis and Mitigation

Perceived Risk	Risk Rating (low, medium, high)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Financial Risks				
Over spending	Low	High	Medium	Continuously monitor project funds & progress.
Cost/Schedule Risks				
Optimizing barrier properties requires longer than expected	Low	Medium	Low	Budgeted 11 months to optimize the individual films before combining them. Additional optimization task at the start of BP3.
Technical/Scope Risks				
Unexpected development needs (e.g. initial formulations don't perform as expected)	Medium	High	Medium	Use expertise at TDA, NREL, and Sulzer to come with needed solutions. Validation work shows promising performance.
TEA/LCA does not show cost improvement relative to traditional multilayer materials	Low	High	Medium	Use team's extensive experience in polymer chemistry to identify alternative materials. Perform a sensitivity analysis on our TEA/LCA to identify the key materials to modify.
Management and Planning Risks				
Insufficient resources	Low	Medium	Low	Continuous monitoring of the labor load profiles particularly for the key personnel.

1 - Approach

Diversity, Equity, and Inclusion (DEI)

- **This project contains three DEI specific Milestones.**

Complete DEI Training [1,2]

Hire an Intern

Hold Career Development Events

1. https://dpa.colorado.gov/about-us/edi **2.** https://www.nationalacademies.org/event/05-25-2021/diversity-equity-and-inclusion-in-chemistry-and-chemical-engineering-a-workshop-of-the-chemical-sciences-roundtable#sl-three-columns-bcad5f6f-601f-44de-aa00-3510051762aa

2 – Progress and Outcomes

- **Two Milestones are ongoing at this time according to the PMP, both of which are on schedule.**

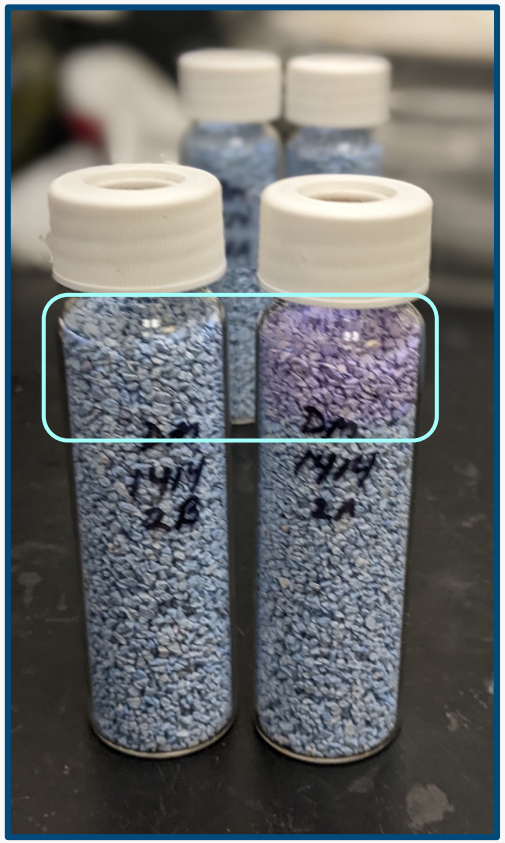
- **Milestone 1.0: Initial Verification**
  - The Initial Verification meeting was held March 9, 2023.
  - **We have completed recreating our preliminary data and recorded videos to share with the verification team to demonstrate how the two polymer layers were created.**

