BASF・NAO – IC LECTURE

2025/6/27

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

Introduction

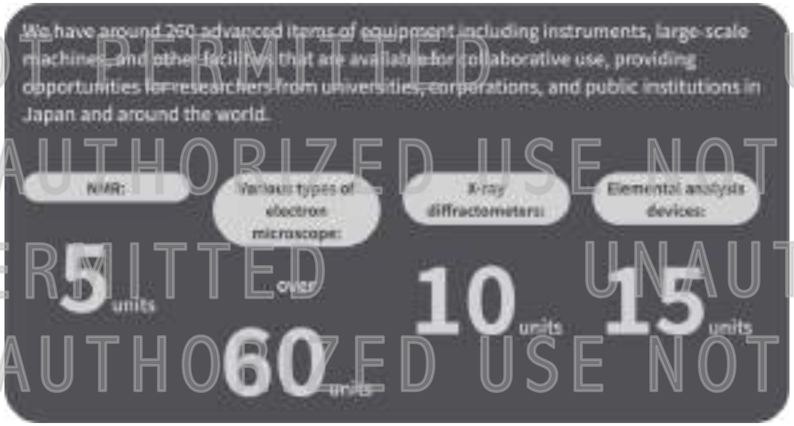
About NIMS

- 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

Top-level facilities



Worldwide academic collaboration

About NIMS

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

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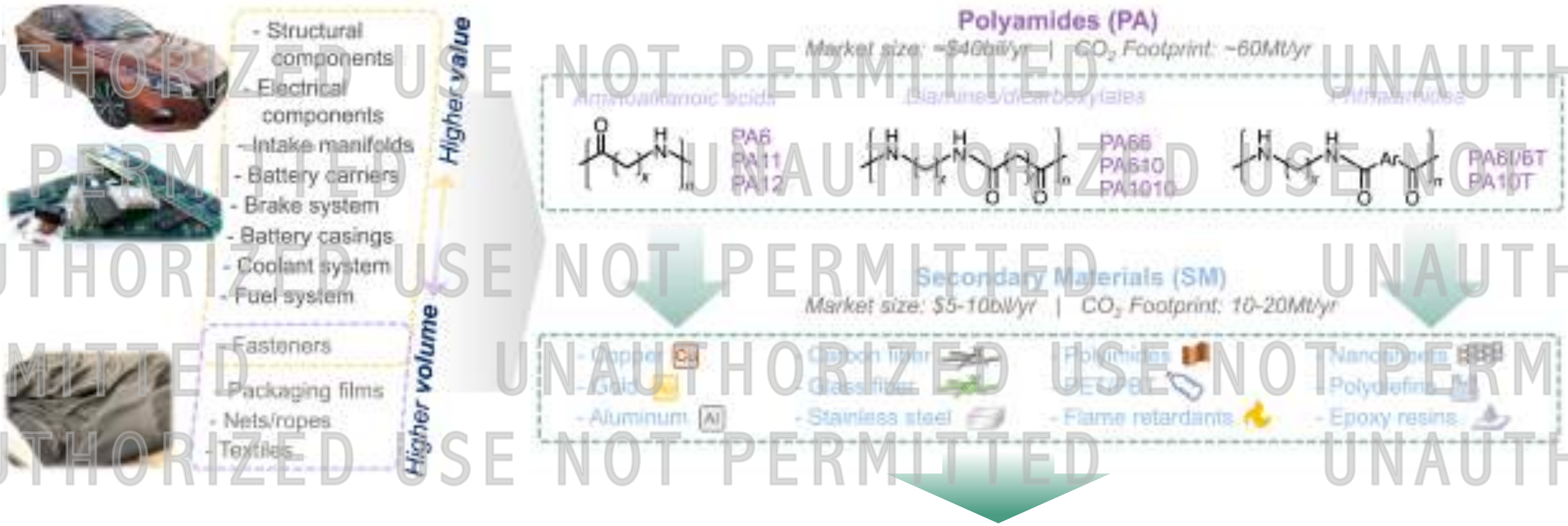
About NIMS

- Research Centers
  - Materials Nanoarchitectonics
  - Magnetic and Spintronic Materials
  - Basic Research on Materials
  - Energy and Environmental Materials
  - Macromolecules and Biomaterials
  - Structural Materials
    - Polymer Matrix Composites Group (Tanks)
  - Electronic and Optical Materials

Sustainability Challenges for Polymers and Composites

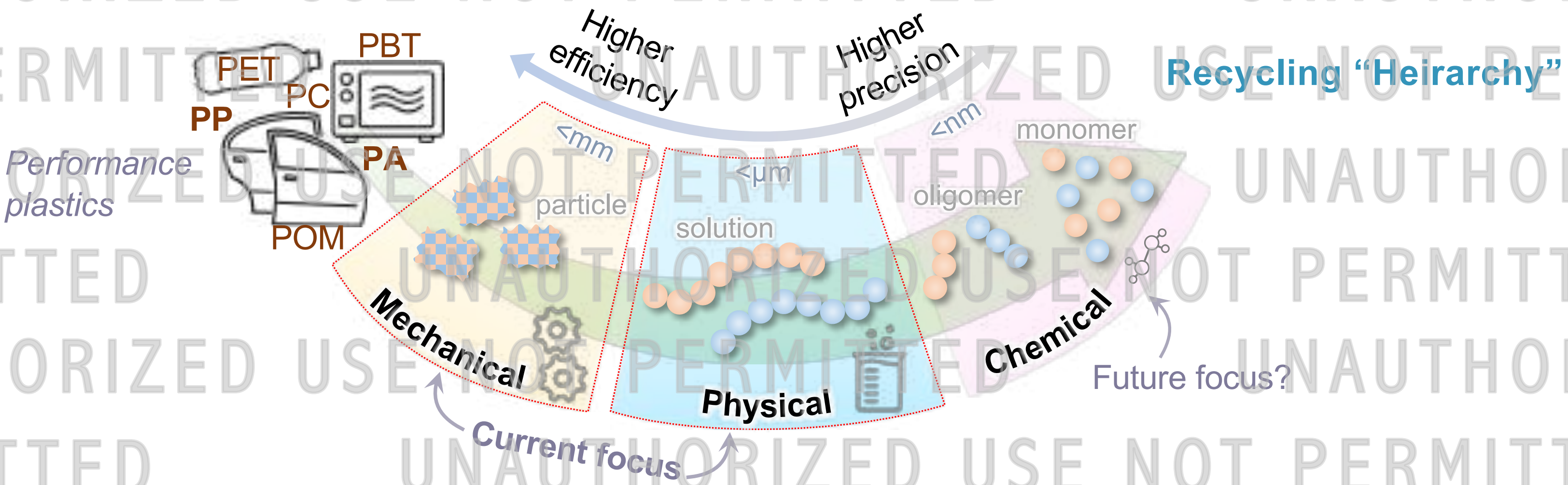
- Composition of blends/composites is designed to meet target performance.
  - Demanding applications: automotive, electrical/electronic, energy, aerospace
    - Density, strength/modulus, heat resistance, electrical resistance, processability, energy storage
  - Blend/composite for target performance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



