Technical Challenges to Reduce Energy Use in the Production of Paper

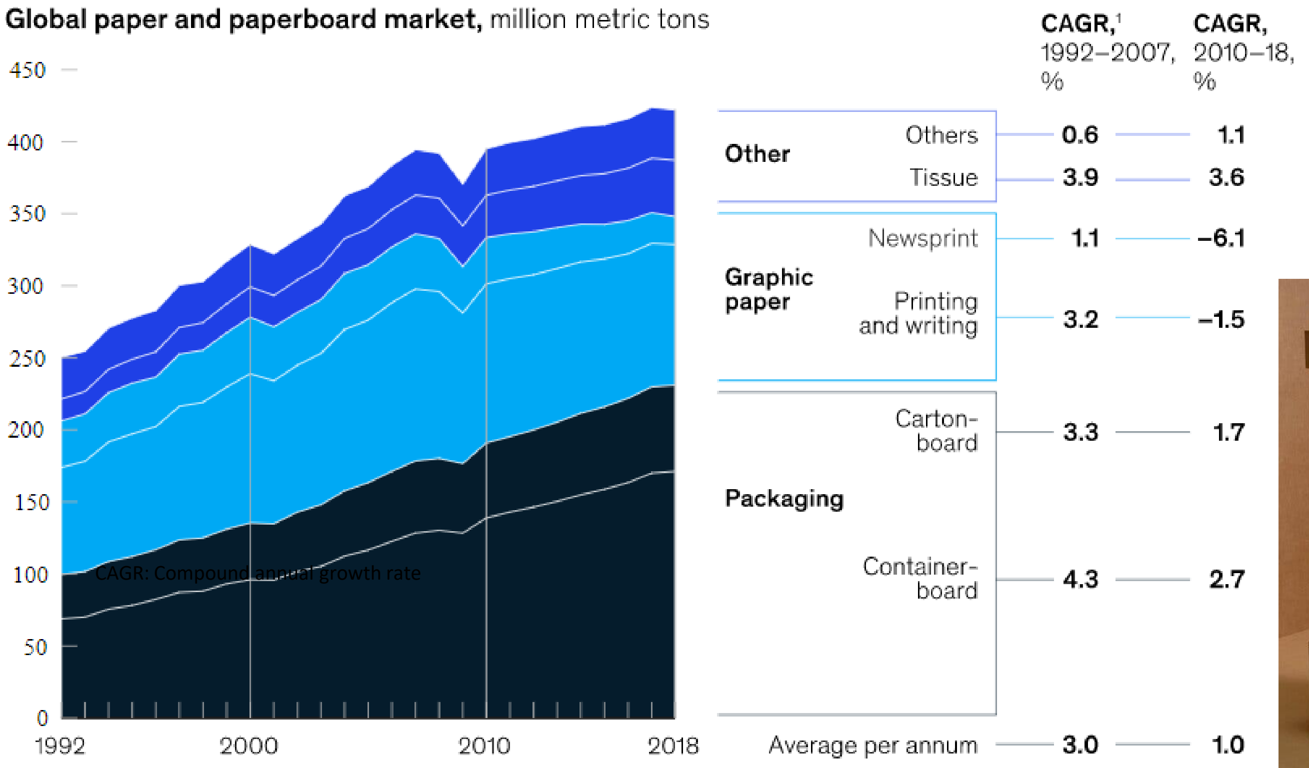
U.S. DOE IEDO Decarbonization Challenges and Priorities in Forest Products Industry Workshop, Atlanta, GA

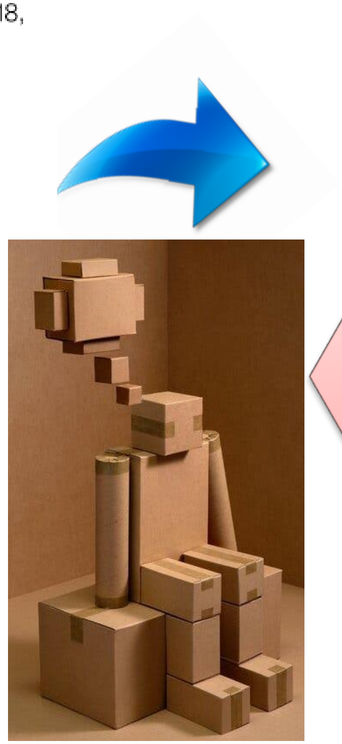
Dr. Lokendra Pal, EJ Woody Rice Professor, Department of Forest Biomaterials | NC State University Faculty Scholar | Director, Paper Pilot Plant Smart Manufacturing Innovation (P3-SMIC) | Co-Director, Tissue Pack Innovation Lab (TPIL)

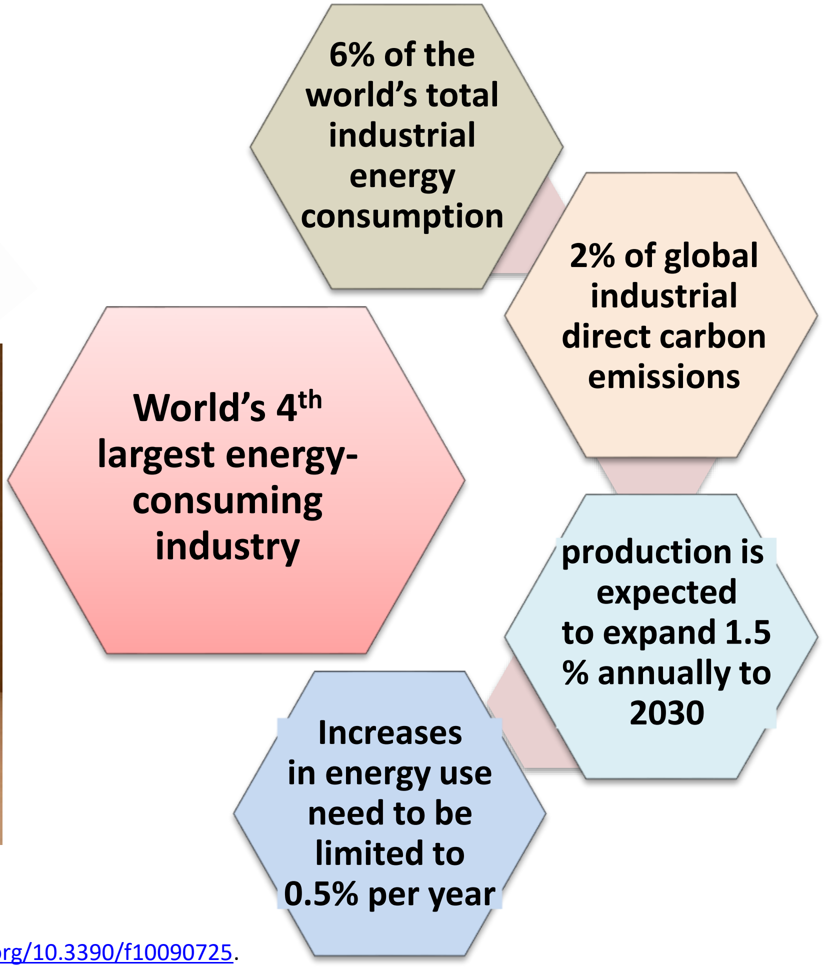
Email: Lokendra_pal@ncsu.edu

Pulp and Paper Industry (PPI) - Contribution and Challenges

- PPI is a global $360 billion business and continues to grow despite the decline in the graphic paper segment.
- The energy use varies by product and mill type. The Industry needs to break the dependency on fossil sources and improve the generation and use of energy.







(1) IEA. Pulp & paper - Fuels & Technologies. https://www.iea.org/fuels-and-technologies/pulp-paper
(2) IEA (2021), Tracking Industry 2021, IEA, Paris https://www.iea.org/reports/tracking-industry-2021
(3) Zhao, Q.; Ding, S.; Wen, Z.; Toppinen, A. Energy Flows and Carbon Footprint in the Forestry-Pulp and Paper Industry. *Forests* **2019**, *10* (9). https://doi.org/10.3390/f10090725.
(4) McKinsey & Company. https://www.mckinsey.com/industries/paper-forest-products-and-packaging/our-insights/pulp-paper-and-packaging-in-the-next-decade-transformational-change

PPI Process Heating

- Over 55% of the processed energy consumed goes to process heating. The temperature can vary widely from less than 200 °C for process heating, at about 500 °C for steam boilers, and 800 °C or higher in lime kilns operations.
- In pulp mills, the lime kiln is typically the dominant energy-demanding operation using fossil fuels. Its operation requires high temperatures of ~ 800 °C at the calcination zone of the kiln, which is reached by combusting oil and natural gas.
- In paper mills, the drying section of the paper machine is the highest thermal energy consumer with many complex configurations such as multi-cylinder dryers (steam cans) for paper and packaging grades drying; Yankee and through air-dryers (TAD) for tissue and towels products; and air caps and IR dryers for coated paper drying.
- The drying process temperature can range from average 150 °C for multicylinder dryers heated with low-pressure steam to 1000 °C for IR dryers powered by natural gas heaters.

Barrios, N., Marquez, R., McDonald, J.D., Hubbe, M.A., Venditti, R.A., Pal, L.*, Innovation in lignocellulosics dewatering and drying for energy sustainability and enhanced utilization of forestry, agriculture, and marine resources - A review, Advances in Colloid and Interface Science, 2023, 102936, ISSN 0001-8686, https://doi.org/10.1016/j.cis.2023.102936.

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Paper Grades Design and Various Inputs

- The production of paper, packaging, and hygiene products depends on the sources of fiber raw materials, the processing chemicals, the degree of processing, and the manufacturing technology.
- The properties of various lignocellulose fibers change significantly during pulping and papermaking when subjected to chemical/ mechanical pulping, refining, pressing, drying, creping, surface and bulk treatments, converting, or repulping.

Salem, K.H., Jameel, H., Lucia, L., Pal, L.*, "Sustainable high-yield lignocellulosic fibers and modification technologies educing softness and strength for tissues and hygiene products for global health," Materials Today Sustainability, V(22), 2023, 100342, ISSN 2589-2347, https://doi.org/10.1016/j.mtsust.2023.100342.

