

Material Recycling/Upcycling Technologies for Sustainable Polymer Composites

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Overview

- Introduction

- About NIMS
- Motivation – Sustainability Challenges for Polymers and Composites

- Biomass Blends and Composites

- Fabrication of Polypropylene (PP) / Lignin Blends and Composites
- Fabrication of Polyamide (PA) / Lignin Blends and Composites
- Mechanical Recycling of PP/Lignin Blends

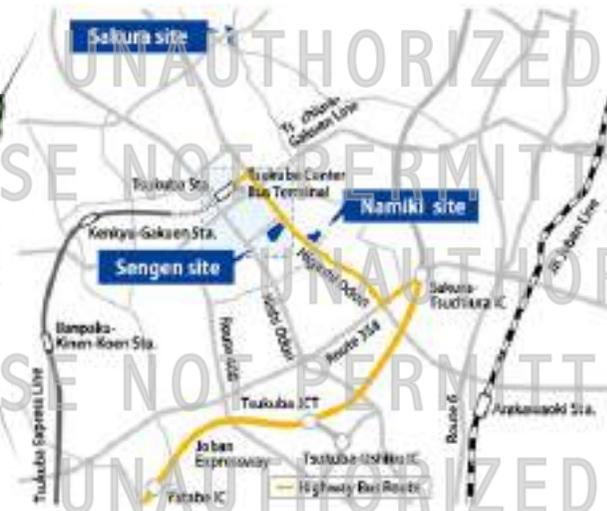
- Functional Materials

- Highly Thermally Conductive Polymers and Nanocomposites

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About NIMS

- National Institute for Materials Science (NIMS)
 - Research institute devoted to the creation, characterization, and application of materials that support a sustainable society



About NIMS

- National Institute for Materials Science (NIMS)

- 7 Research Centers
- 473 Full-time researchers
- 157 Postdoctoral/contract researchers
- 151 Graduate students
- 392 Technical staff

Worldwide academic collaboration



Top-level facilities

We have around 250 advanced items of equipment including instruments, large-scale machines, and other facilities that are available for collaborative use, providing opportunities for researchers from universities, corporations, and public institutions in Japan and around the world.



About NIMS

- National Institute for Materials Science (NIMS)
 - Industry Collaboration – Centers of Excellence

		
TOYOTA-NIMS Collaboration Center Development of fundamental technologies based on essential understanding of materials phenomena. Aiming to contribute to mobility in general as well as promotion of applications. Established: July 2008 Collaboration Partner: Toyota Motor Corporation	NIMS-DENKA Center of Excellence for Next-Generation Materials Development of advanced next-generation materials and manufacturing technologies in the fields of Healthcare, ICT & Energy, and Sustainable Living. Established: June 2013 Collaboration Partner: Denka Company Limited	SAIT-NIMS Innovation Center Innovative materials research and development for a society of convenience powered by energy. Established: December 2015 Collaboration Partner: Samsung Advanced Institute of Technology (SAIT), South Korea

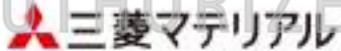
About NIMS

- National Institute for Materials Science (NIMS)
 - Industry Collaboration – Centers of Excellence

 <p>MITSUBISHI CHEMICAL GROUP</p> <p>三菱ケミカル株式会社</p>	 <p>SoftBank</p>	 <p>L'ORÉAL RESEARCH & INNOVATION</p>
<p>MCC-NIMS Center of Excellence for Next-generation Functional Materials</p> <p>Fundamental research and development of base technologies for next-generation advanced functional materials</p> <p>Established: December 2015</p> <p>Collaboration Partner: Mitsubishi Chemical Corporation</p>	<p>SoftBank-NIMS Advanced Technologies Development Center</p> <p>Collaboration aiming at the practical application of innovative batteries, such as lithium metal batteries, all solid-state batteries, essential for the IoT era</p> <p>Established: April 2018</p> <p>Collaboration Partner: SoftBank Corp.</p>	<p>L'ORÉAL-NIMS Materials Innovation Center for Science and Beauty</p> <p>Creation of innovative products for the Japanese domestic, Asian, and global markets using cutting-edge novel materials developed at NIMS</p> <p>Established: July 2018</p> <p>Collaboration Partner: Nihon L'Oréal K.K.</p>

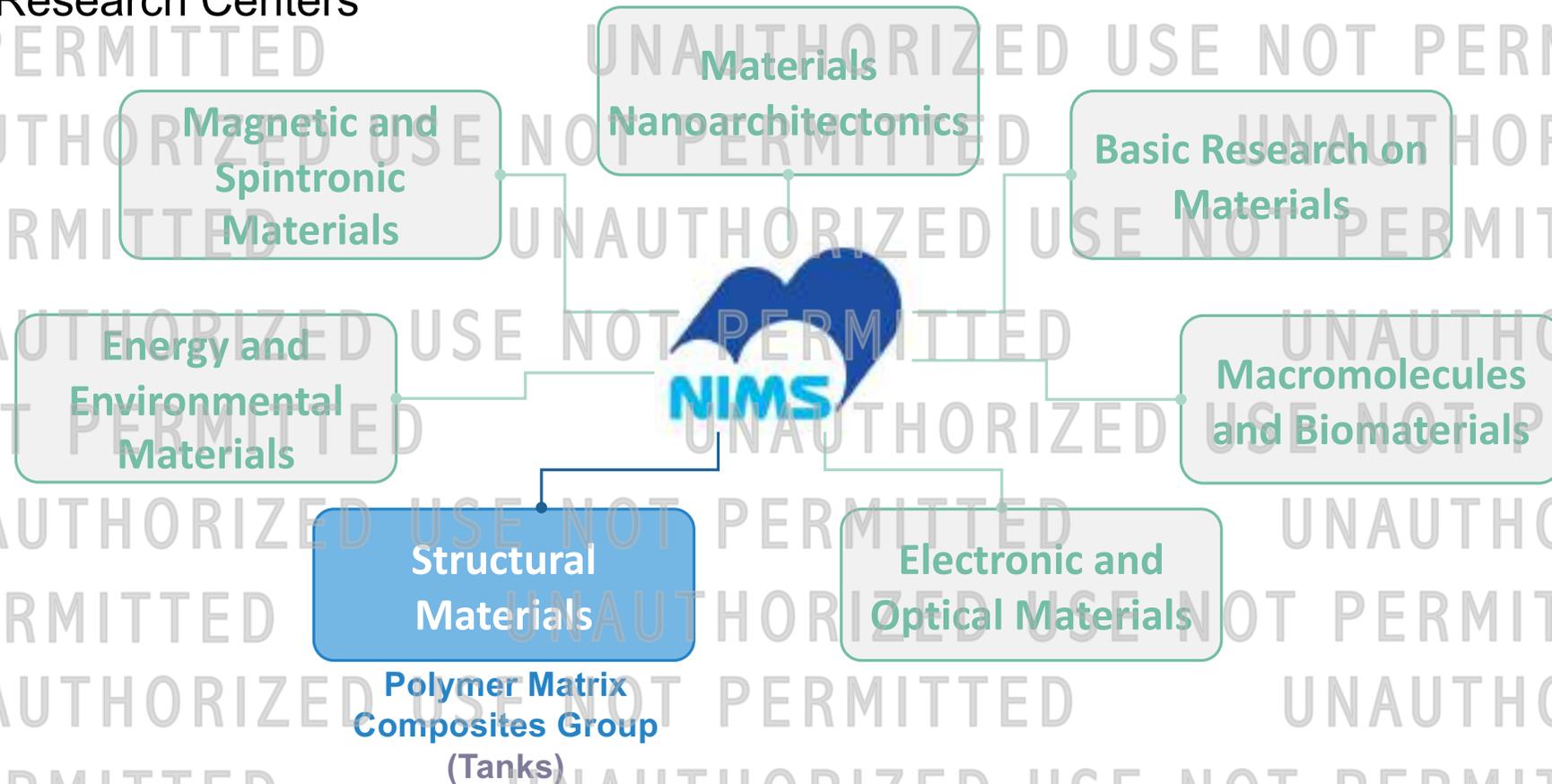
About NIMS

- National Institute for Materials Science (NIMS)
 - Industry Collaboration – Centers of Excellence