Reuse existing plastics + recover secondary materials

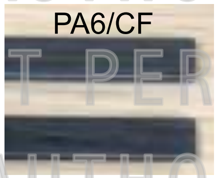
Sustainability Challenges for Polymers and Composites

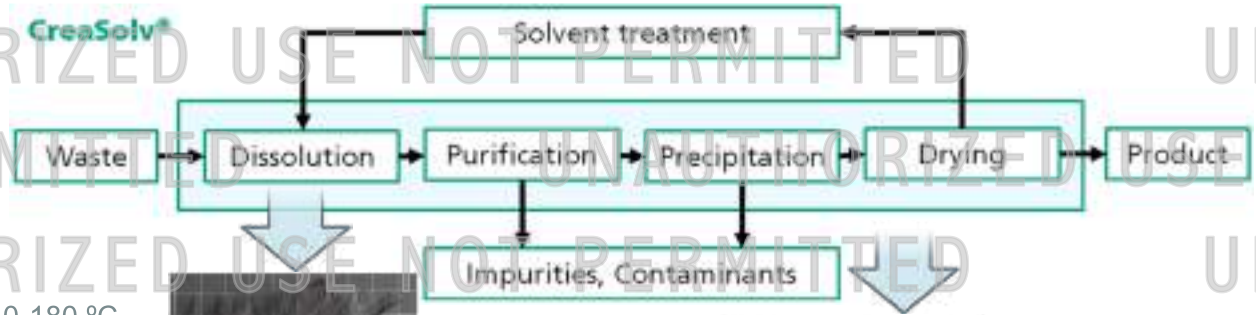
- The optimum recycling approach depends on the material(s) and application(s).
  - PP, PA, PBT etc. in demanding applications are often mixed with other materials.
    - Separation and purification can be difficult depending on waste stream.
  - There is a spectrum in terms of efficiency vs quality/precision.
    - 「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 CO_2-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.





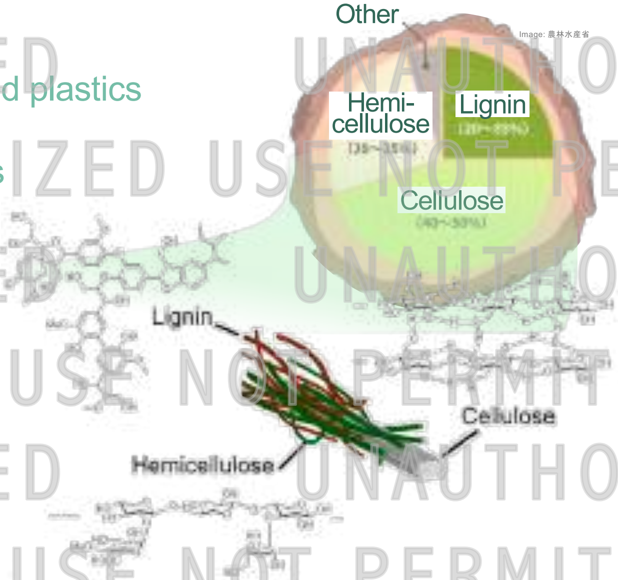
Temp: 140-180 °C
Time: 1-3 hr
Solids: 10 wt%
Solvents: Polar-protic, Polar-aprotic

Waste Management **85** (2019) p.73

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)

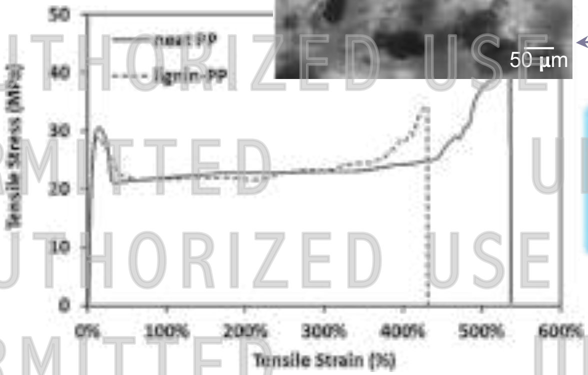
Sustainability Challenges for Polymers and Composites

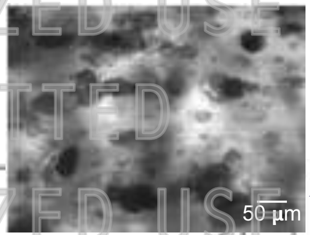
- Poor compatibility remains an issue for many biomass blends/composites.
  - Biomass (lignin) blends suffer from poor compatibility with polyolefins, nylons etc.
    - Agglomerations lead to reduced mechanical properties.
  - Chemical modification of lignin is only one part of the picture.
    - Alkylation,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

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

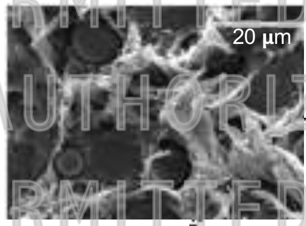
Specimen Label	Tensile Strength, MPa	Tensile Modulus, GPa
10SKL/MAPP	20.25 ± 0.68	1.04 ± 0.17
30SKL/MAPP	20.23 ± 1.23	1.19 ± 0.18
50SKL/MAPP	16.36 ± 2.37	1.76 ± 0.33
PP	24.87 ± 0.52	1.24 ± 0.11