Salem, K.S., Naithani, V., Jameel, H. Lucia, L, Pal, L.* (2022) A Systematic Examination of the Dynamics of Water- Cellulose Interactions on Capillary Force-Induced Fiber Collapse, Carbohydrate Polymers, 295, 119856, https://doi.org/10.1016/j.carbpol.2022.119856.119856.

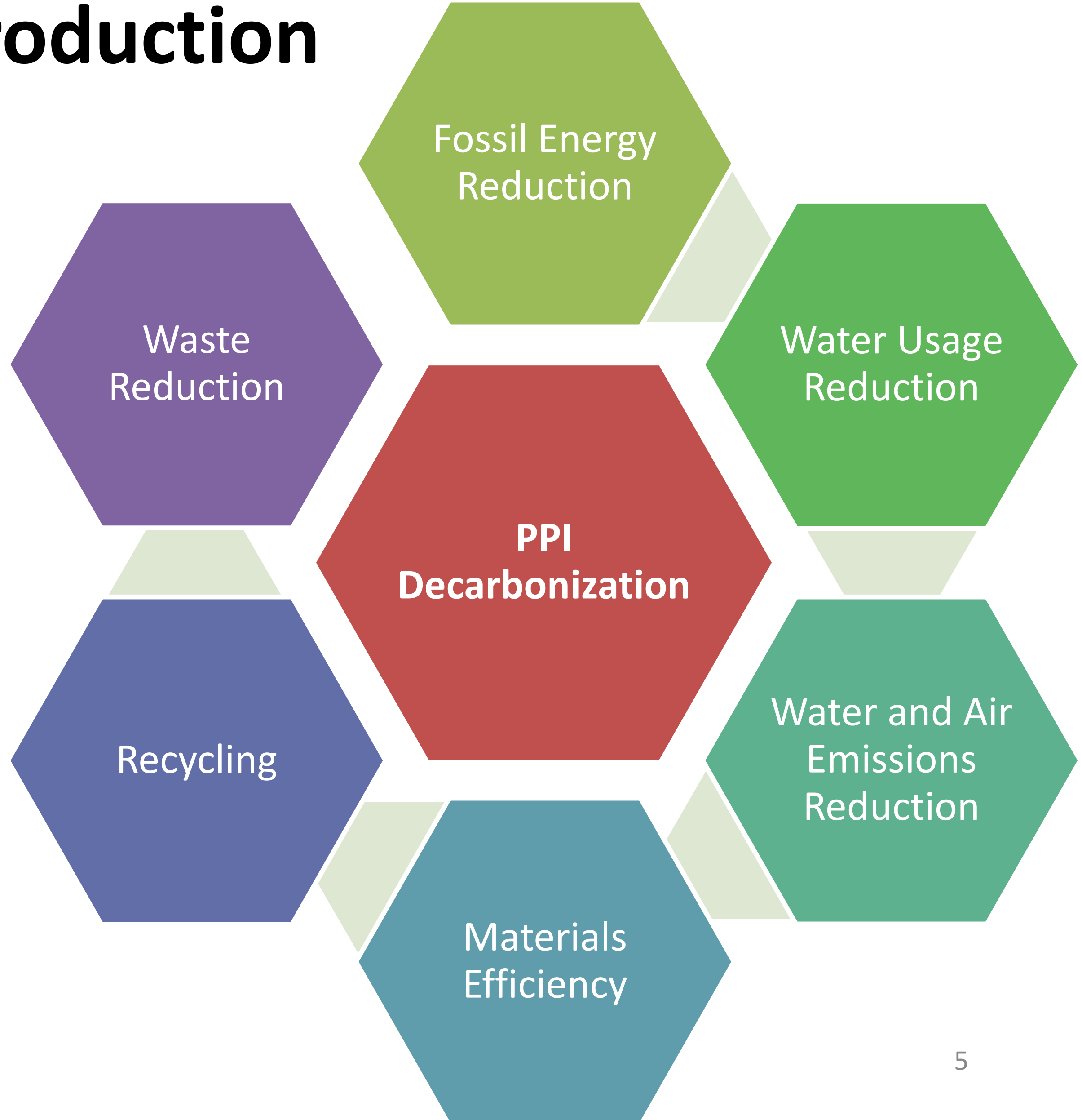
Salem, K.S., Naithani, V., Jameel, H. Lucia, L, Pal, L.* (2020) Lignocellulosic Fibers from Renewable Resources Using Green Chemistry for a Circular Economy, Global Challenges, https://doi.org/10.1002/gch2.202000065

V. Naithani, P. Tyagi, H. Jameel, L.A. Lucia, L. Pal, Ecofriendly and Innovative Processing of Hemp Hurds Fibers for Tissue and Towel Paper, BioResources. 15 (2020) 706–720.

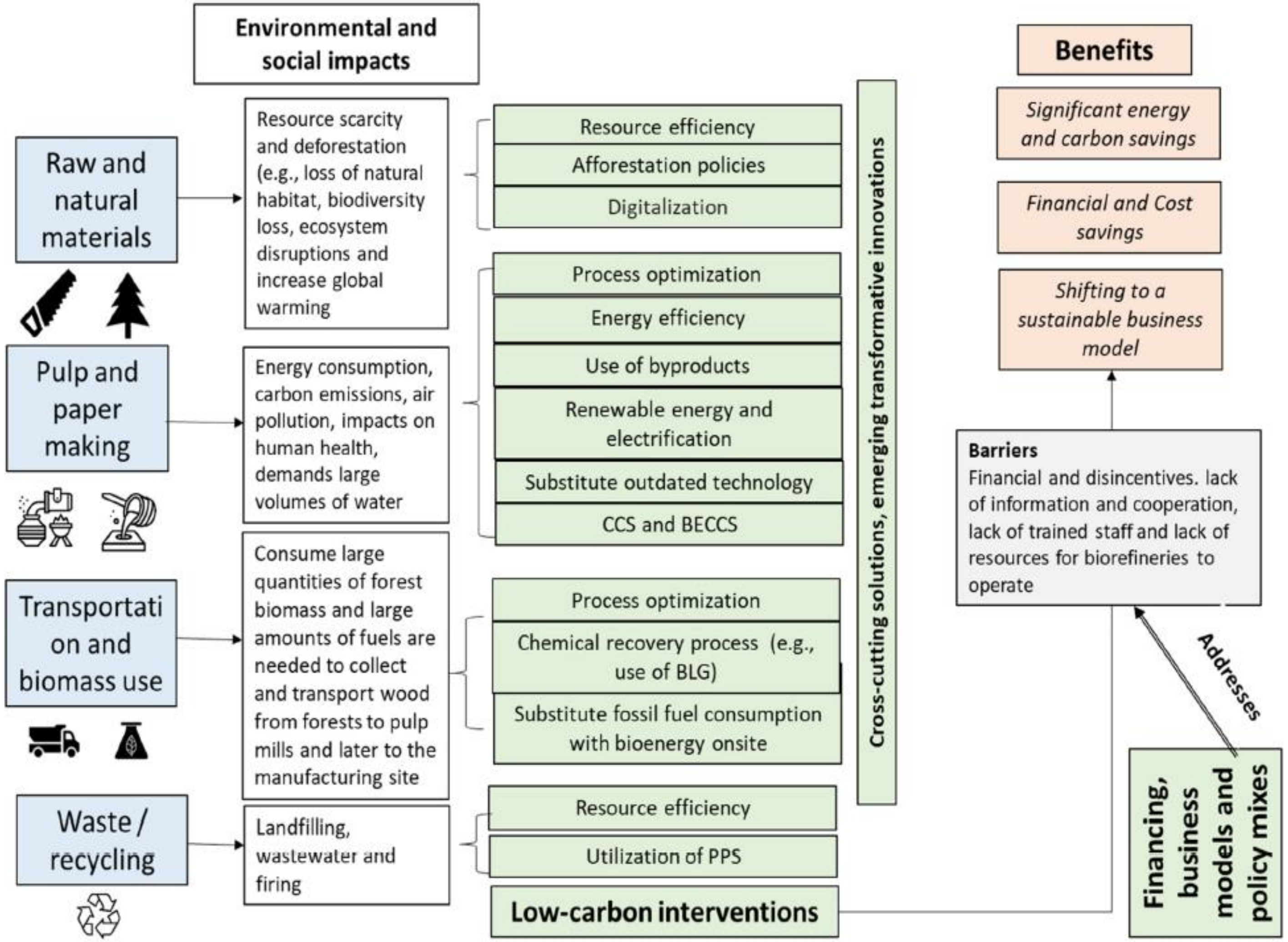
PPI Decarbonization – Paper Production

In the pursuit of PPI decarbonization, beyond just reducing energy consumption, there's a significant emphasis on curtailing water usage, minimizing both air and water pollution, conserving natural resources, and decreasing the volume of waste destined for landfills.

Enhancing energy efficiency and reducing the consumption of raw materials, water, and waste byproducts are pivotal strategies. These efforts not only lead to a reduction in GHG emissions but also result in lower operational costs while maintaining the desired output levels.