		
Saint-Gobain CNRS-NIMS International Collaboration Center	Mitsubishi Materials NIMS Center of Excellence for Materials Informatics Research	WD-NIMS Center for Storage Frontier
Innovation based on exchange and integration of materials science and engineering between Japan and France	Construction of an integrated information materials development system that predicts performance and lifespan of materials manufactured from combinations of various materials and processes	Materials research related to technology for further increasing capacity and reliability of hard disks
Established: January 2019	Established: June 2020	Established: April 2023
Collaboration Partners: Saint-Gobain S.A. (France), French National Scientific Research Center (CNRS)	Collaboration Partner: Mitsubishi Materials Corporation	Collaboration Partner: Western Digital Corporation

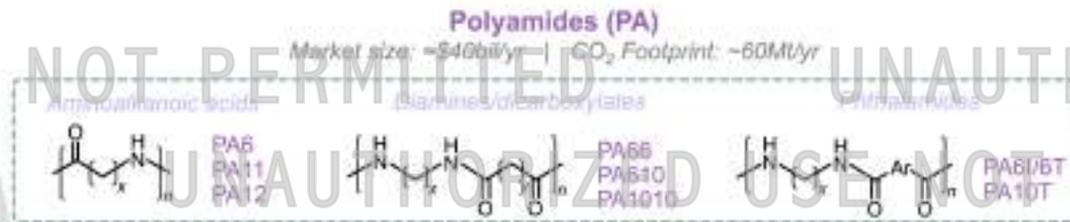
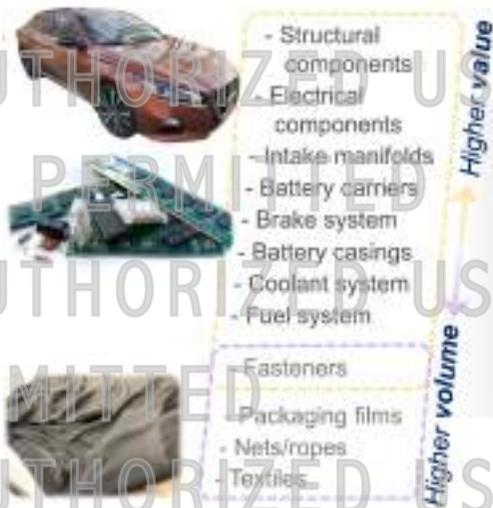
About NIMS

- Research Centers



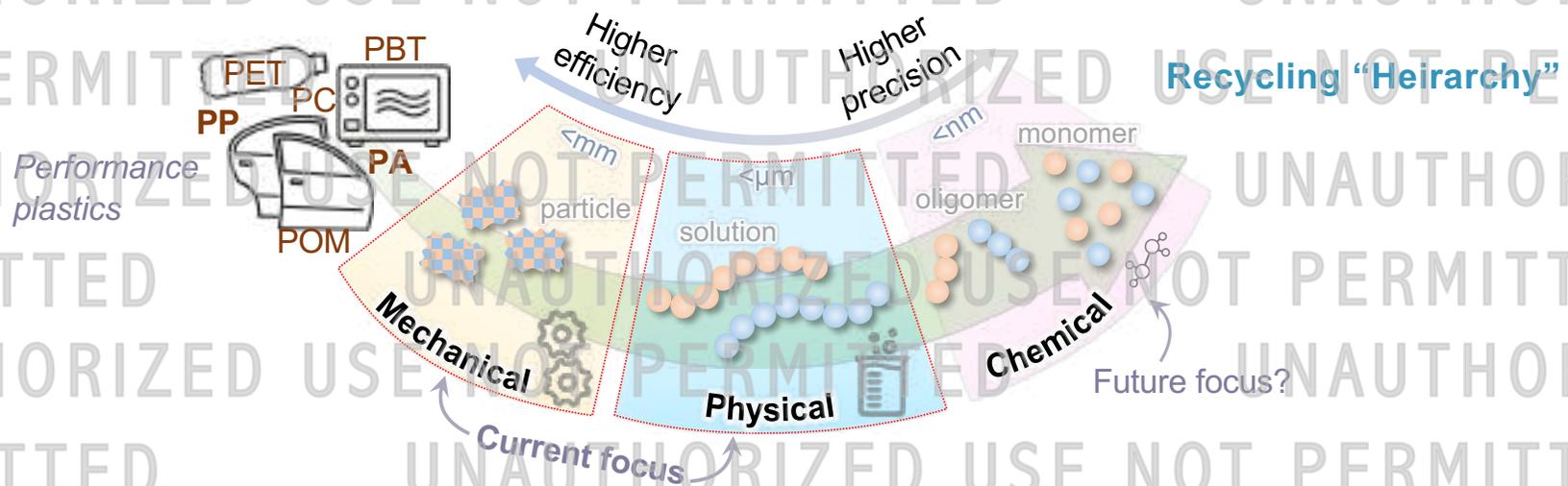
Sustainability Challenges for Polymers and Composites

- Composition of blends/composites is designed to meet target performance.
 - Demanding applications: automotive, electrical/electronic, energy, aerospace
 - Density, strength/modulus, heat resistance, electrical resistance, processability, energy storage
 - Blend/composite for target performance
 - Carbon fiber (CF), glass fiber (GF), silica, alumina, clay, BN, carbon black (CB), elastomer



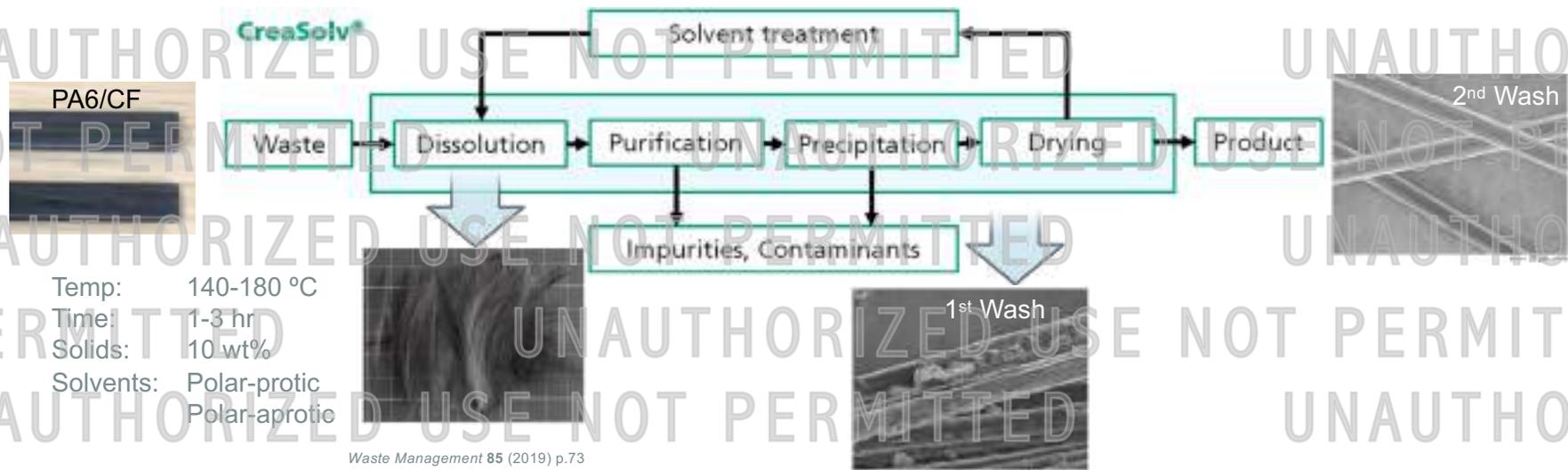
Sustainability Challenges for Polymers and Composites