J. Ind. Eng. Chem. **31** (2015) p. 80.

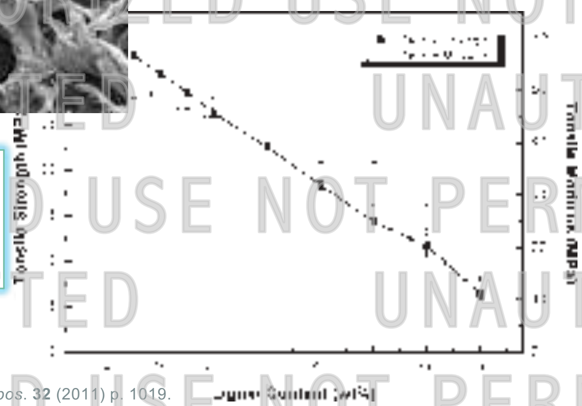




Large agglomerations



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

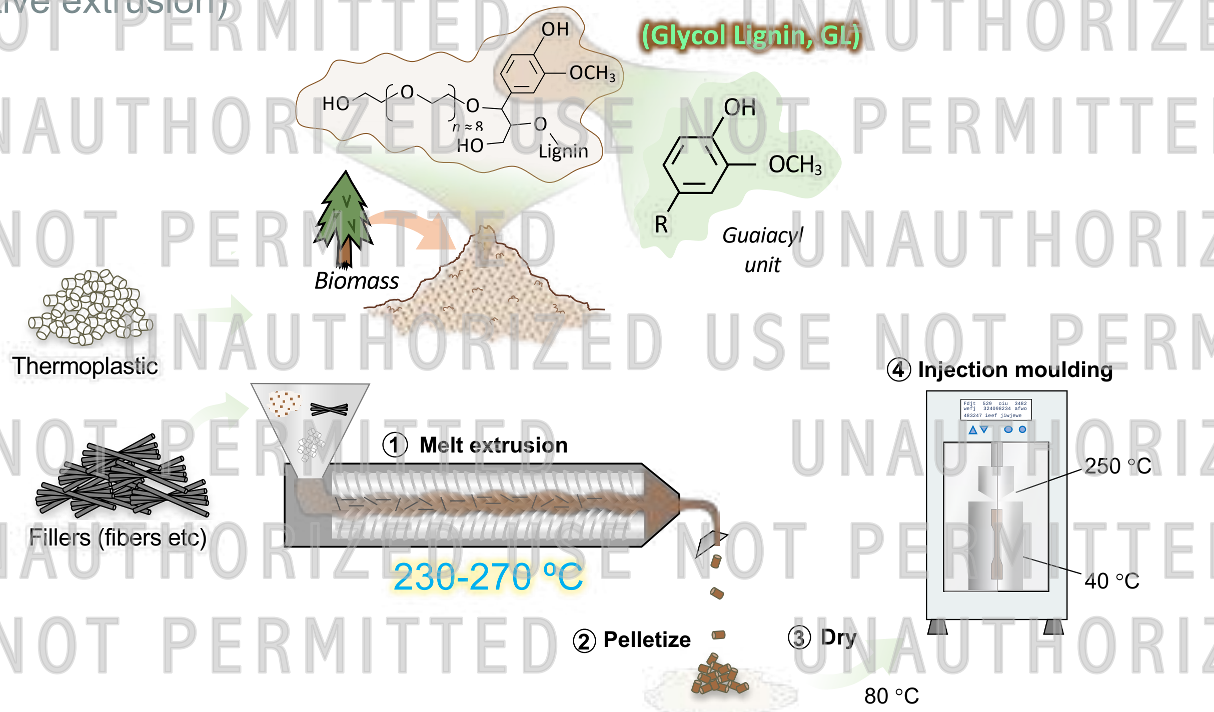


Polym. Compos. **32** (2011) p. 1019.

Biomass Blends and Composites

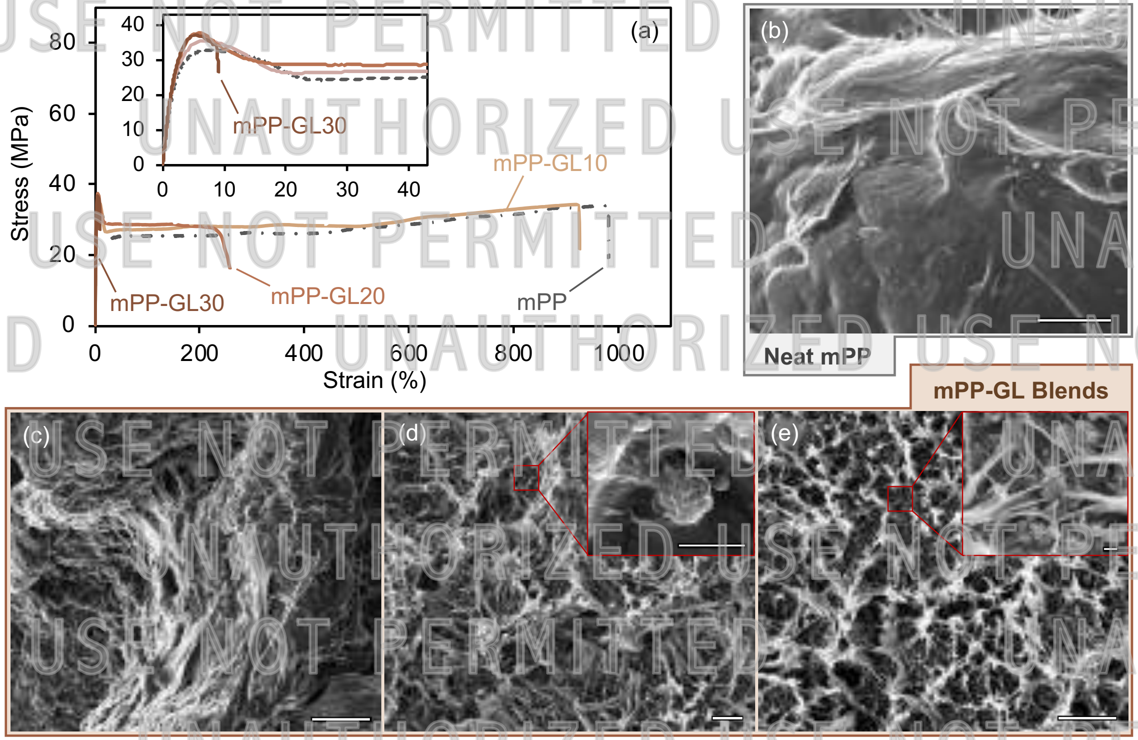
Biomass Blends and Composites

- 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 ºC
    - PA6I/6T: 250-270 ºC
  - Mix at high temperature
    - PP: 235-245 ºC
    - PA6: 240-250 ºC
    - PA11: 230-240 ºC
    - PA6I/6T: 250-270 ºC