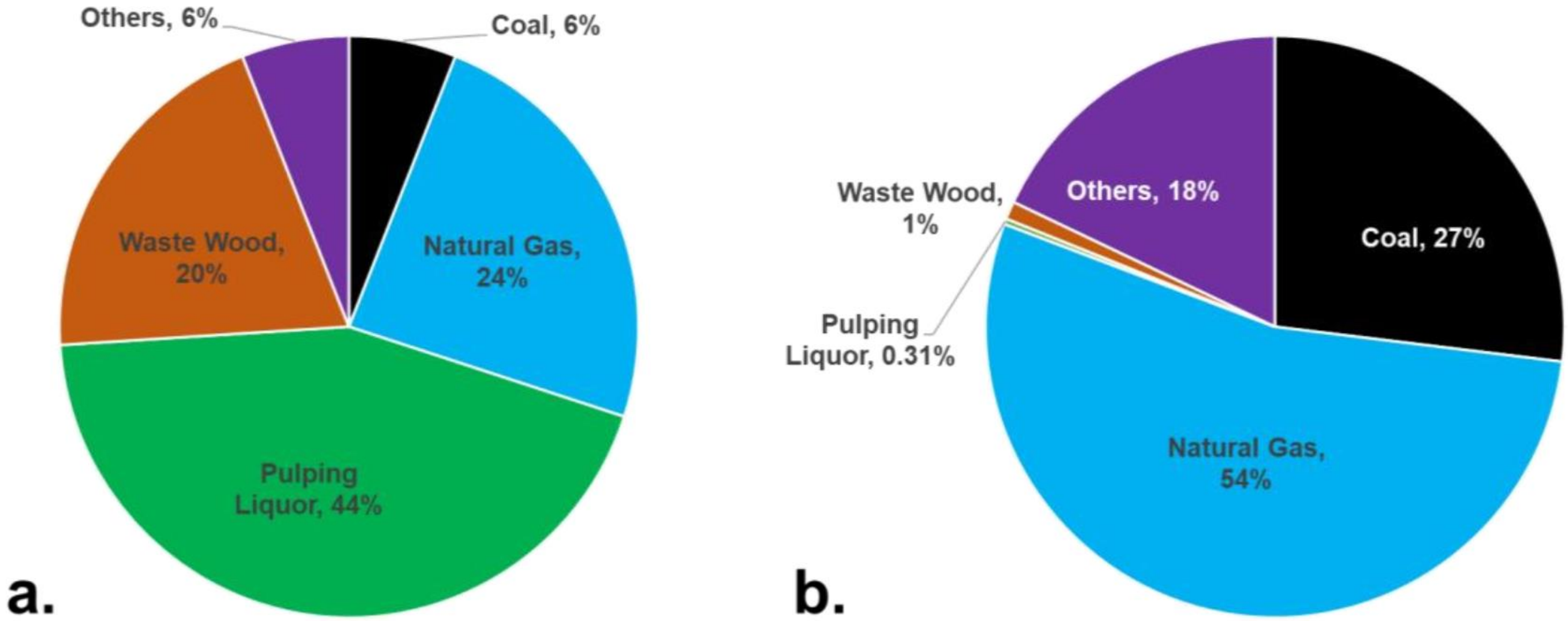
Policies, Benefits, Barriers, and Interventions for Decarbonizing PPI Sociotechnical System



Dylan D. Furszyfer Del Rio, Benjamin K. Sovacool, Steve Griffiths, Morgan Bazilian, Jinsoo Kim, Aoife M. Foley, David Rooney, Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options, Renewable and Sustainable Energy Reviews, Volume 167, 2022, doi.org/10.1016/j.rser.2022.112706.

US PPI Energy Consumption by a) major fuel types and b) GHG emissions

64% of the energy consumption (excluding electricity) of the US PPI is provided by pulping liquor and waste wood sources.

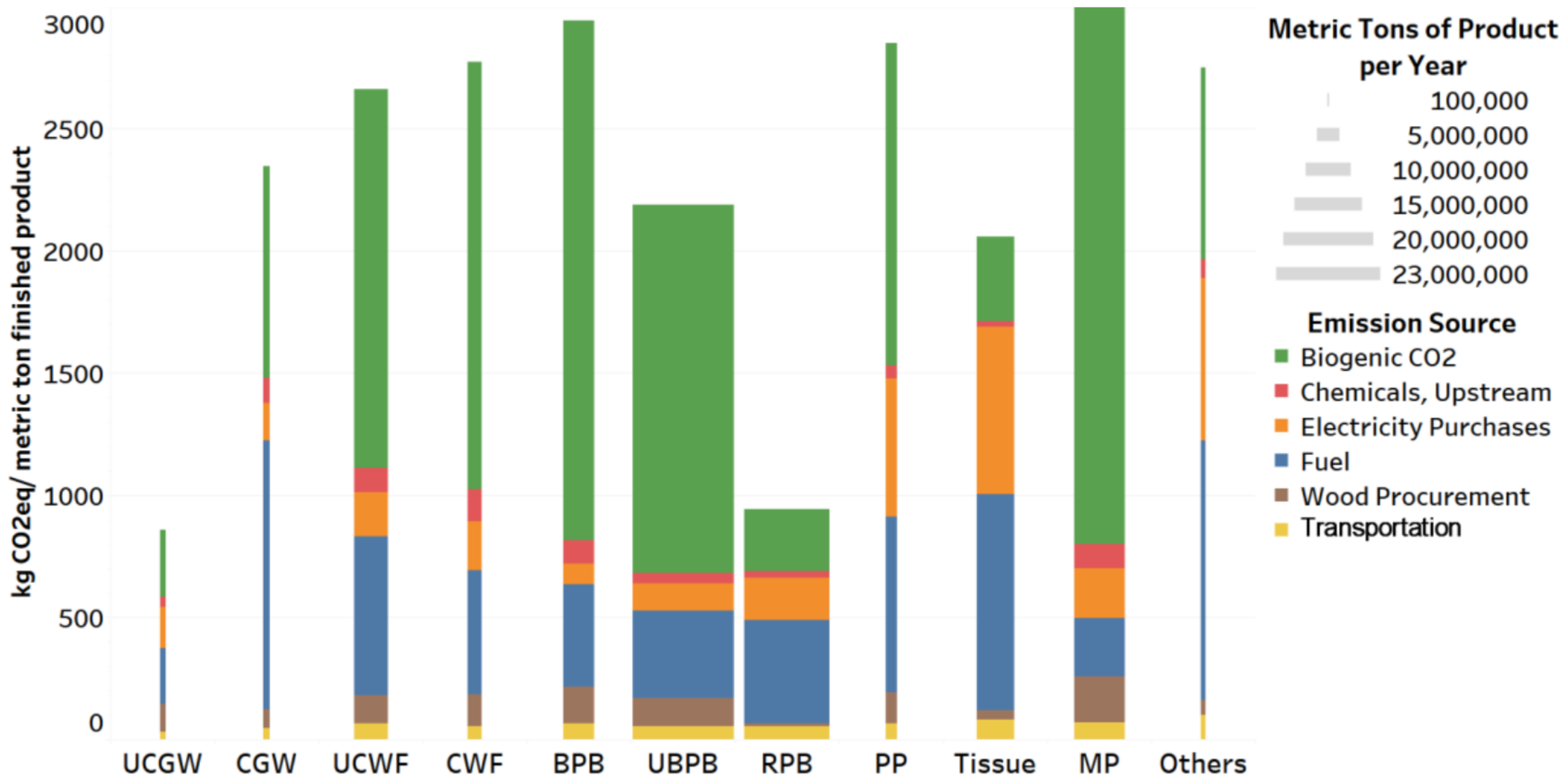


Tomberlin et al. (2020) "Pulp and Paper GHG emissions." BioResources 15(2), 3899-3914

GHG Intensity Sources and Biogenic CO_2 Comparisons

US Emissions P&P (84.4 Mt/y) Average Emissions: 942 kg CO2e/t average, 1232 kg CO2 biogenic/t

5 of 11 categories, biogenic CO_2 emissions exceeded fossil-based GHG emissions



Tomberlin et al. (2020) "Pulp and Paper GHG emissions." BioResources 15(2), 3899-3914