- The optimum recycling approach depends on the material(s) and application(s).
 - PP, PA, PBT etc. in demanding applications are often mixed with other materials.
 - Separation and purification can be difficult depending on waste stream.
 - There is a spectrum in terms of efficiency vs quality/precision.
 - **「Mechanical」** grinding/pulverizing followed by molding.
 - **「Physical」** dissolution/precipitation followed by molding.
 - **「Chemical」** depolymerization, repolymerization followed by molding.



Sustainability Challenges for Polymers and Composites

- Both resource circularity *and* carbon neutrality must be goals for recycling.
 - De-/re-polymerization yields a high-value product, but is still CO₂-intensive.
 - Various dissolution/precipitation technologies have been patented/reported.
 - CreaSolv, STRAP, etc. use solubility predictions to select optimal solvents.
 - A common drawback is relatively high temperature and long dissolution times.



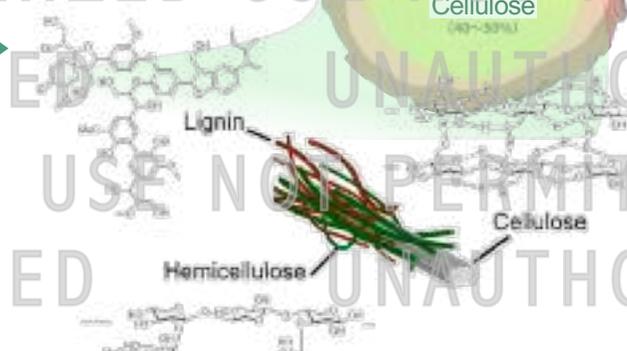
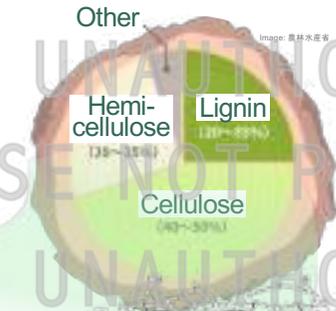
Sustainability Challenges for Polymers and Composites

- Utilizing renewables in high-performance materials is a promising intermediate.
 - Finding ways to reduce existing conventional plastics is an important step.
 - Incorporation of biomass at production can reduce carbon emissions by substitution.
 - Improving compatibility is crucial for maintaining high performance.
 - Decrease in performance from the conventional material hinders implementation.



Reduce petroleum-based plastics

Utilize biomass



Polypropylene (PP)
Polyamide (PA)
 Polycarbonate (PC)

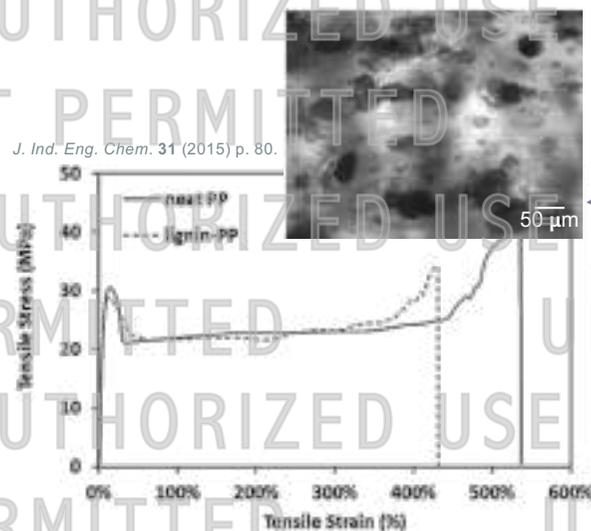
Acrylonitrile-butadiene-styrene (ABS)
 Polybutylene-terephthalate (PBT)
 Polyurethanes (PU)

Sustainability Challenges for Polymers and Composites

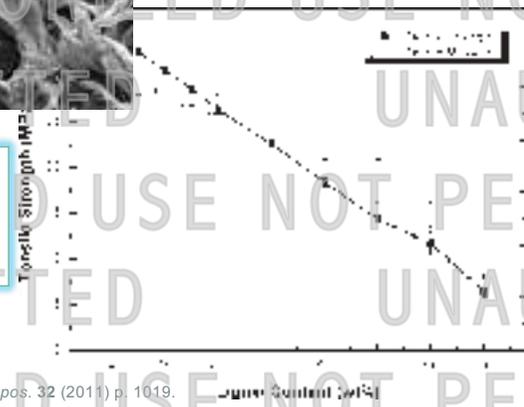
- Poor compatibility remains an issue for many biomass blends/composites.
 - Biomass (lignin) blends suffer from poor compatibility with polyolefins, nylons etc.
 - Agglomerations lead to reduced mechanical properties.
 - Chemical modification of lignin is only one part of the picture.
 - Alkylation, acetylation etc. improve chemical compatibility.
 - Melt-mixing conditions must ensure sub-micron level dispersion.

J. Appl. Polym. Sci. 134 (2017) p. 44669

Specimen Label	Tensile Strength, MPa	Tensile Modulus, GPa
10SKL/MAPP	20.25 ± 0.68	1.04 ± 0.17
30SKL/MAPP	20.23 ± 1.23	1.19 ± 0.18
50SKL/MAPP	16.36 ± 2.37	1.76 ± 0.33
PP	24.87 ± 0.52	1.24 ± 0.11



PP/lignin blended at 180°C in the literature
→ Poor dispersibility



Polym. Compos. 32 (2011) p. 1019.