Biomass Blends and Composites

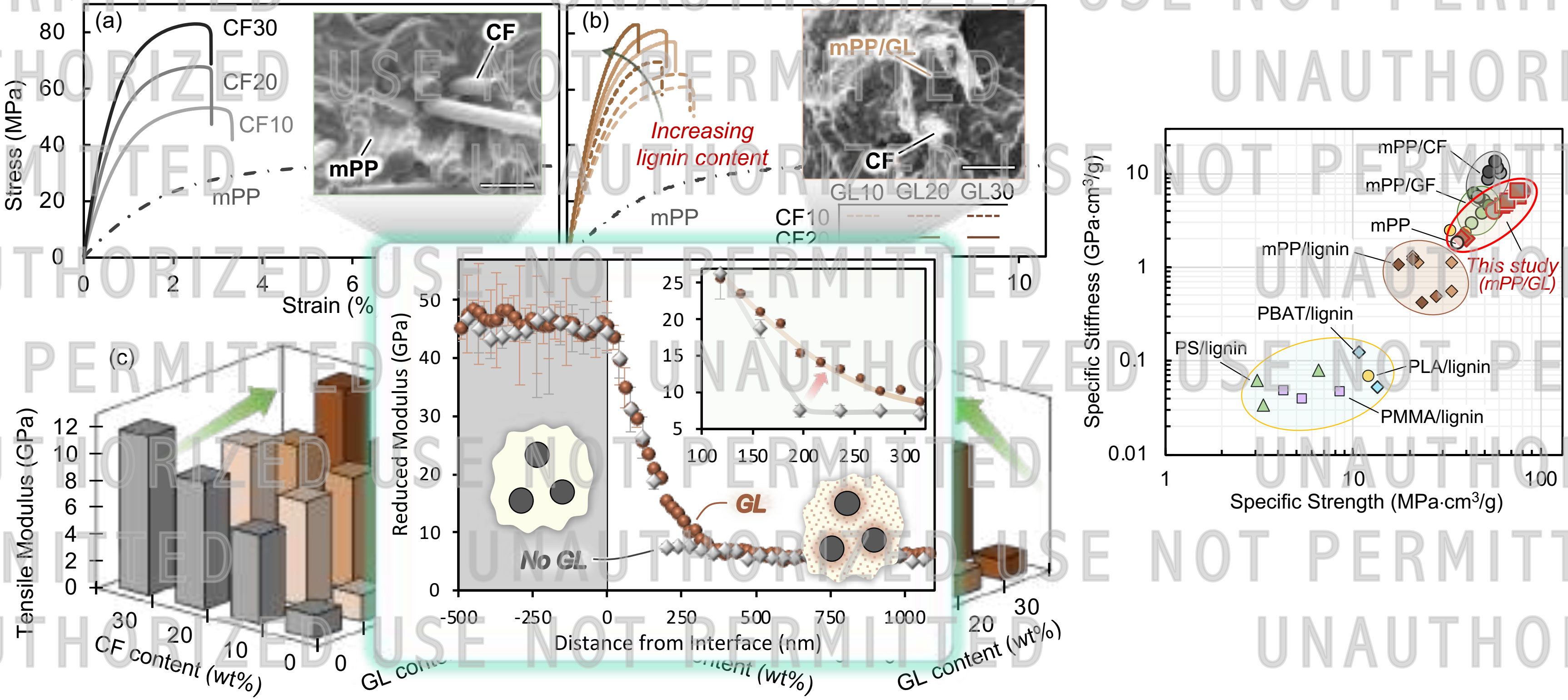
- PP/Lignin blends and composites
  - Sub-micron lignin domains covalently grafted to MAH-*g*-PP



Tanks et al., *Compos. Sci. Technol.* 238 (2023) p. 110030

Biomass Blends and Composites

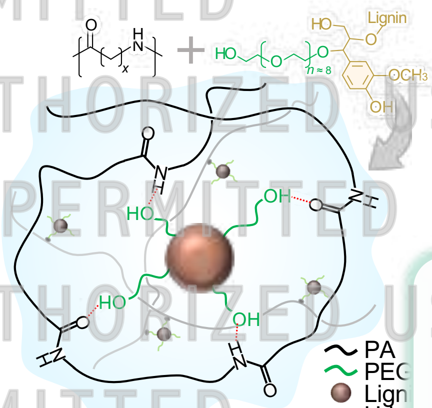
- PP/Lignin blends and composites

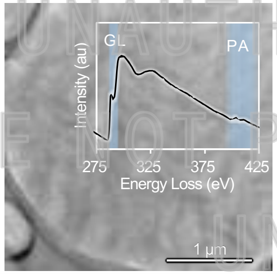


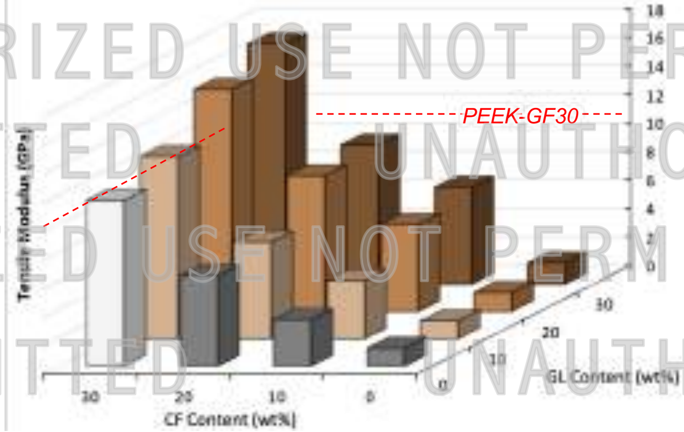
Tanks et al., *Compos. Sci. Technol.* 238 (2023) p. 110030