US PPI GHG Intensity for Paper Production and Drying

Fiber Production

Pulping/ Chemical Recovery and Other Operations

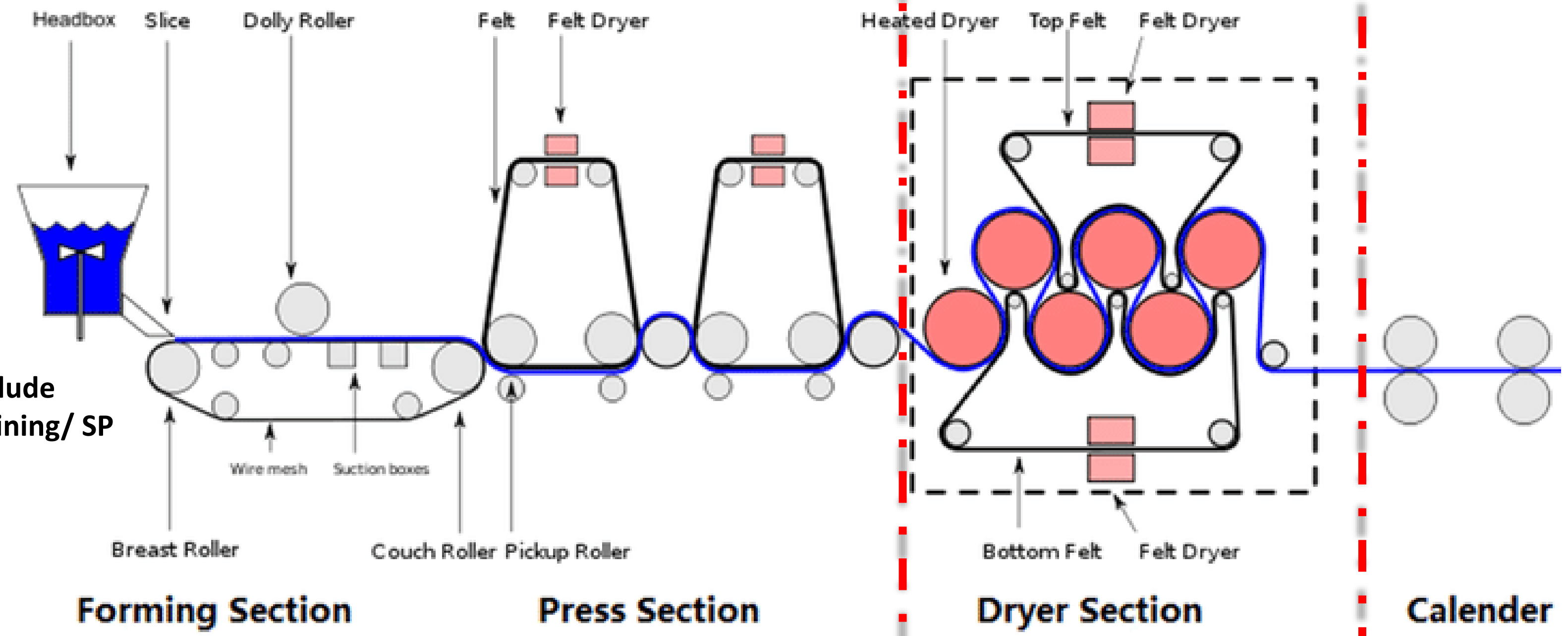
46% of CO_2 Emissions

Paper Production

54% of CO_2 Emissions

Hotspot

Include refining/ SP



~91% of CO_2 Emissions

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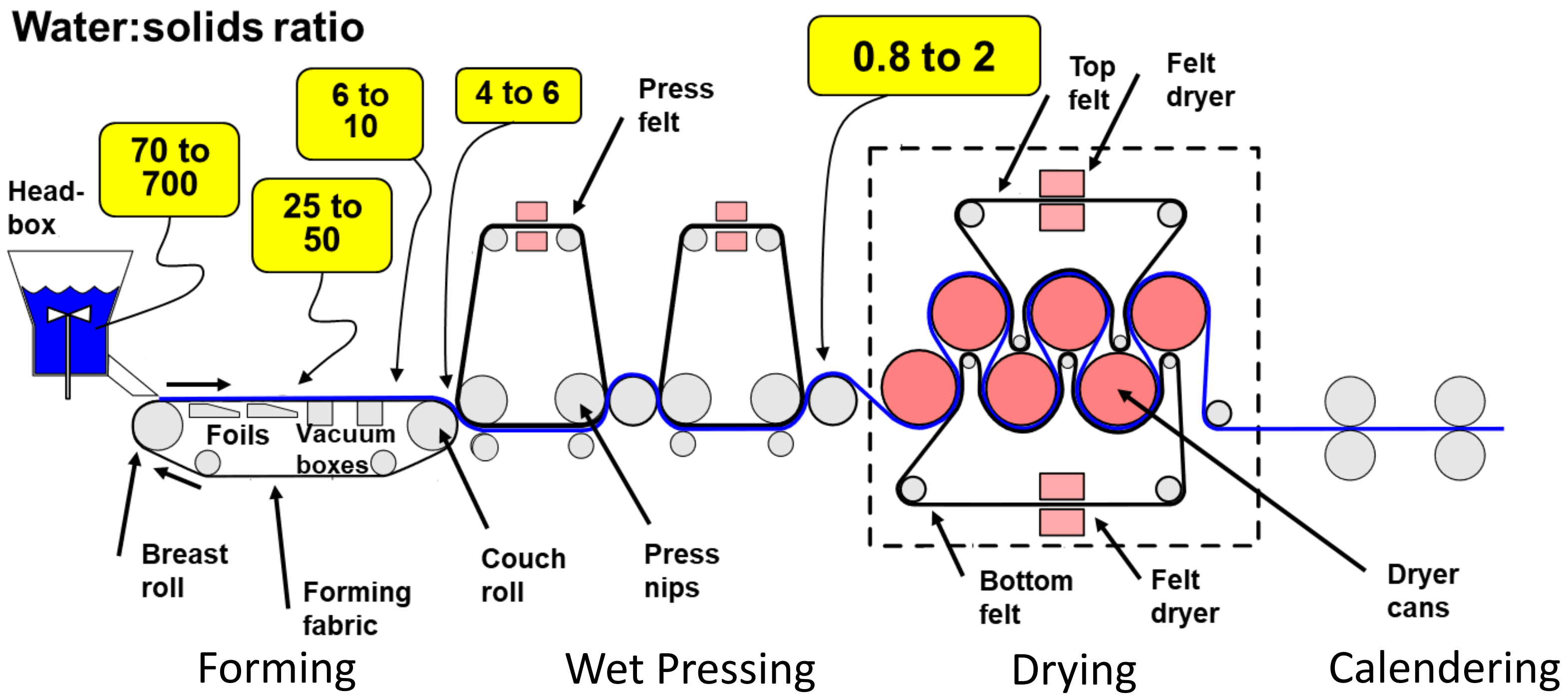
Del Rio et al. 2022. Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options. Renewable and Sustainable Energy Review. https://doi.org/10.1016/j.rser.2022.112706
Salem et al. Computational and experimental insights into the molecular architecture of water-cellulose networks. Matter. https://doi.org/10.1016/j.matt.2023.03.021

Paper drying is one of the most energy-intensive operations

Paper Drying Energy Reduction

In the US, **400 million GJ/year** of energy is required to dry paper at a cost of **$1.5 billion**.

Typically, water removed in the dryer section is ***< 1%*** of the original water in the stock; however, the dryer section uses >60% of all energy consumed in the paper mill.

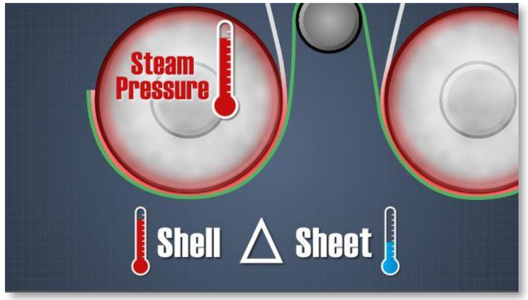


Papermaking is essentially a massive dehydration operation.

$$\boldsymbol{Forming\ Section}: 200\ \frac{Kg\ of\ water}{Kg\ of\ paper}$$

$$\boldsymbol{Press\ Section}: 2.6\ \frac{Kg\ of\ water}{Kg\ of\ paper}$$

$$\boldsymbol{Dryer\ Section}:\ 1.1 - 1.3\ \frac{Kg\ of\ water}{Kg\ of\ paper}$$



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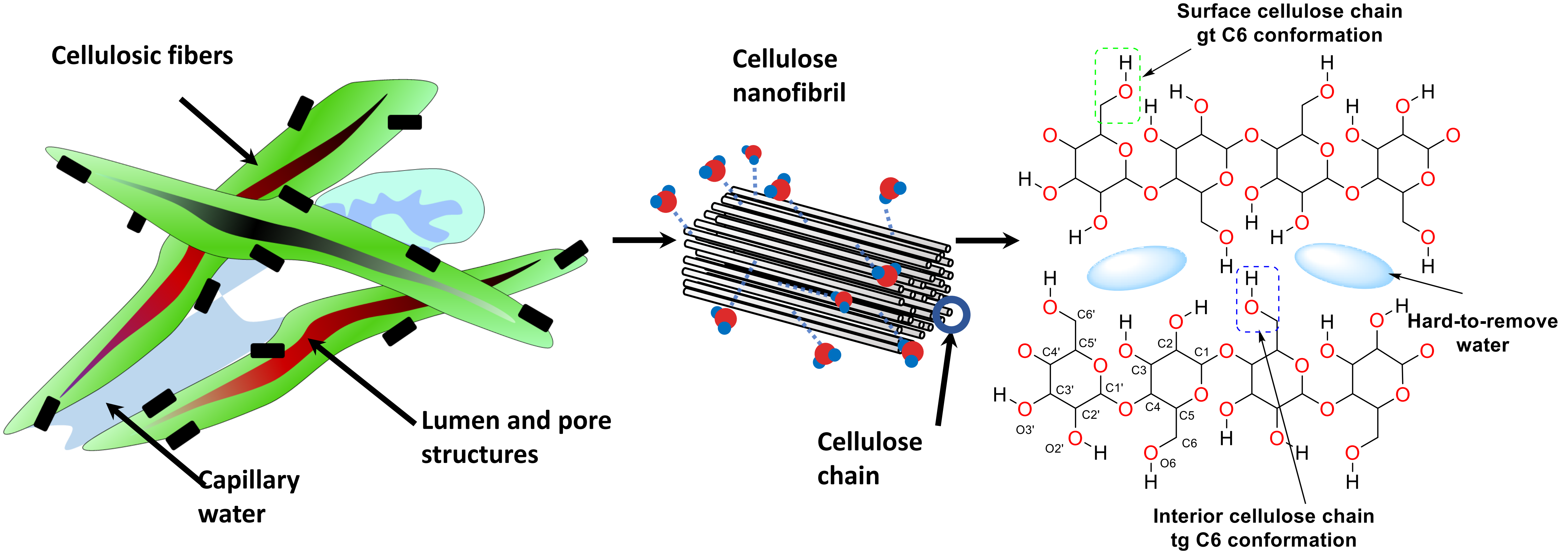
Brown, Ron, Hansen, Fred, Mallory James, et al., "Forest Products Industry Technology Roadmap," www.agenda2020. org.
Salem, K., Pal, L. et al. Lignocellulosic Fibers from Renewable Resources Using Green Chemistry for a Circular Economy (2021).
Images source: https://www.convergencetraining.com/paper-machine-dryer-hood-air-systems.html

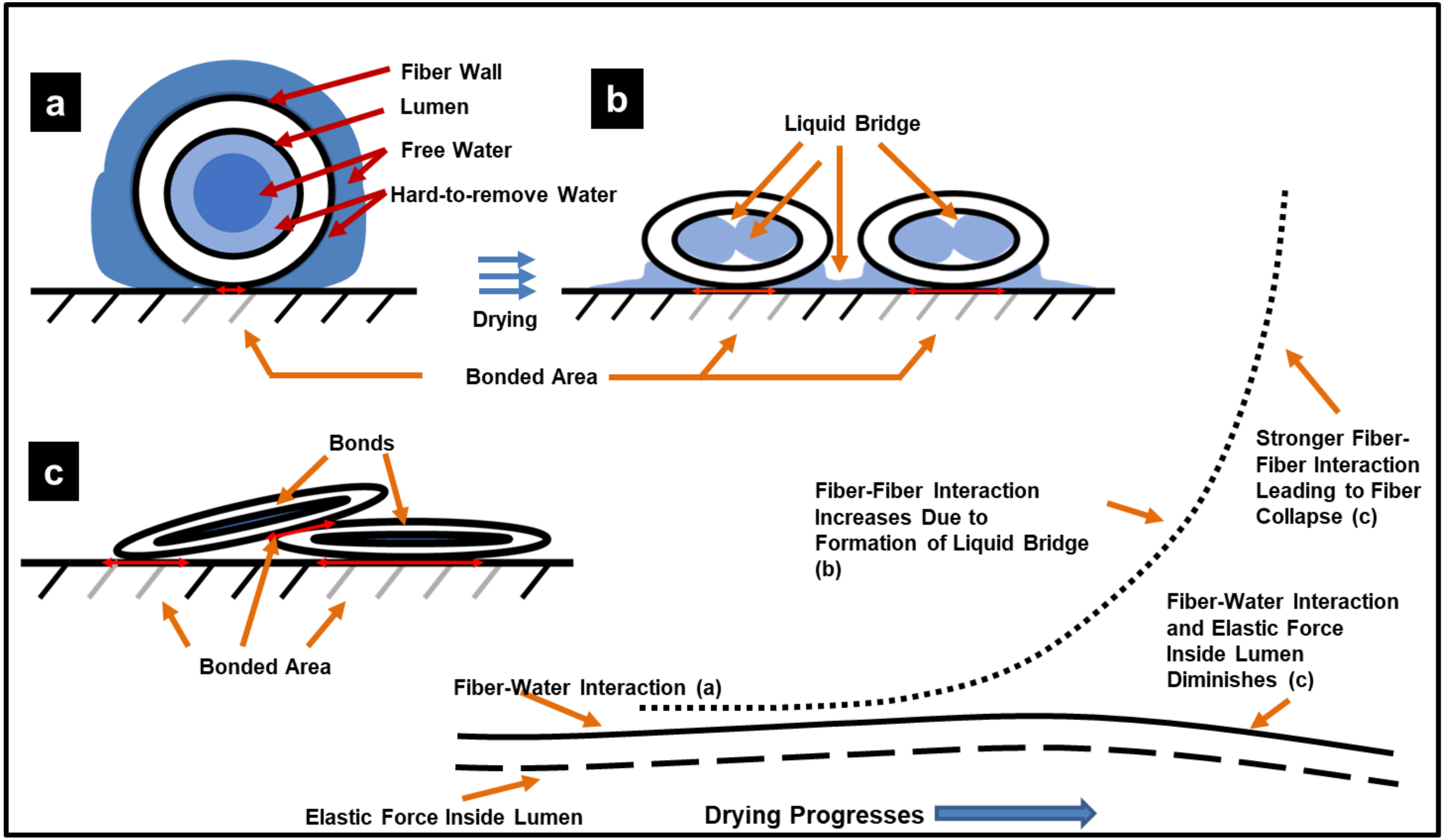
Understanding of Cellulose-Water Interaction