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Biomass Blends and Composites
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Biomass Blends and Composites

▪ Scalable Melt-Blending Method

- PEG-grafted glycol lignin shows excellent compatibility with a range of plastics

- Forms covalent bonds (reactive extrusion)
- Forms hydrogen bonds

- PA11: 230-240 °C

- PA6I/6T: 250-270 °C

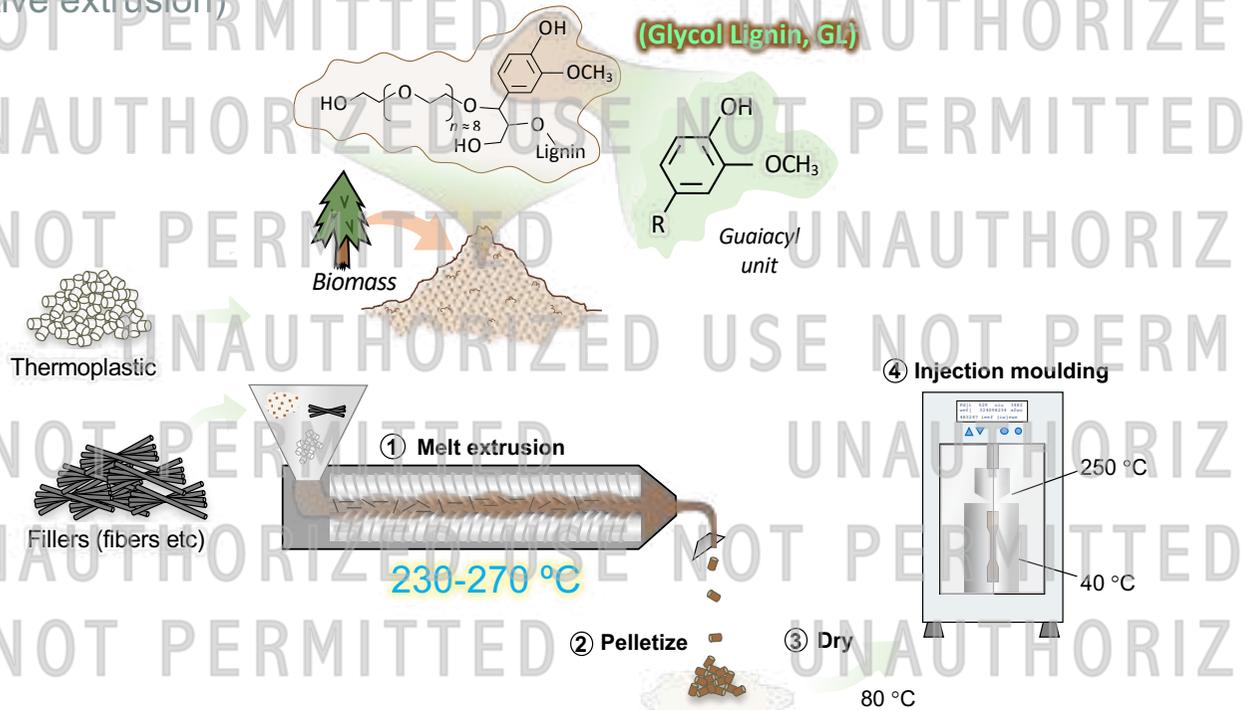
- Mix at high temperature

- PP: 235-245 °C

- PA6: 240-250 °C

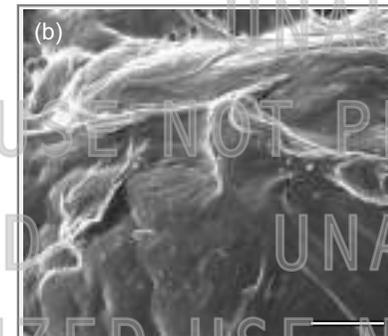
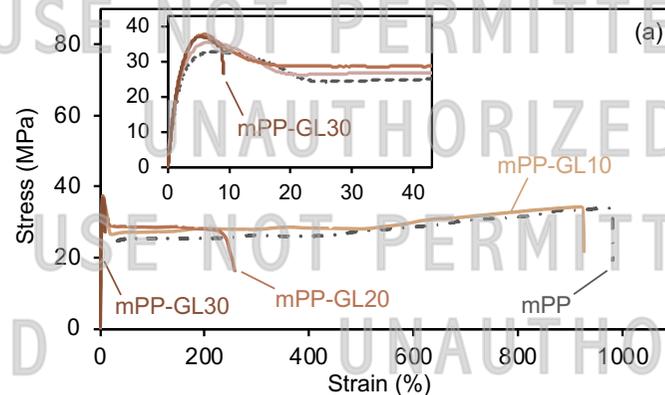
- PA11: 230-240 °C

- PA6I/6T: 250-270 °C

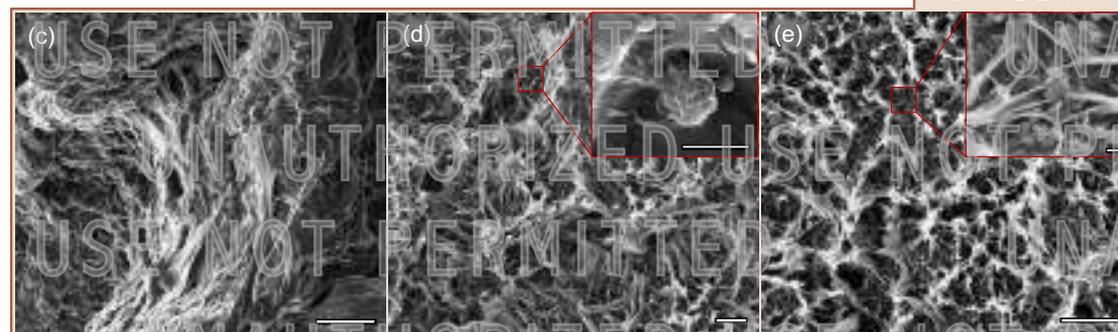


Biomass Blends and Composites

- PP/Lignin blends and composites
 - Sub-micron lignin domains covalently grafted to MAH-g-PP

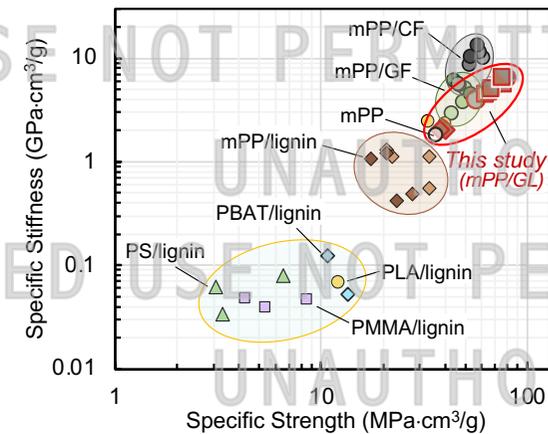
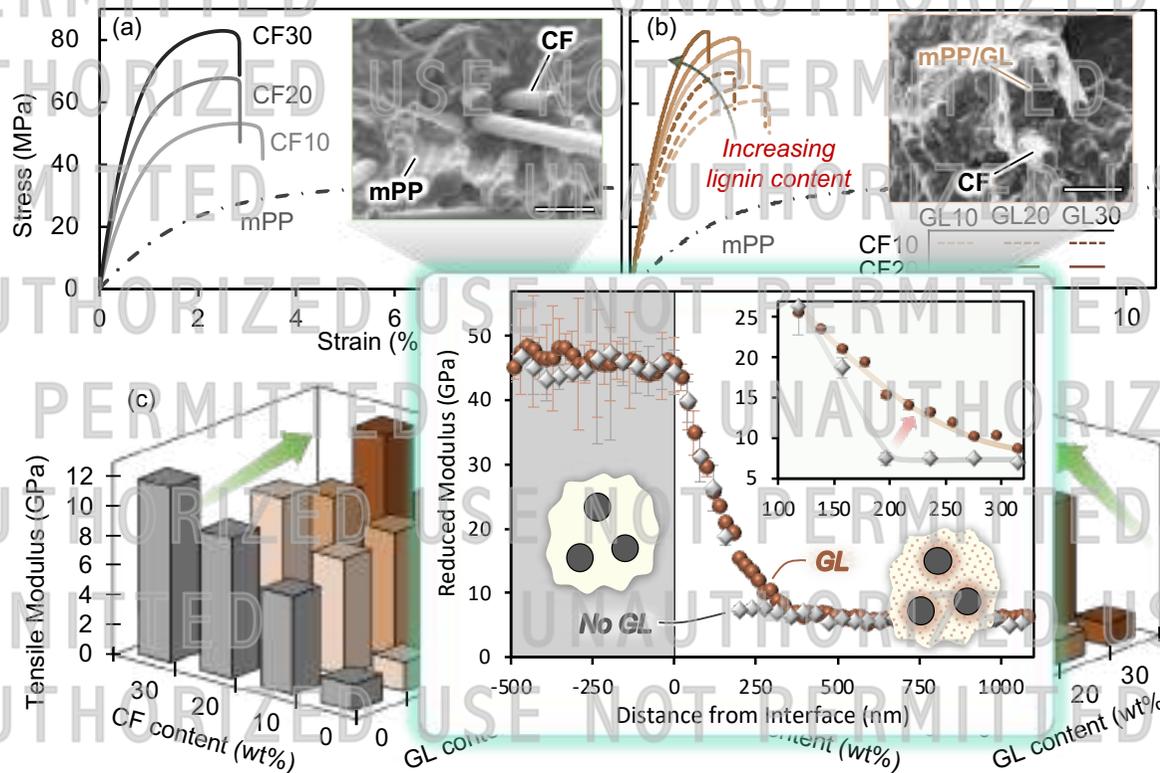


