Structurally Optimized Fire-Resistant Cellulose Nanocrystal Hydrogels

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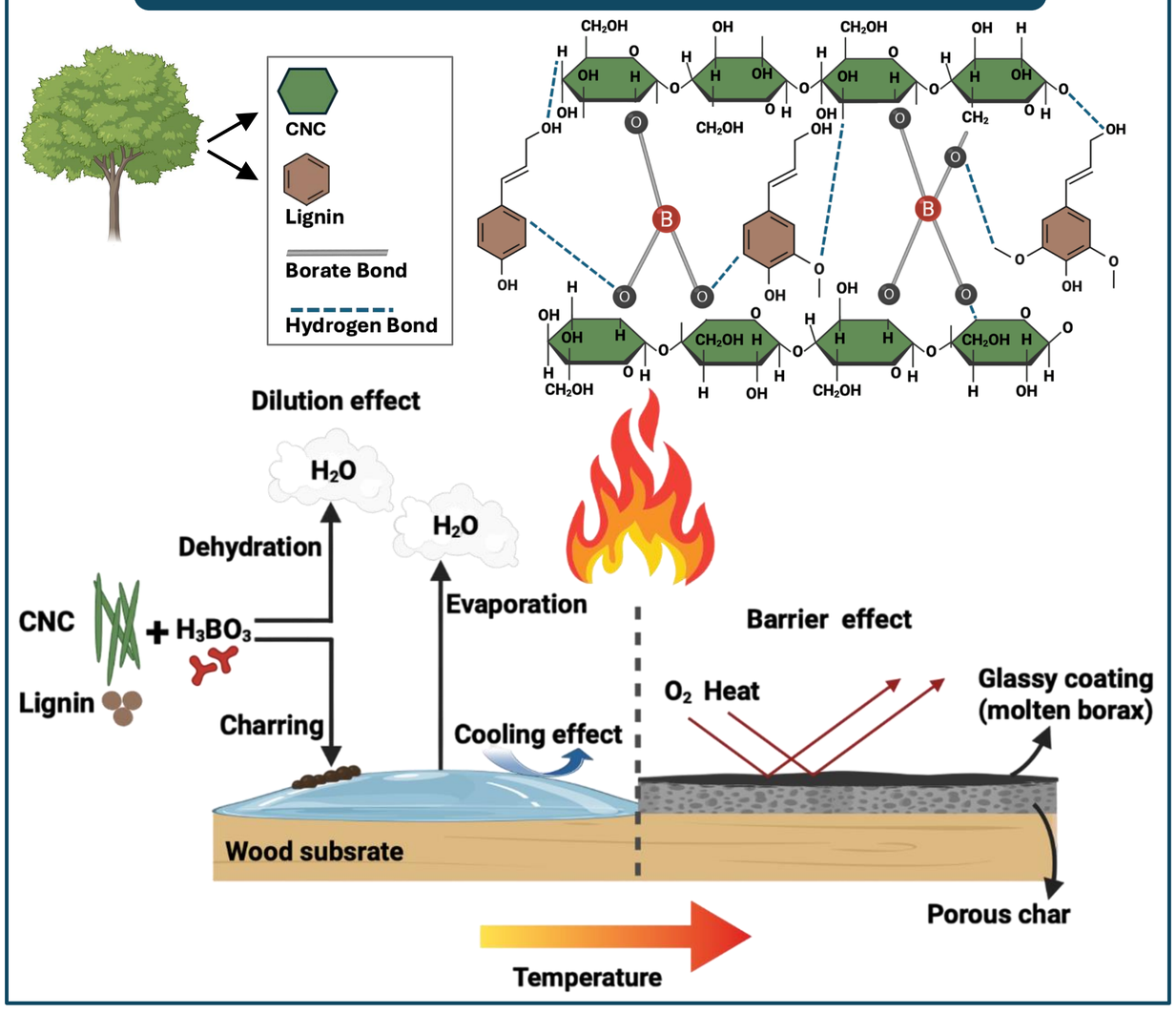
Highlights

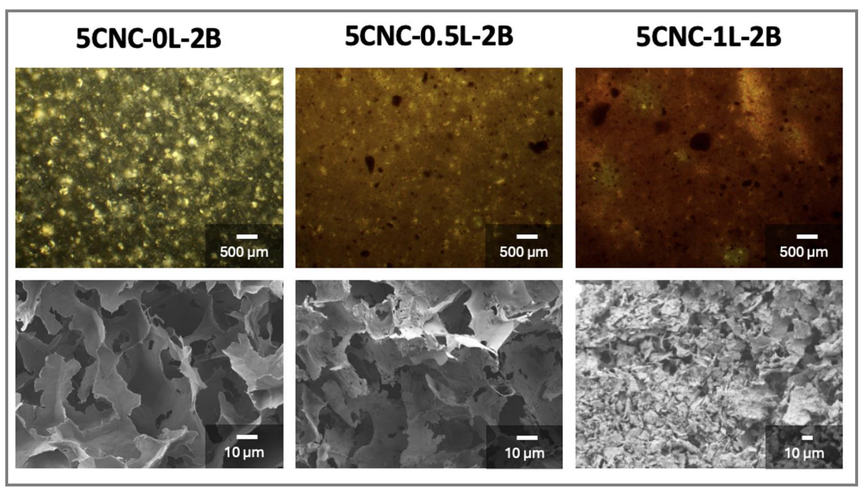
- Hydrogels have emerged as promising **materials for fire prevention and flame-retardant** due to their water retention capacity, thermal barrier properties, and environmental compatibility.
- Most conventional hydrogel systems depend on synthetic polymers or inorganic fillers, raising concerns about environmental persistence.
- Bio-based nanocomposite hydrogel **composed of cellulose nanocrystals (CNC), borax, and lignin** was developed, offering a sustainable and structurally optimized solution.
- CNCs form a **robust and porous scaffold**; borax introduces **cross-linking** enhances the structural integrity, providing stability; lignin, with its aromatic structure, enhances **char formation** and reinforces the gel network via hydrogen bonding.