Cellulose-water interactions have fundamental importance for paper manufacturing and recycling; however, knowledge of its dynamic behavior is limited and requires further investigation to define how it controls physical (e.g., drying) and chemical (e.g., reactions) processes.

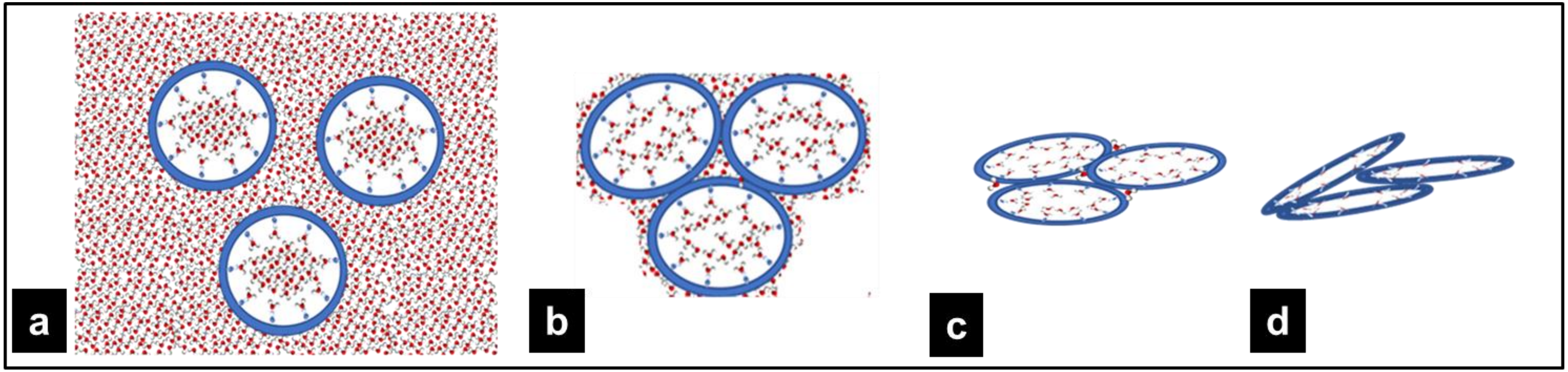


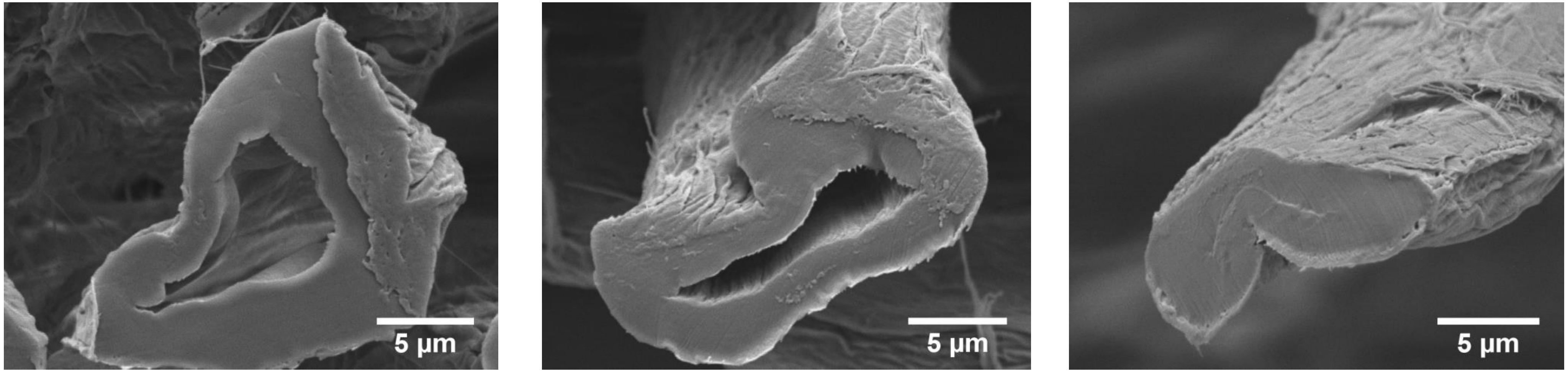
K.S. Salem, Barrios, N., Jameel, H., Pal, L*., Lucia, L.*, “Computational and experimental insights into the molecular architecture of water-cellulose networks, Matter 6, 1366–1381, 2023

Effect of Drying on Fiber Collapse



Theory & Visualization of Fiber Collapse





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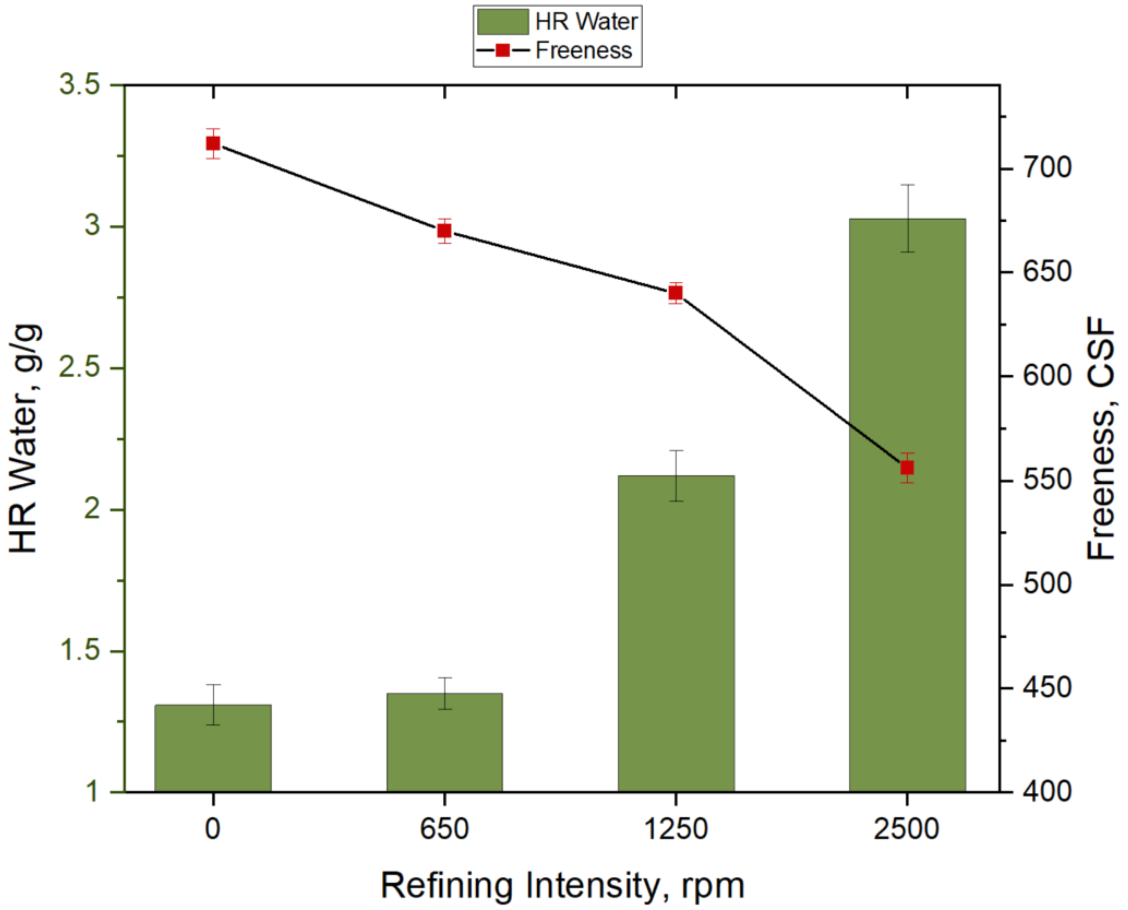
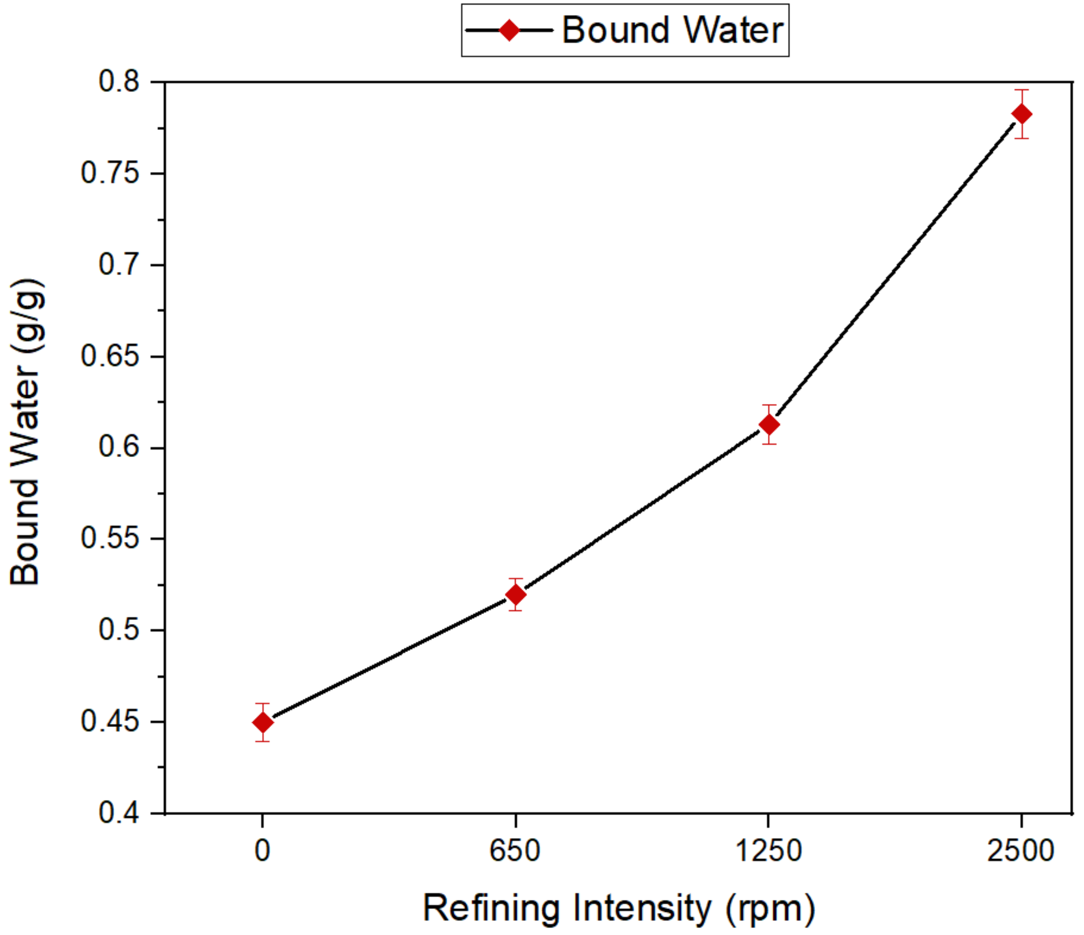
Refining Affecting Cellulose-Water Interaction