Neat mPP



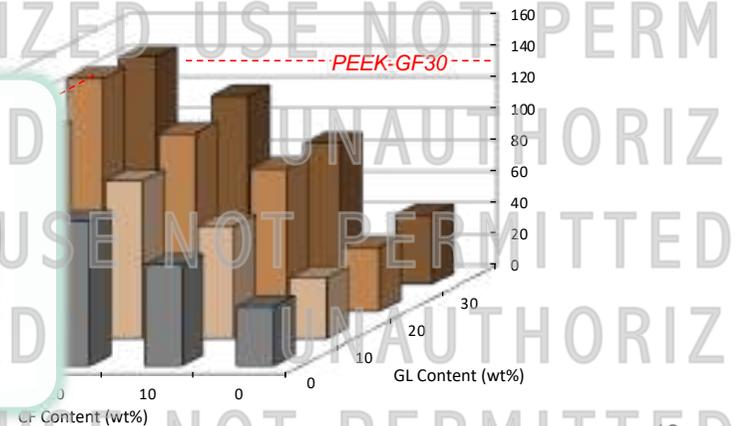
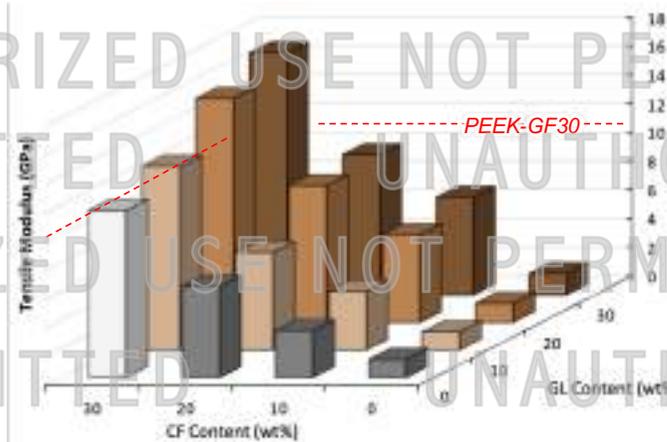
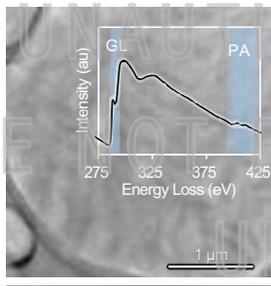
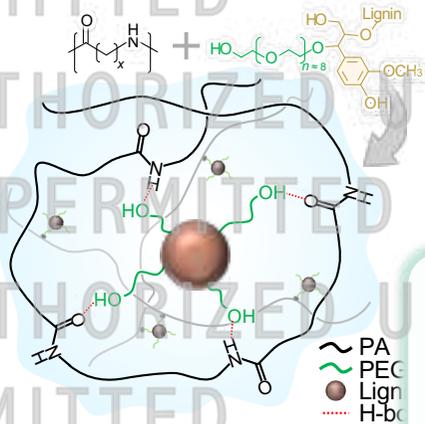
Biomass Blends and Composites

- PP/Lignin blends and composites



Biomass Blends and Composites

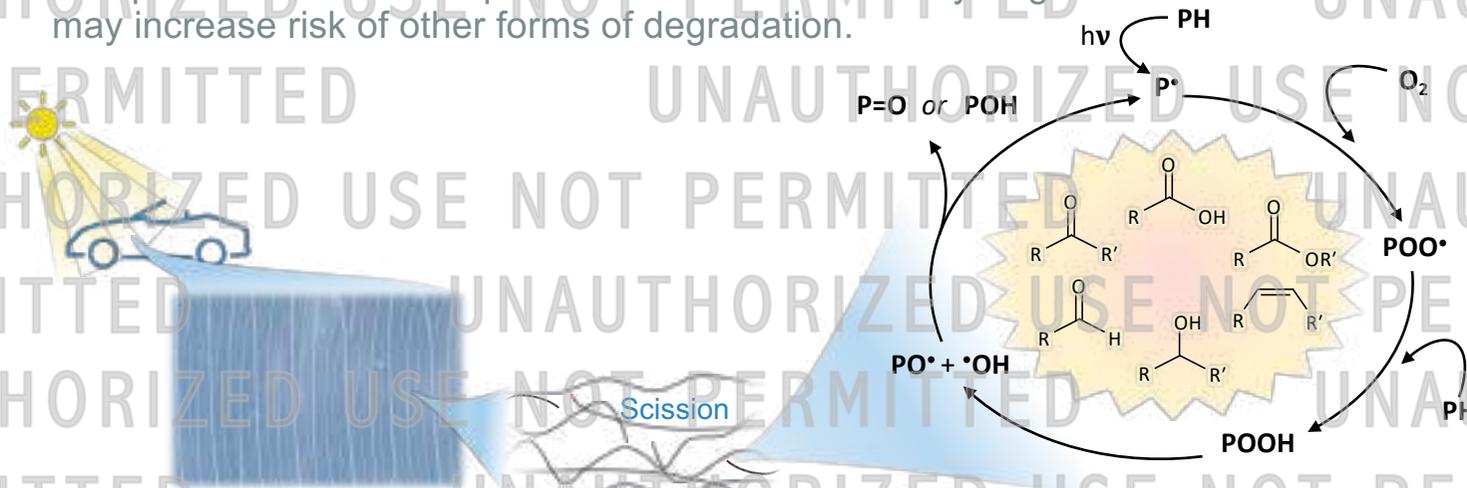
- PA/Lignin blends and composites
 - Highly dispersed lignin can make PAs (even bio-based PA11) achieve PEEK-like properties.



Biomass Blends and Composites

▪ Mechanical recycling of PP/lignin blends

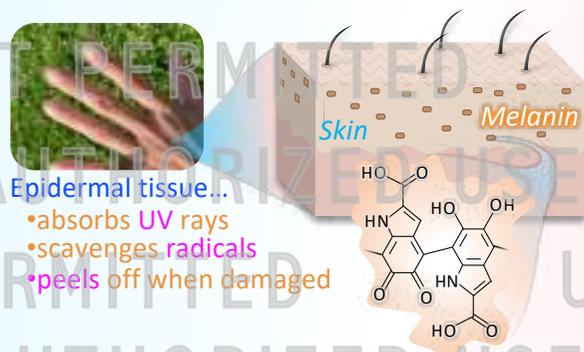
- Polymers like PP are highly susceptible to oxidative degradation through backbone attack.
 - Radicals created by heat or UV turn oxygen into highly reactive radical species.
- Degradation makes plastics more difficult to effectively recycle.
 - Oxidative reaction products are highly variable (non-uniform).
 - Recycled material exhibits reduced performance compared to virgin material.
 - Incorporation of oxidation products via mechanical recycling may increase risk of other forms of degradation.