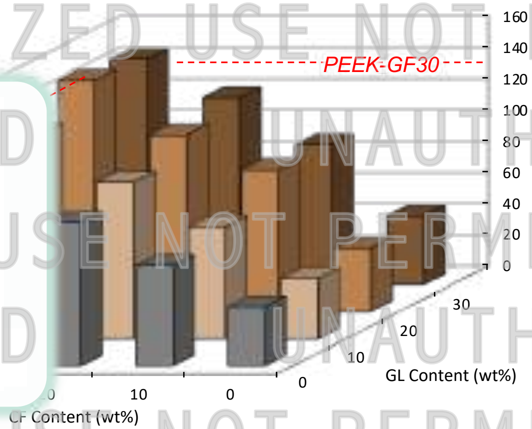
Biomass Blends and Composites

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





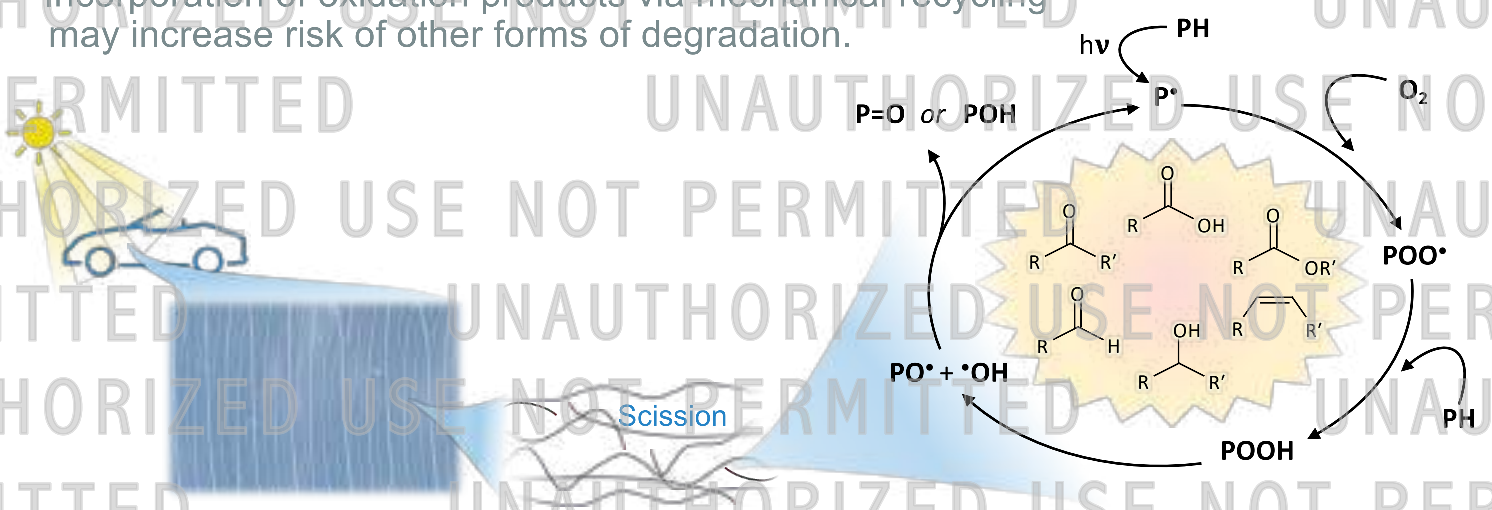




Tanks et al. *under review (2025)*

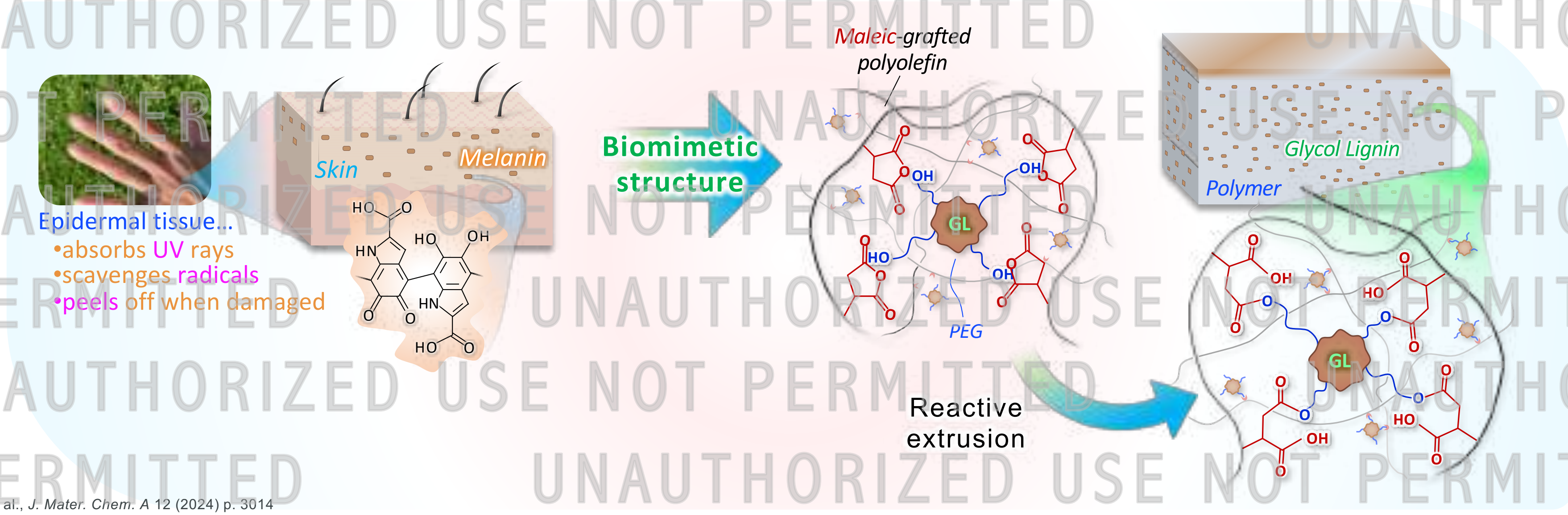
Biomass Blends and Composites

- 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

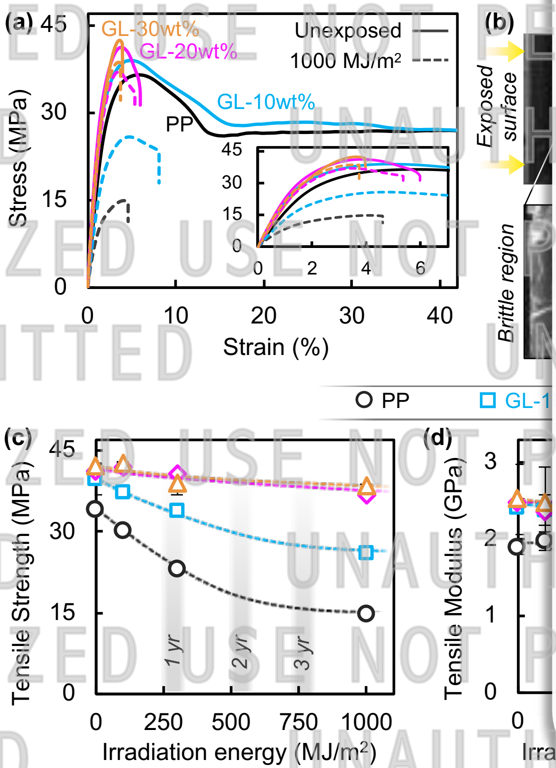
- Mechanical recycling of PP/lignin blends
  - Lignin can act as a simultaneous UV absorber, radical scavenger, and reinforcement.
    - Mimics melanin in the human skin.
  - Non-toxic alternative to conventional stabilizers (Irganox, Tinuvin etc).
    - Moderate molecular weight and polymer interaction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