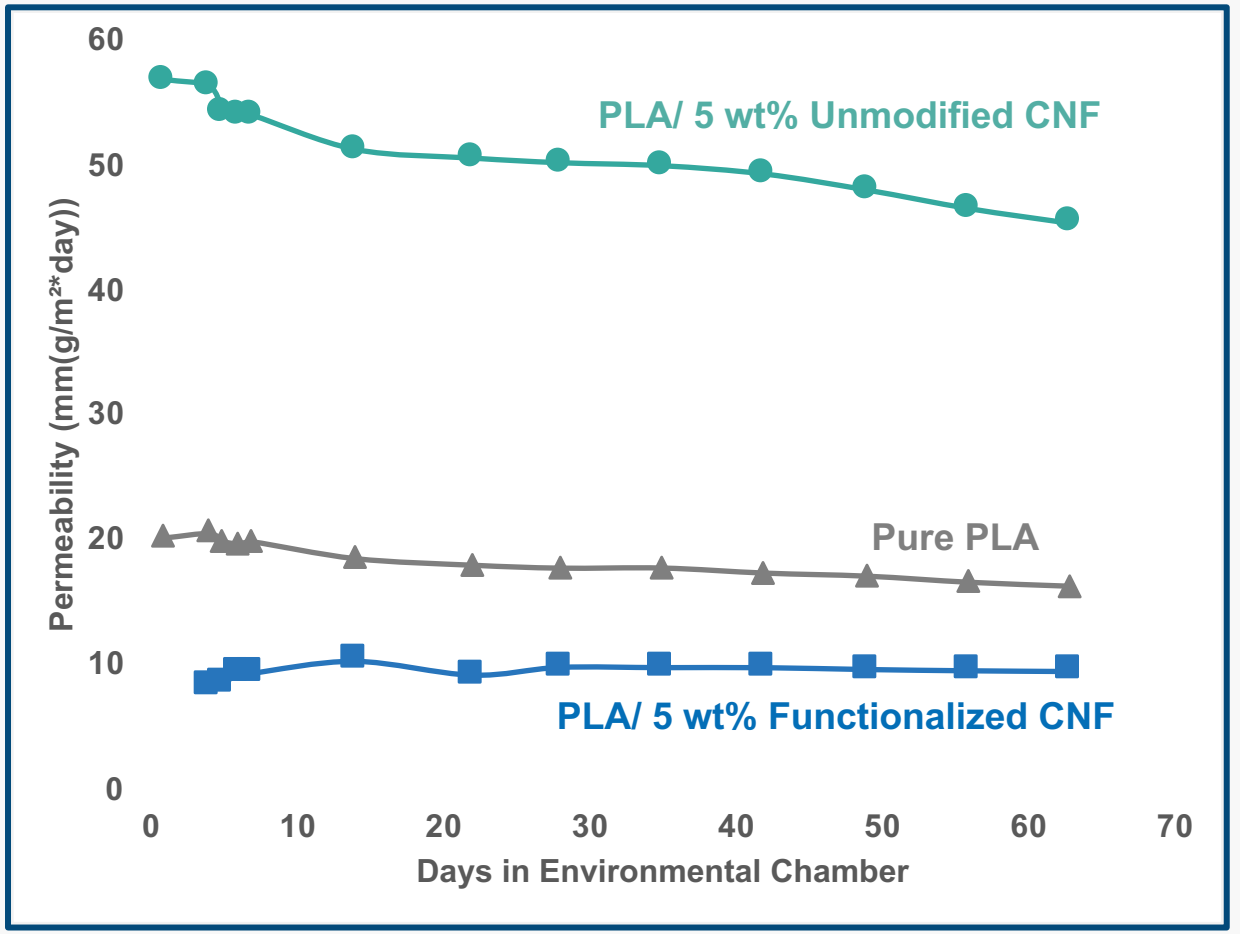
- **Milestone 1.1: Complete DEI Training**
  - Materials for training were identified, including documents and videos from:
    - DOE Guidance for Project Teams on Diversity, Equity, Inclusion, and Accessibility Plans from August 2022
    - DOE Office of Science Community DEI Informational Resources page
    - The National Academies training materials for Diversity, Equity, and Inclusion in Chemistry and Chemical Engineering
    - State of Colorado Department of Personnel and Administration DEI Training, including hiring considerations
  - The project management team has reviewed these documents and prepared a DEI plan that will be implemented throughout the remainder of the project.

2 – Progress and Outcomes

PLA Composite

- Functionalized CNF was prepared and blended into PLA to make films.
- Films were used to seal vials of desiccant, which were stored in a sealed chamber at room temperature and 99% relative humidity.
- Moisture that penetrates the film is adsorbed and the mass of the vial increases.



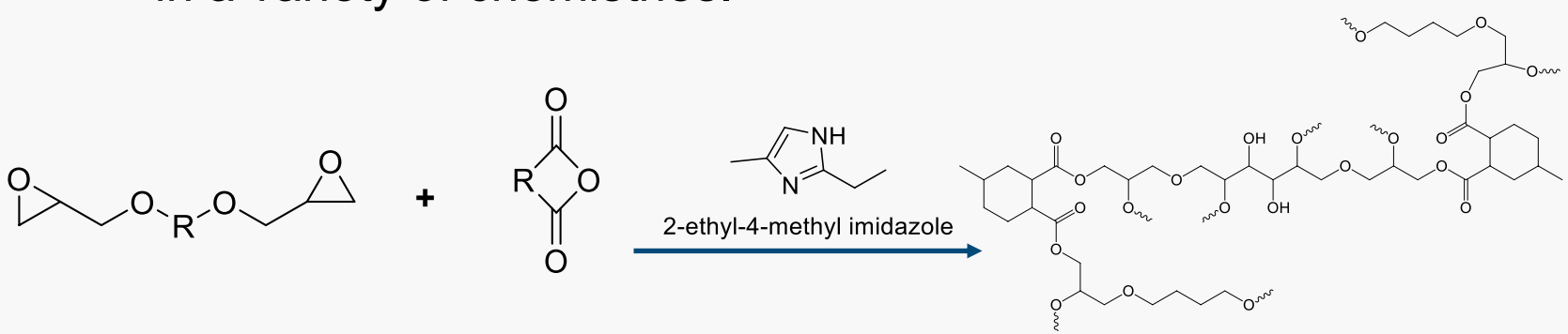


- **Results are consistent with preliminary data; functionalized CNF reduces vapor permeability.**