Biomass Blends and Composites

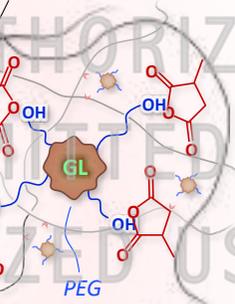
▪ Mechanical recycling of PP/lignin blends

- Lignin can act as a simultaneous UV absorber, radical scavenger, and reinforcement.
 - Mimics melanin in the human skin.
- Non-toxic alternative to conventional stabilizers (Irganox, Tinuvin etc).
 - Moderate molecular weight and polymer interaction prevent migration.

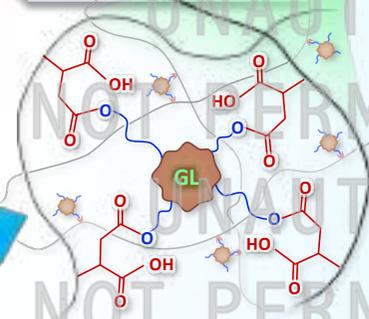
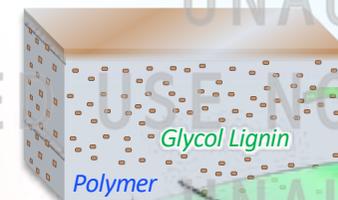


Biomimetic structure

Maleic-grafted polyolefin

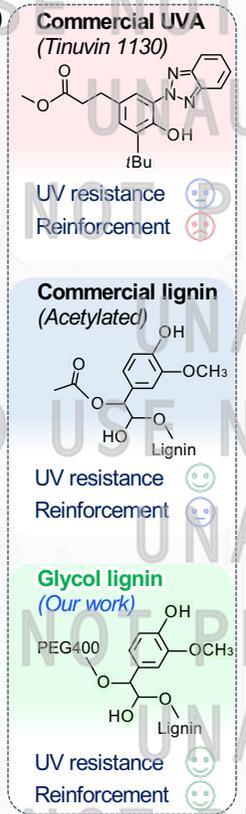
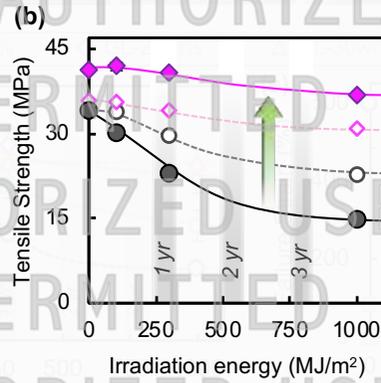
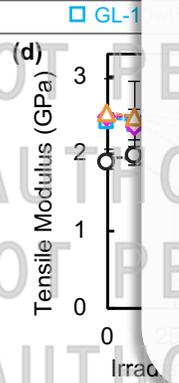
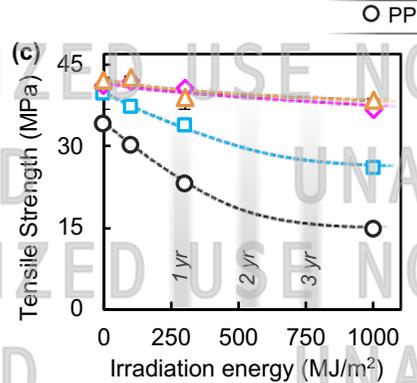
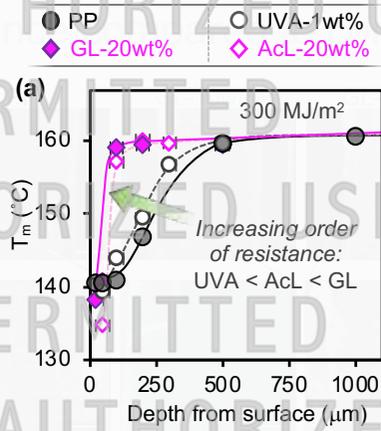
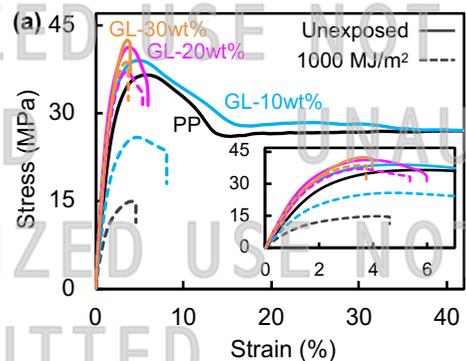


Reactive extrusion



Biomass Blends and Composites

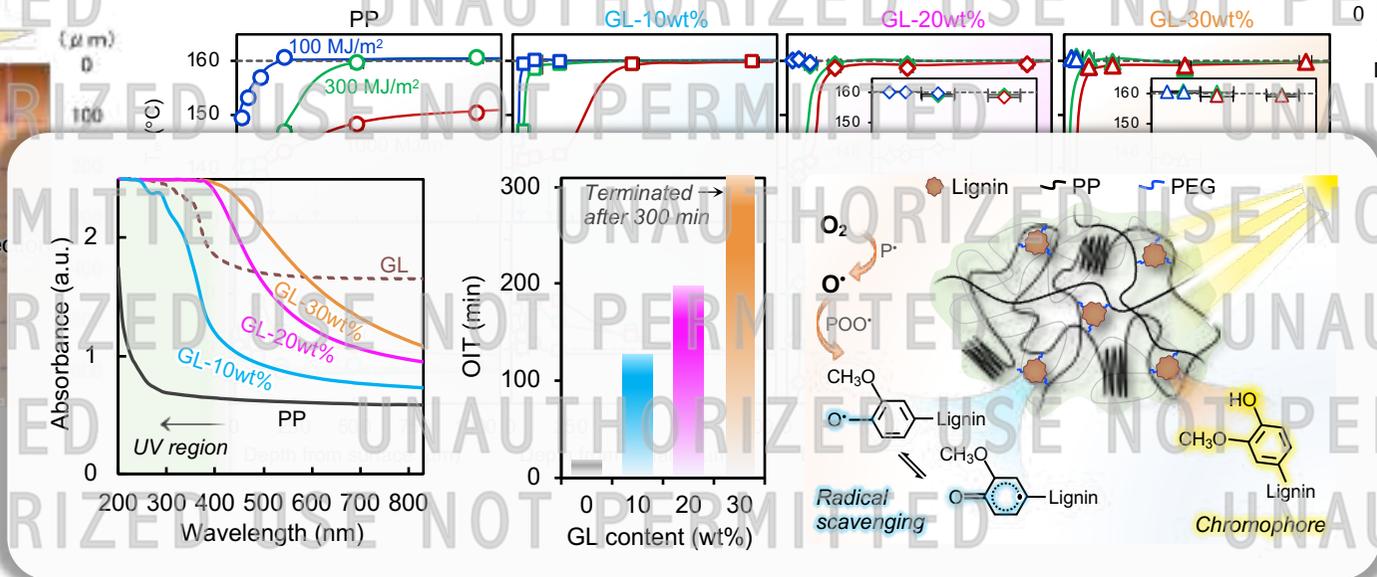
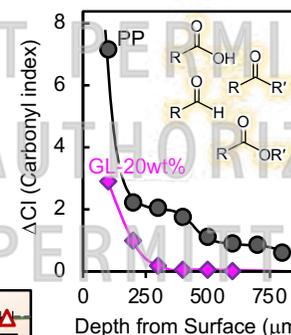
- Mechanical recycling of PP/lignin blends
 - PP/lignin blends show superior UV resistance



Biomass Blends and Composites

- Mechanical recycling of PP/lignin blends

- Lignin limits chain scission to the surface of the bulk specimen.
 - Chain scission progresses through the thickness of neat PP.