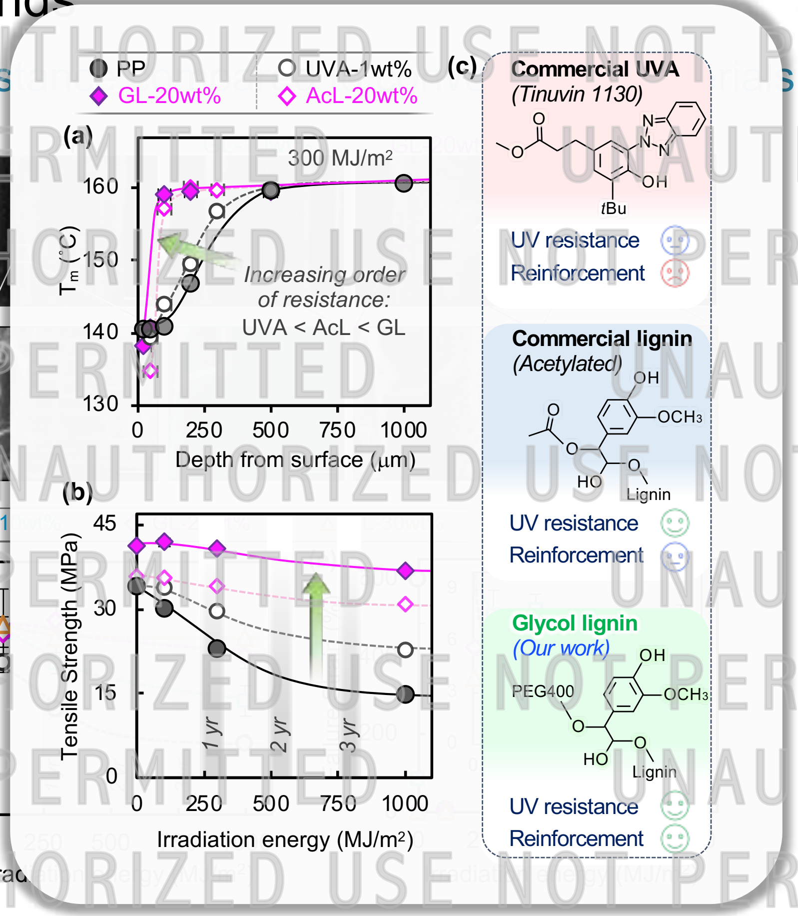


Tanks et al., *J. Mater. Chem. A* 12 (2024) p. 3014

Biomass Blends and Composites

- Mechanical recycling of PP/lignin blends
  - PP/lignin blends show superior UV resis … s.

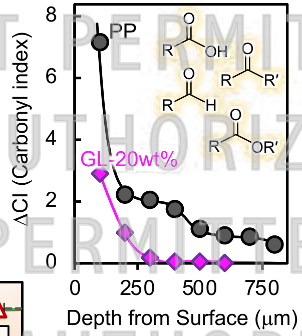


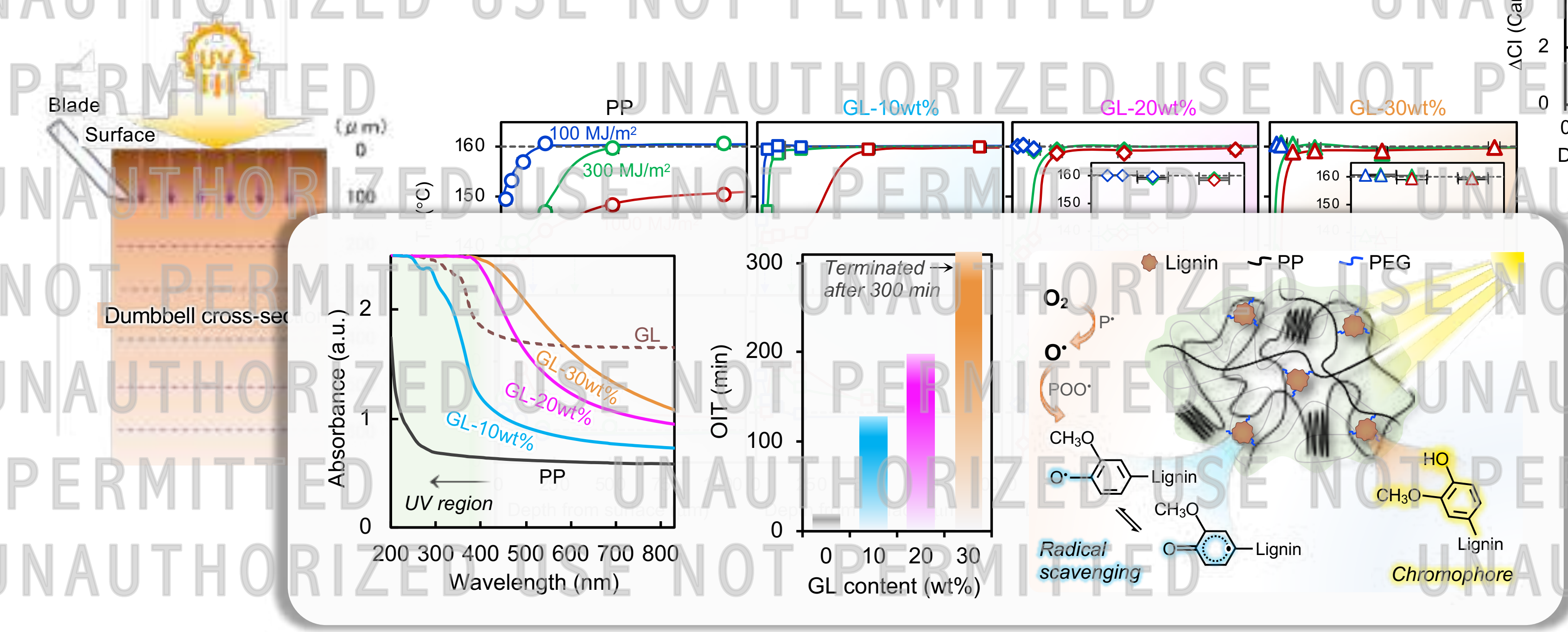


Tanks et al., *J. Mater. Chem. A* 12 (2024) p. 3014

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.