Effect of refining on HR water and bound water





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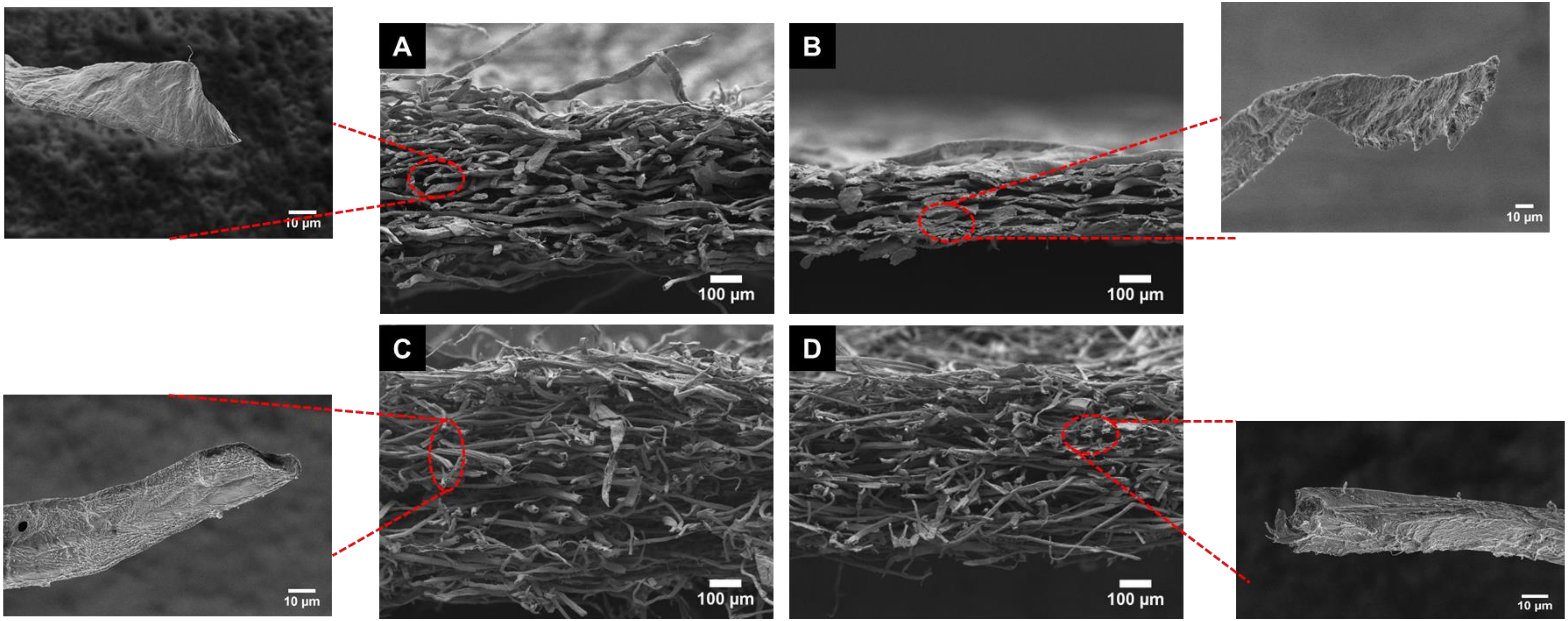
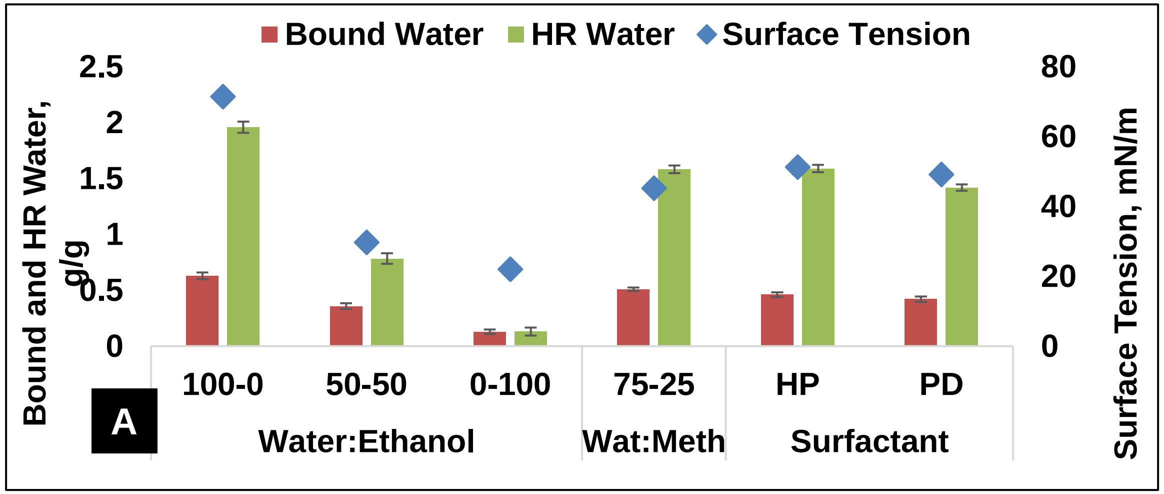
Effect of Refining and Drying on Fiber Collapsing

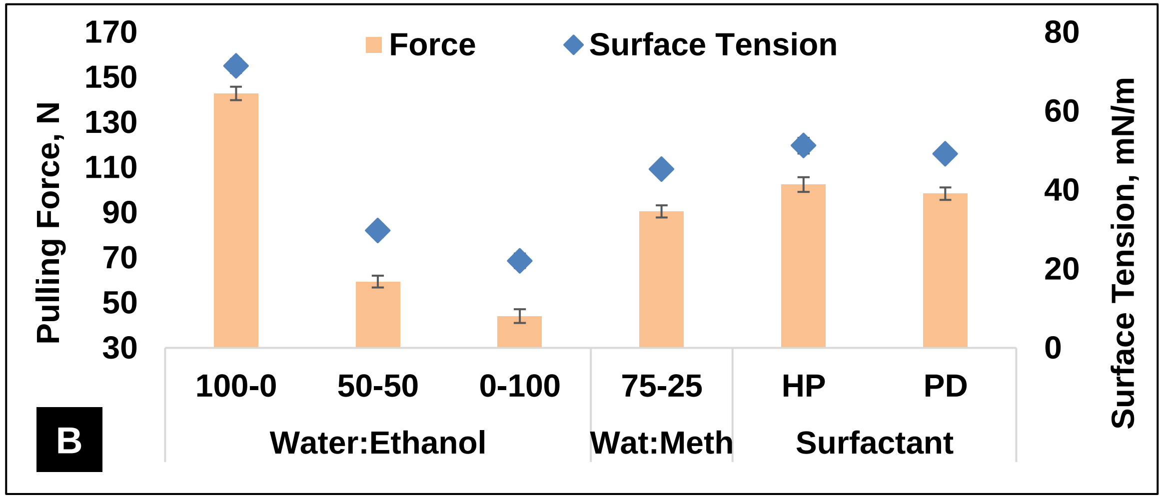


SEM images showing the effect of refining on fiber collapsing with different drying techniques. Fig. A) and B) are oven-dried Unrefined and Refined BEK samples, respectively. Whereas fig. C) and D) represent the freeze-dried Unrefined and Refined BEK samples, respectively. Inset shows a single fiber suffering collapsing to different extents for different drying methods depending on the presence of HR water content in the fiber.