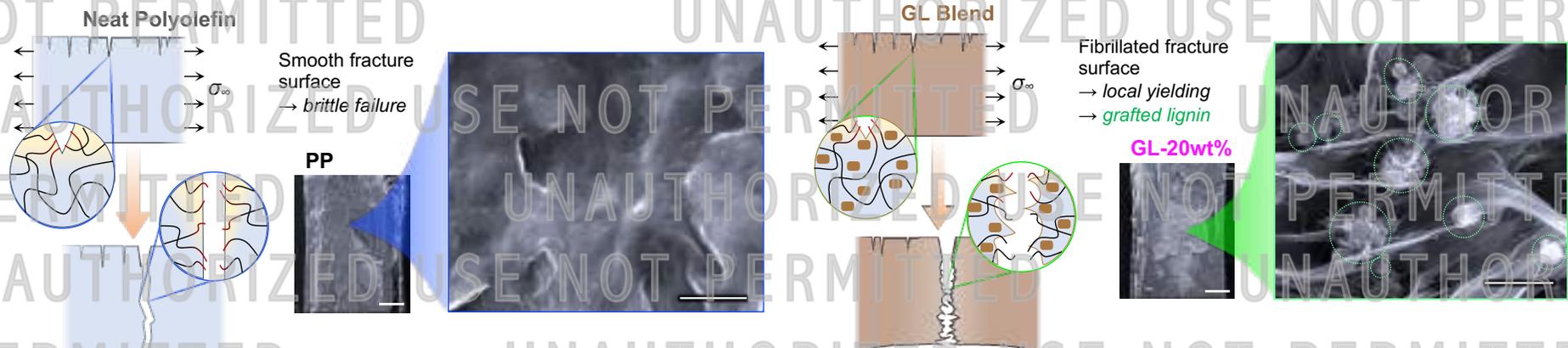
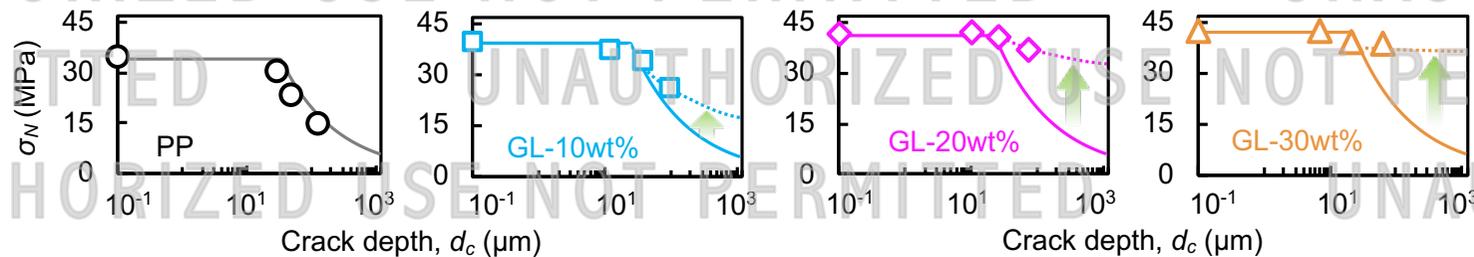


Biomass Blends and Composites

- Mechanical recycling of PP/lignin blends

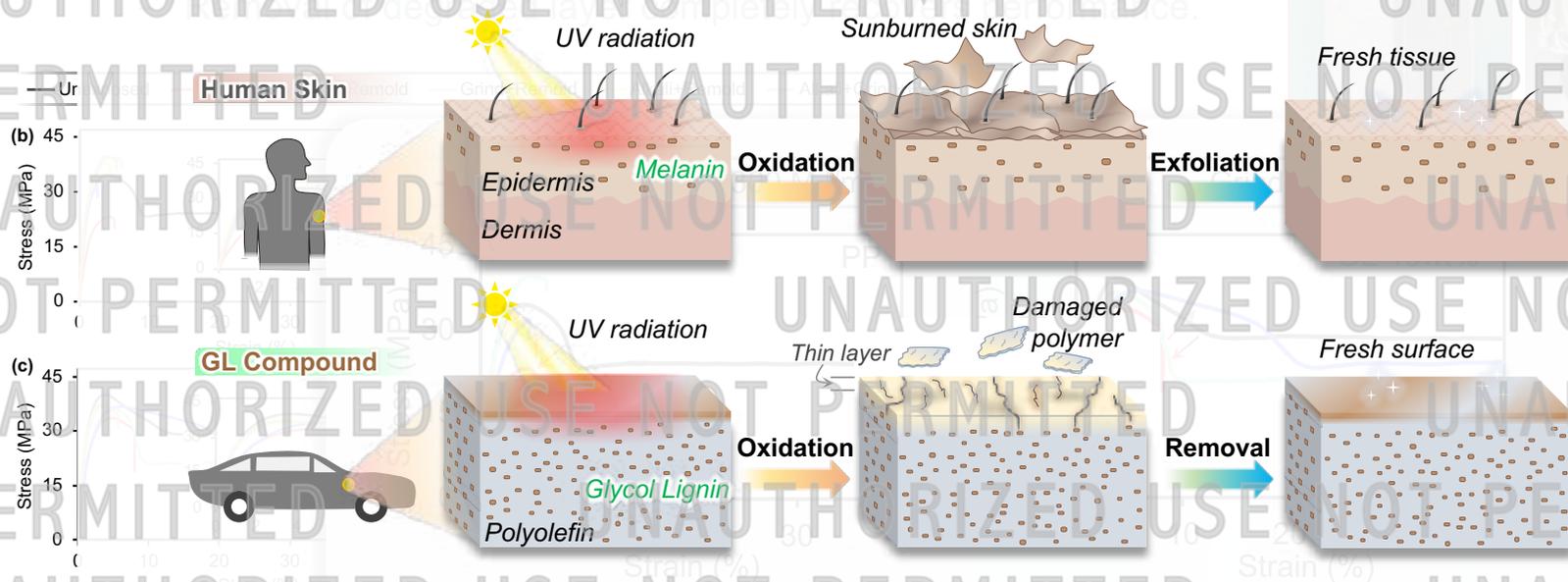
- Lignin suppresses crack growth to the surface of the bulk specimen.

– Crack density increases while crack depth decreases, and toughness increases.