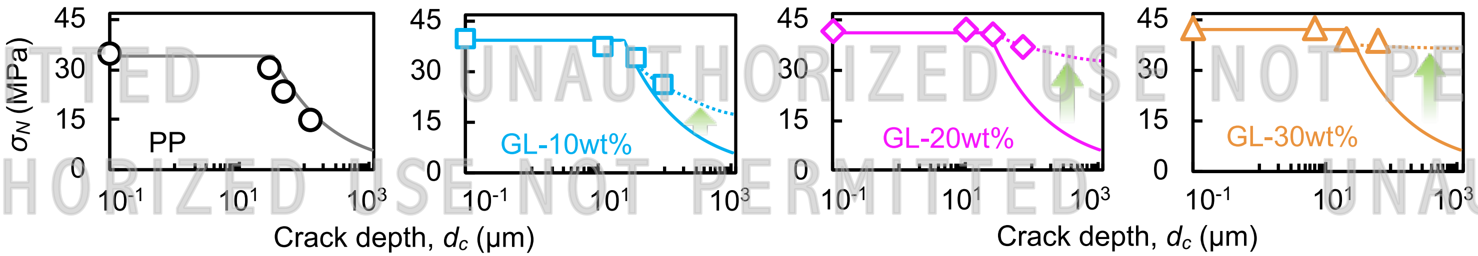


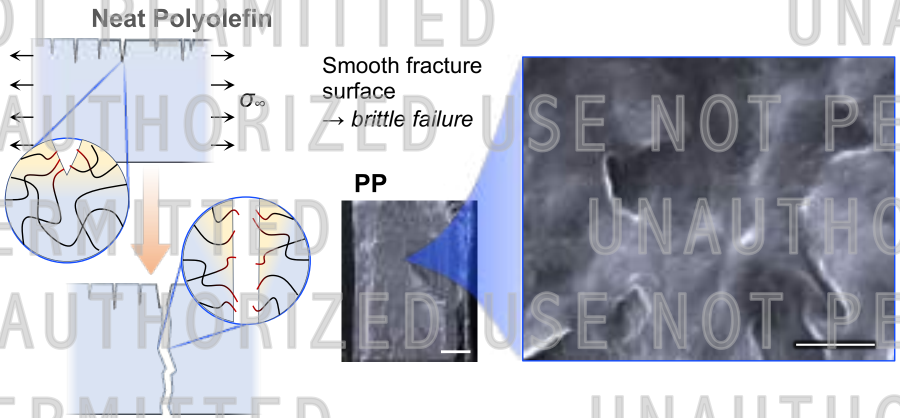


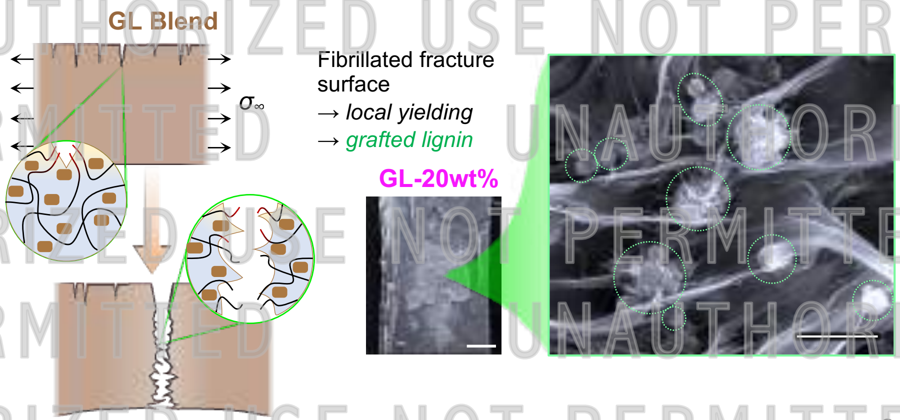
Tanks et al., *J. Mater. Chem. A* 12 (2024) p. 3014

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.



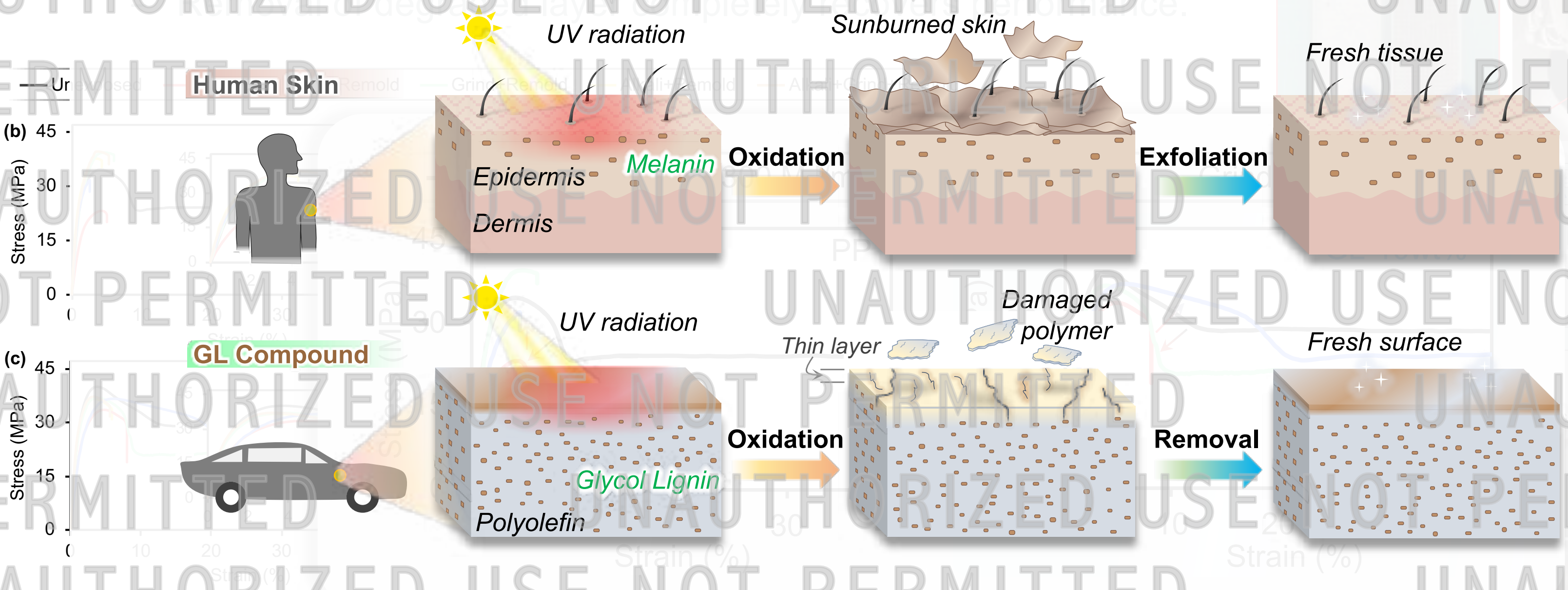




Tanks et al., *J. Mater. Chem. A* 12 (2024) p. 3014

Biomass Blends and Composites

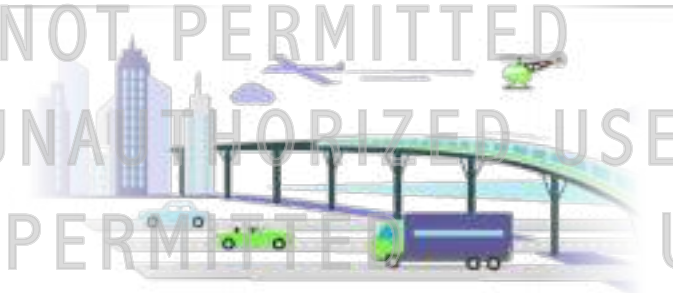
- Mechanical recycling of PP/lignin blends
  - Fully closed-loop recycling is possible with lignin blends