Effect of Drying on Paper Properties

A)The relation of the surface tension with bound and hard-to-remove (HR) water for different solvent systems B)Change in the pulling force exerted on the fiber as the water leaves for a different solvent system, and C) SEM images showing with the increase in bulk as surface tension, bound and HR water decreases





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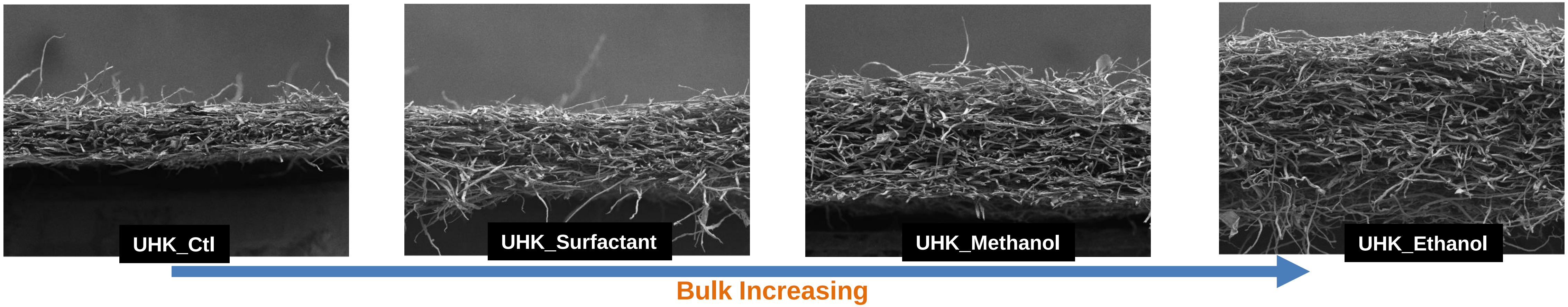

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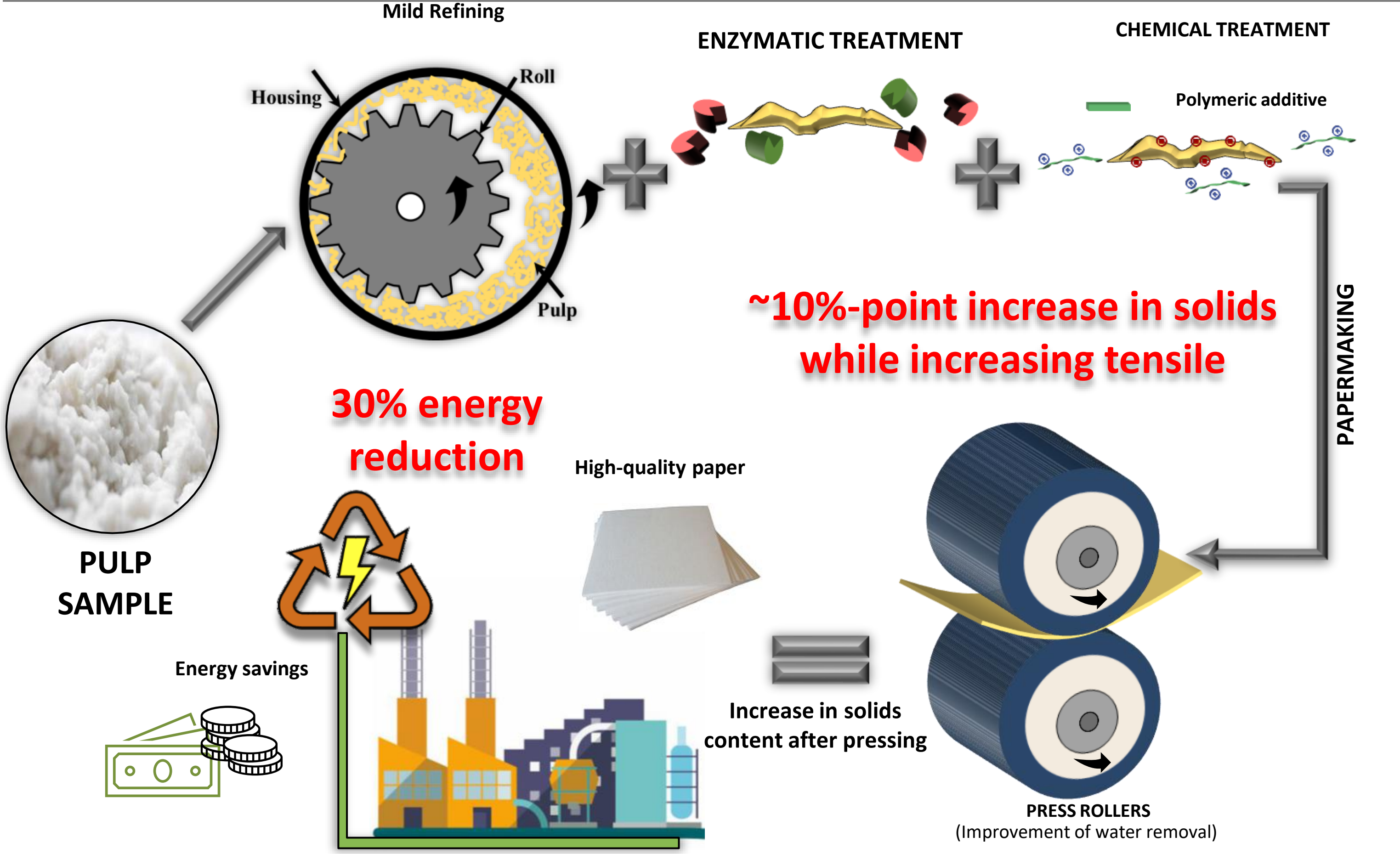
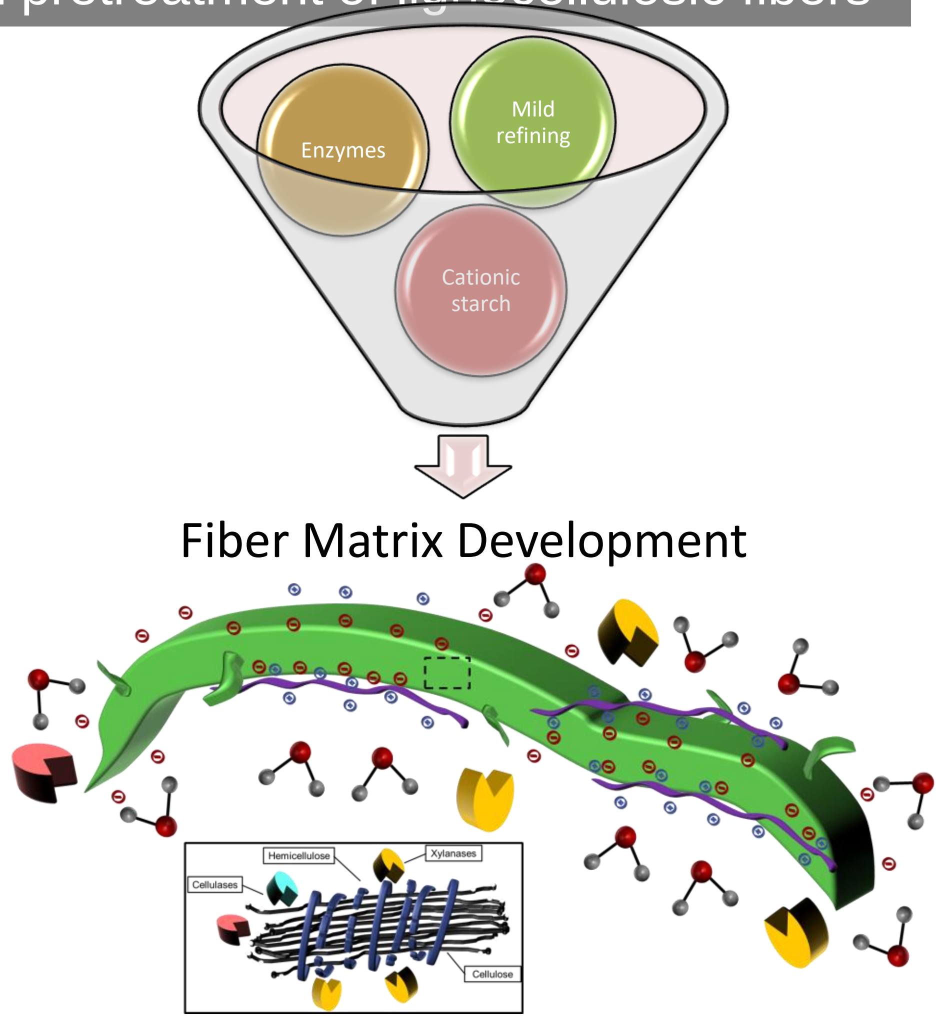
Advanced Fiber Matrix for Enhanced Press Dewatering

Innovate advanced fiber matrixes through bio-chemo-mechanical pretreatment of lignocellulosic fibers



Significant reduction in EMC while maintaining and increasing tensile strength



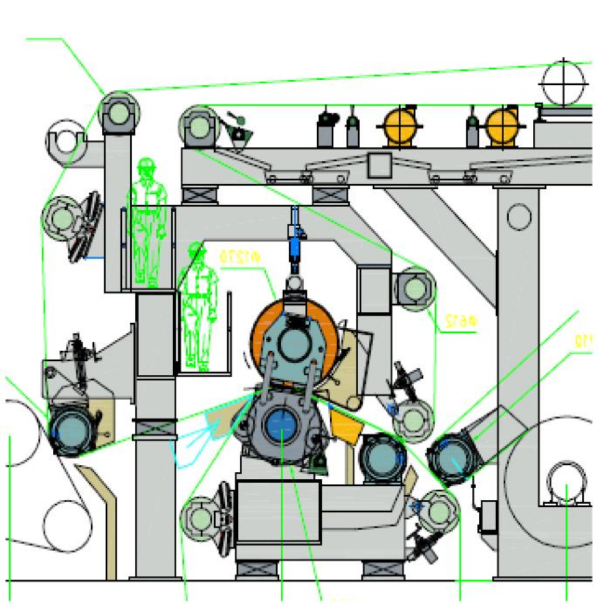
Barrios, N., Smith, N.M., Venditti, R.V., Pal, L.* "Enzyme-Assisted Dewatering and Strength Enhancement of Cellulosic Fibers for Sustainable Papermaking: A Bench and Pilot Study, Journal of Cleaner Production, JCLEPRO-S-23-08505

Current Status and Best Available Technology (BAT)

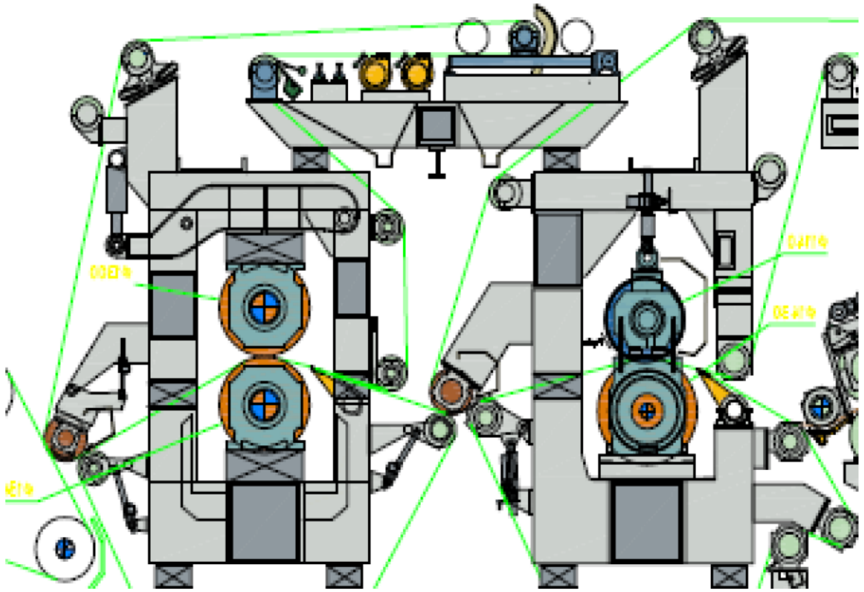
Increasing the dryness of paper webs from 45%-55% to 65% solids could save $240-$400 million.