Biomass Blends and Composites

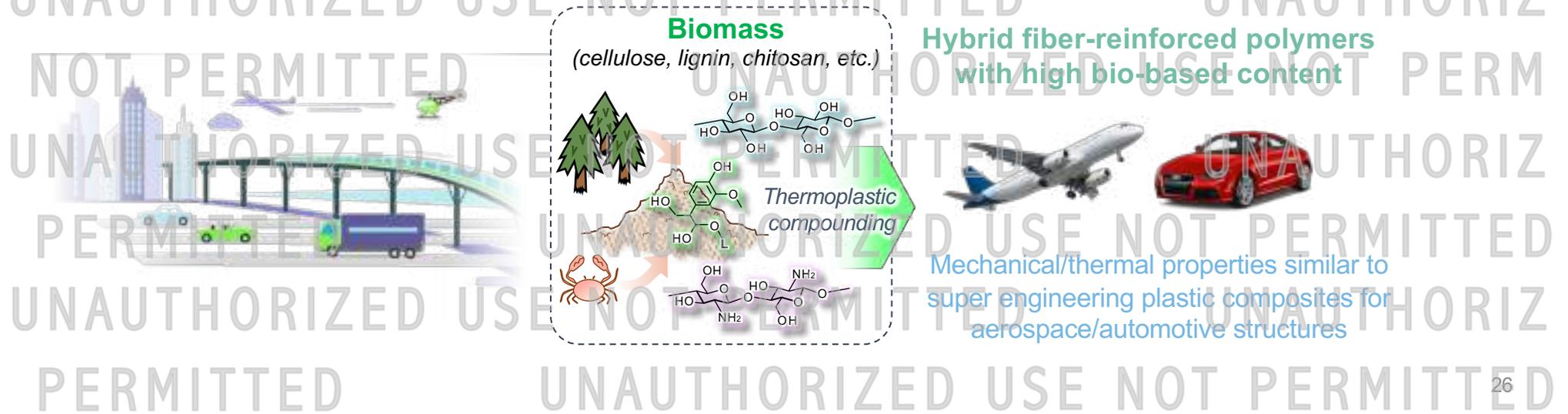
- Mechanical recycling of PP/lignin blends
 - Fully closed-loop recycling is possible with lignin blends



Biomass Blends and Composites

- Current/future research on biomass blends and composites:

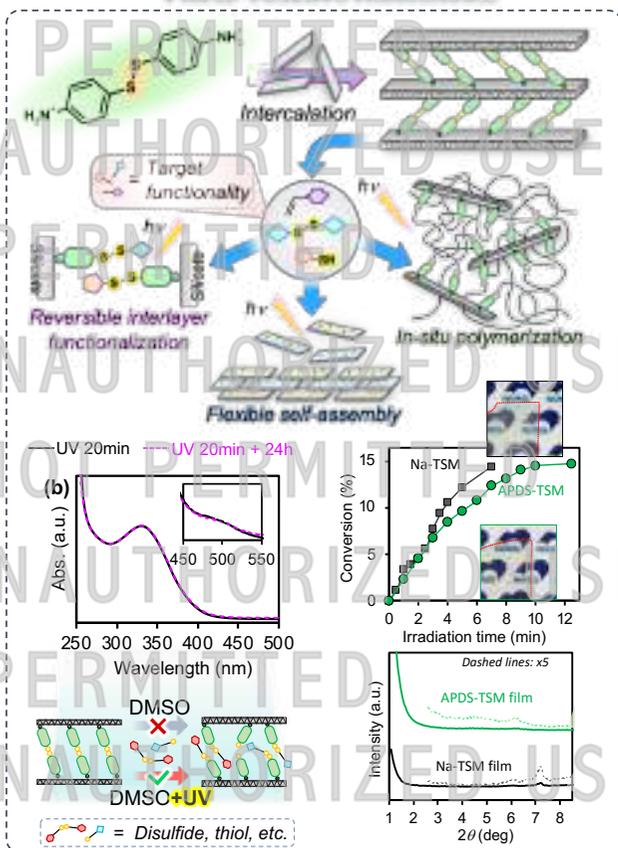
- Precise control over lignin dispersion and blend morphology.
- Using lignin to turn waste plastics into high-performance vitrimers.
- Upcycling of the oxidation products removed from waste materials during recycling.
- All-biomass high-performance composites by controlling interfaces.



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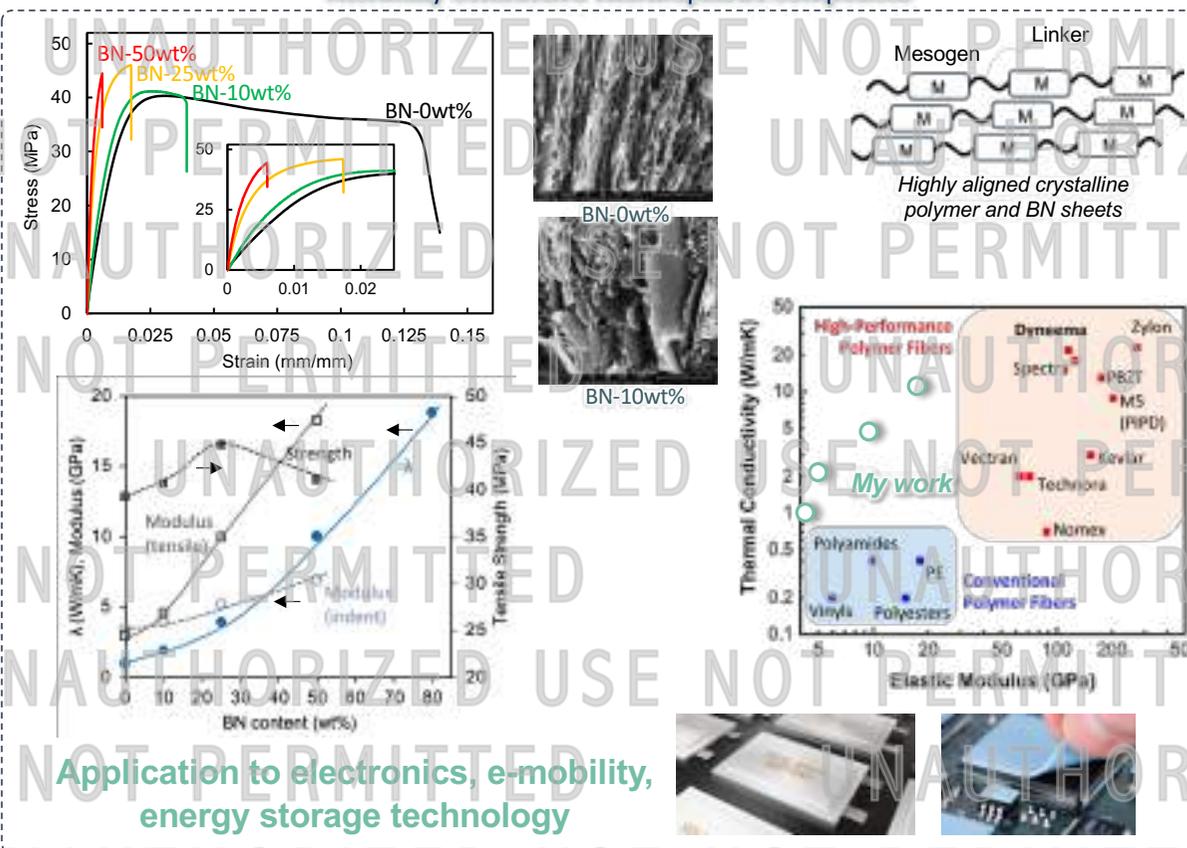
Functional Materials

Photo-reactive Nanosheets



Tanks et al., Bull. Chem. Soc. Jap. 96 (2023) 65.

Thermally Conductive Thermoplastic Composites



Tanks et al., to be submitted (July 2025)

— Thank you for listening —



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