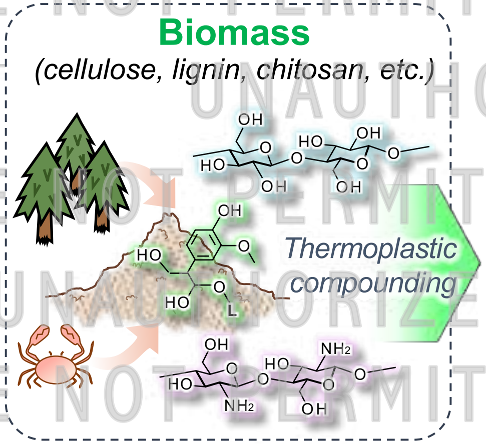


Tanks et al., *J. Mater. Chem. A* 12 (2024) p. 3014

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.





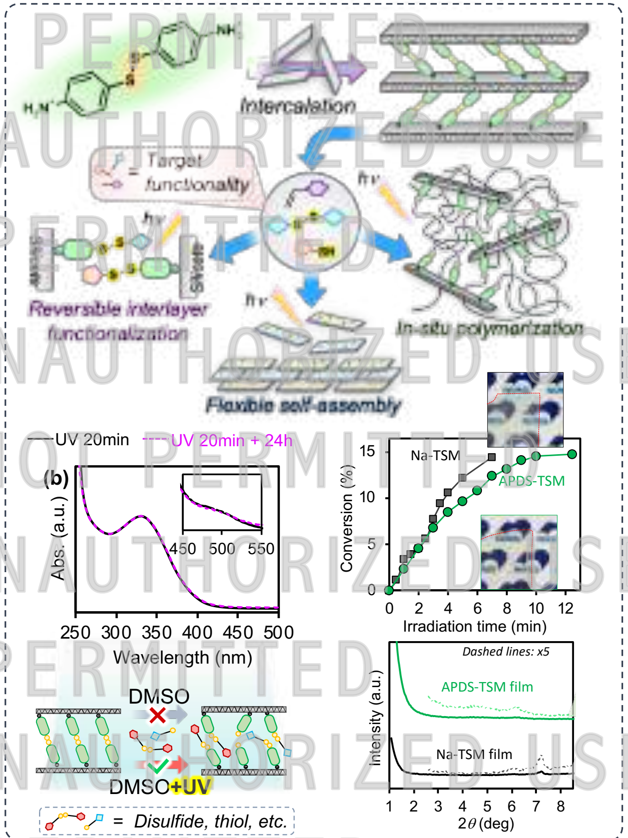
Hybrid fiber-reinforced polymers with high bio-based content

Mechanical/thermal properties similar to super engineering plastic composites for aerospace/automotive structures

Functional Materials

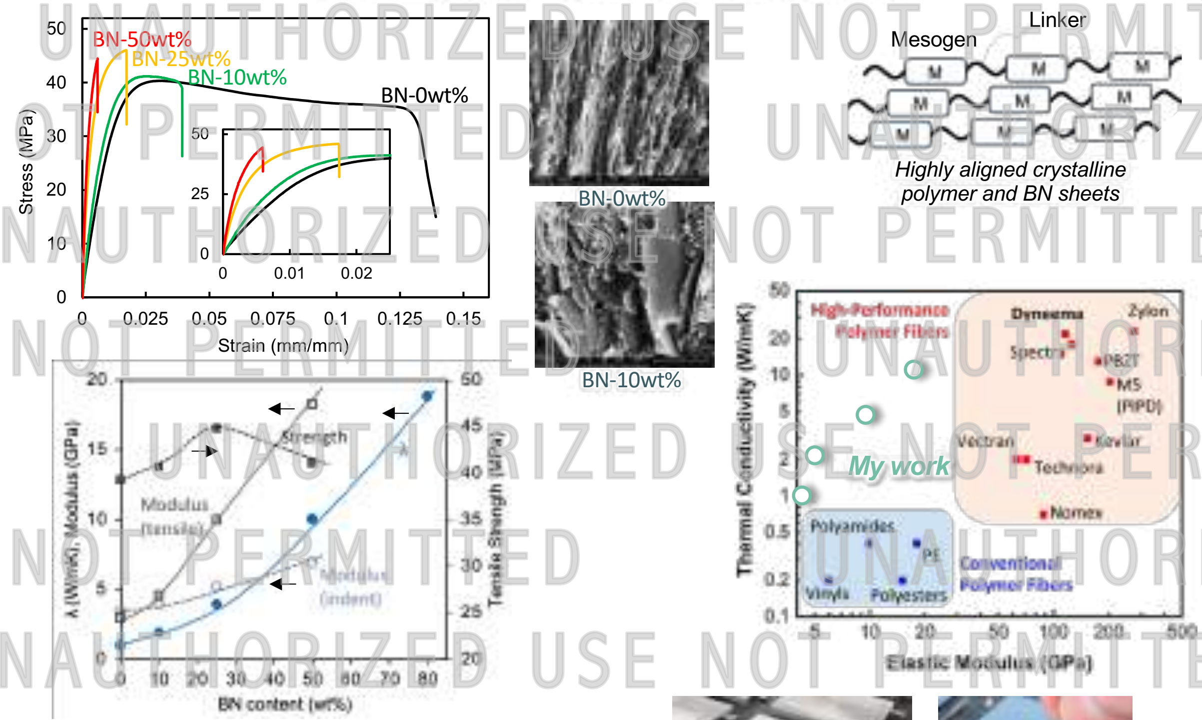
Functional Materials

Photo-reactive Nanosheets



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

Thermally Conductive Thermoplastic Composites



Application to electronics, e-mobility, energy storage technology

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

— Thank you for listening —

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