Property-Limited Grades

Grade	Actual Limit	Dryness Limit
Tissue & Towel	Absorbency	45%
Copy Paper	Stiffness & Opacity	55%
Sack Kraft	Porosity	40%
Light Weight Liner	Ring Crush	50%
Liquid Packaging Board	Stiffness	45%
Folding Box Board	Stiffness	50%
White Lined Chipboard	Stiffness	50%
Fluff Pulp	Fluffing	50%



Single Nip Shoe Press



Large Roll Press + Shoe Press

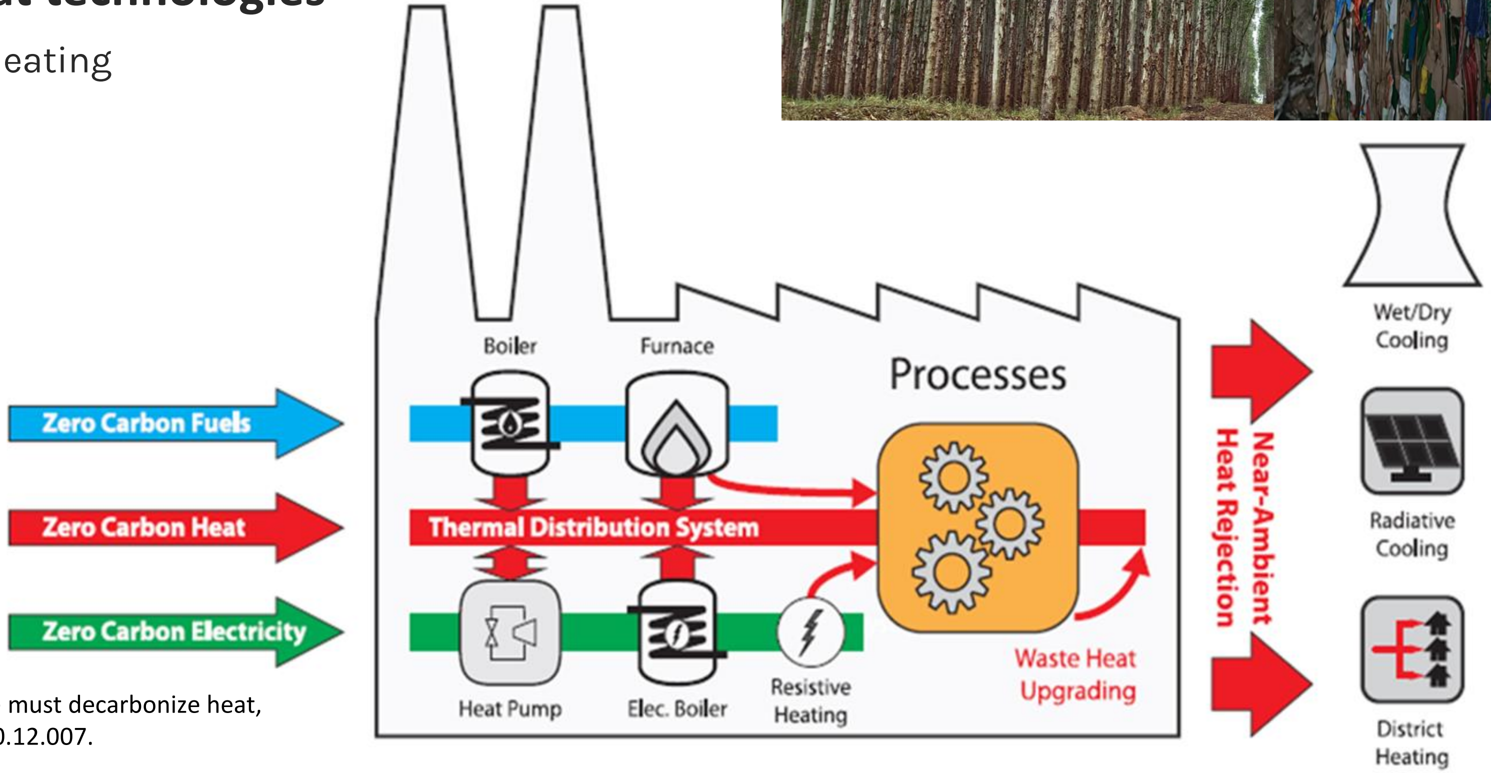
Alliance for Pulp and Paper Technology and Innovation (APPTI). (2020). Drier Web before the Dryer Section.

Road to Industrial Decarbonization

- **Expand the use of clean biofuels and waste to energy systems**
- **Implement waste heat management technologies**
- **Install flexible combined heat and power (CHP) systems**
- **Electrification of process heating**
- **Transformative low- or no-heat technologies**

Adopted from IEDO Research in Process Heating

Enable zero-carbon industrial heat through the utilization of zero-carbon fuels, zero-carbon heat, electrification of heat, and better heat management technologies



Gregory P. Thiel, Addison K. Stark, To decarbonize industry, we must decarbonize heat, Joule, 5 (3), 2021, Pages 531-550, doi.org/10.1016/j.joule.2020.12.007.

Road to Paper Production Energy Reduction/ Decarbonization

- Refining control, homogenization
- Steam box
- Enzymatic pre-treatments
- Polyelectrolyte chemistry
- Increased recycled fibers
- Gap forming
- Extended nip/shoe press
- Waste heat recovery
- Infrared profiling
- Reduced air requirements
- Reduced water requirements
- Porous foamed surface pressing
- Reduce rewet
- Drying – fabric and ventilation
- Condebelt drying
- Hot pressing
- Dry sheet forming
- Direct drying cylinder firing
- Electric assist pressing

- Ultrasonic - nonthermal
- Infrared drying
- Plasma-assisted drying
- Impulse drying
- Airless drying
- Press drying
- Air impingement drying
- Steam impingement drying
- Foam forming
- Heat pumps
- Hydrogen boiler
- Biomass boiler
- Electric steam boiler
- Combined heat and power systems
- Direct carbon capture and storage
- Solar/Wind turbines
- AI- digital twins/CPS
- Hybrid systems

To reach net-zero emissions, significant efforts are needed to decarbonize heat and electricity

Challenges for implementation

- Highly complex processes/mill specific
- Net-zero CO_2 emissions pathway may increase energy costs
- Lack of access to large capital/longer payback period
- Cost of production disruption
- Risk of quality deterioration
- Lack of demonstration at pilot scale
- Uncertainty around carbon policies

Investments in clean energy technologies R&D and pilot testing is needed!

Key pillars for emission reduction	Energy Reduction Technologies	Barriers/ Opportunities	Implementation Timeline
Energy efficiency technologies	**Drier web before drier/wet press – enzymes pretreatment**	Dwell time and compatibility /Reduction in steam demand without major machinery modification	Current state: **pilot scale,** time frame for industrialization ~ 2 - 5 years
	Condebelt drying	Complex design for high speed operations/ suitable for linerboard production, saves ~ 15% in steam demand for paper drying and 20kWh/t in electricity	Current state: **Commercial scale**, successful industrial implementation by Wolsan paper, Korea.
	Foam forming	Machine modification, surfactant wastewater treatments, impact on strength/ >10% reduction in steam demand, bulkier and absorbent paper	Current state: **pilot scale** time frame for industrialization ~ 5-10 years
Industrial electrification technologies	**Electric dryers**	Source of clean energy, electricity cost and price fluctuations, payback period, /substitution of thermal energy by electric energy.	Current state: **Commercial scale**. Several successful installations
	Electric boilers	Capital investment, lack of infrastructure for clean energy for electricity, cost/substitution of thermal energy by electric energy	Status: **Commercia Scale**.
	Ultrasonic dewatering	Cost of machinery, specificity, strength/ improvement in dewatering, steam demand and drying rates.	Current state: **In development.** Commercial time frame ~10 years with investment
Low-carbon fuels, feedstocks, and energy sources (LCFFES) technologies	**Increase use of recycle fibers**	Cleanliness, quality, strength, dewatering/ saves virgin raw materials, waste reduction	Current state: **Commercial scale**
	Biofuels/waste biomass	Capital investment, production and transportation cost, availability/use of biomass and waste resources	Current state: **Commercial scale**.
	Solar/wind turbines	Capital cost, seasonality, location, policies/clean energy	Current state: **Commercial scale**.
	Nuclear reactor	Huge initial investment cost, safety concerns, waste disposal/ clean energy, self-sufficiency, implementation of electric technologies	Current state: **Development scale.** Time frame for industrialization is unknown
Carbon capture, utilization, and storage (CCUS) technologies	**Post-combustion amine capture /calcium loop capture, membranes**	Location/geological site for containment, in development /negative emissions, carbon credit opportunities	Current state: **Development/Pilot Scale**. Time frame for industrialization ~ 10 years

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For details and to register, please visit our website at https://gp4sustainability.ncsu.edu/waste-to-advanced-resources/

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