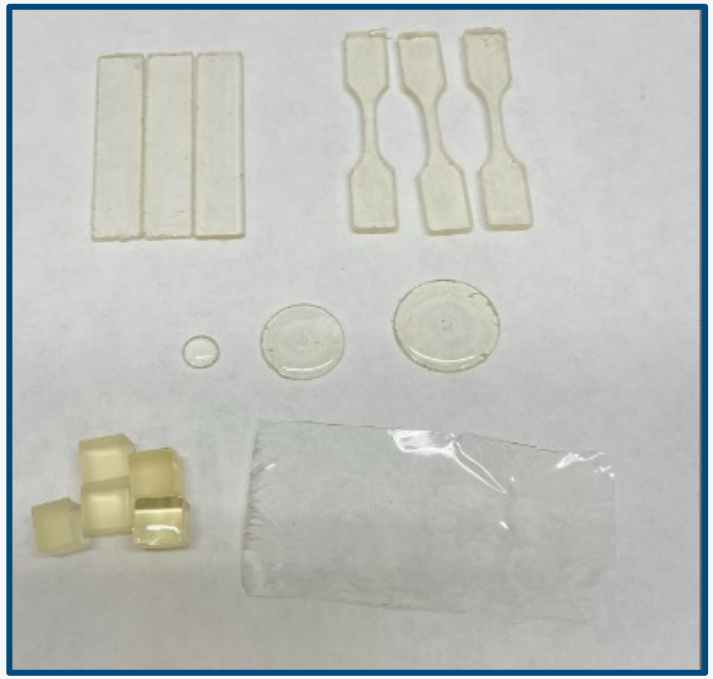
2 – Progress and Outcomes

Epoxy-Anhydride

- Epoxy-anhydride polymers have been produced in a variety of chemistries.



Epoxy **Anhydride** **3-D Polymer Network**



Solidified resin in a variety of formats

- Mixed resin was cast into a variety of formats for thermal and mechanical analysis.

- **Results are consistent with preliminary data; polymers can be created using a variety of epoxy and anhydride monomers, and can be recycled at mild conditions.**

3 – Impact

- The recyclable, biodegradable multilayer films produced in this effort will help decarbonize the packaging industry and reduce plastic waste.
  - Maintain the benefits of single use plastics but using sustainable materials
  - Optimal end-of-life strategy (recycling vs composting) will be determined based on TEA/LCA, considering both the overall cost of the material and the total environmental impact.
- This film will add to the sustainable materials produced in the US.
- Pollution from producing conventional plastics and the impacts of waste plastics both disproportionately affect marginalized communities. Developing sustainable alternatives is a critical component of solving this issue.
- We will work with Sulzer to commercialize the technology; by having an industry partner involved in the R&D we will ensure we develop a material that is well suited for disrupting conventional plastic films on the market.
- Results of this work will be published in peer-reviewed journals, patented, and/or shared with the community at scientific meetings.

Summary

- TDA, NREL, and Sulzer are developing sustainable multilayer packaging to replace single use plastics.
  - This is well aligned with BETO's goals to reduce plastic waste and decarbonize manufacturing.
- We have successfully reproduced our preliminary results and are on schedule to complete the Initial Verification meeting.
  - PLA nanocomposite has been shown to reduce vapor permeability.
  - Epoxy-anhydrides have been produced in a variety of formulations and form factors, and have been demonstrated to be recyclable.
- We have also initiated our DEI plan and are prepared to implement this throughout the remainder of the project.
- The effort is on schedule, with the research and development to begin in BP2.

Quad Chart

Timeline

- ***October 1, 2022***
- ***September 30, 2025***

	FY22 Costed	Total Award
DOE Funding	*The project began in FY23, no FY22 funds were spent*	*$1,604,055*
Project Cost Share	*N/A*	*$402,370*

TRL at Project Start: 4
TRL at Project End: 6

Project Goal

Develop sustainable multilayer packaging that is recyclable and/or biodegradable to replace conventional food packaging materials, maintaining the benefits of disposable packaging without the environmental drawbacks.

End of Project Milestone

Nanocomposite and epoxy-anhydride materials are produced at the 1 kg scale. Testing shows that the multilayer film meets or exceeds all technical requirements (25% reduction in vapor permeability and O_2 permeability of 2.6 cm^3 mil/(100 in^2 day atm). Recyclability studies show >50% recycled monomers with >95% purity and compostability studies show >50% degradation. TEA/LCA analysis shows the material can be produced at a cost equal to or less than the state of the art films ($3.80/kg), and with lower GHG emissions.

Funding Mechanism

Single-Use Plastics Recycling (SUPR) Funding Opportunity (DE-FOA-0002473), Topic Area 2

Submitted August, 2021

Project Partners

- **The National Renewable Energy Laboratory (NREL)**
- **Sulzer**