Methodology

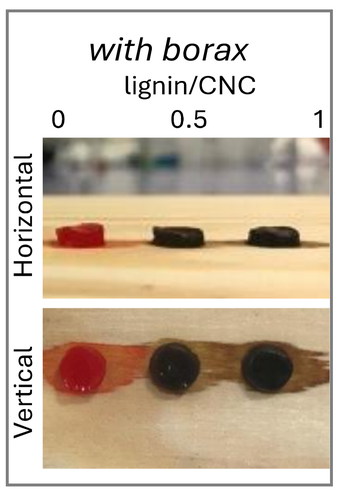


Results

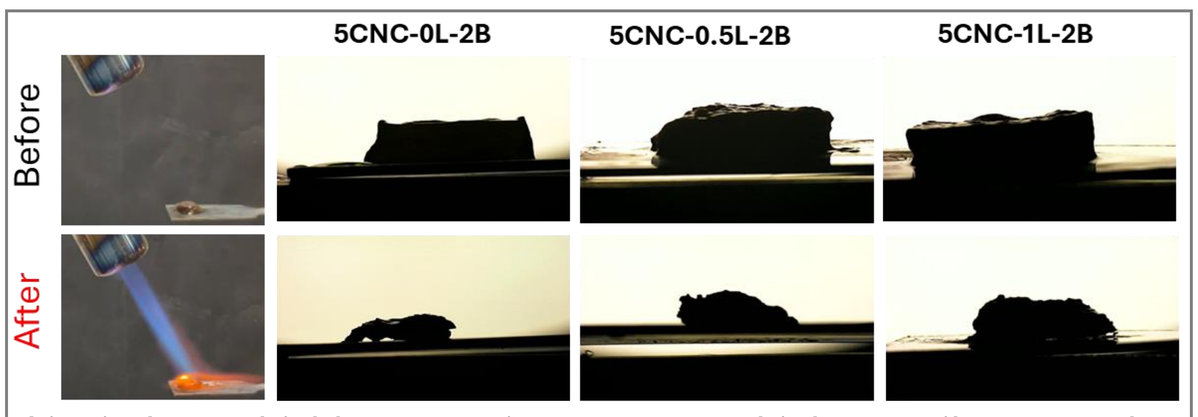
Microstructure



Gelation

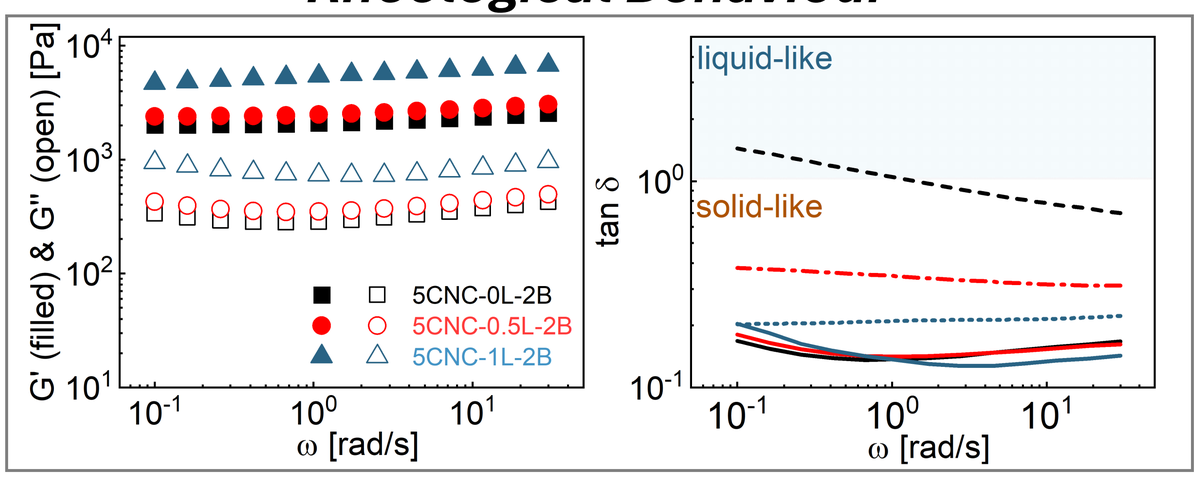


Char Formation

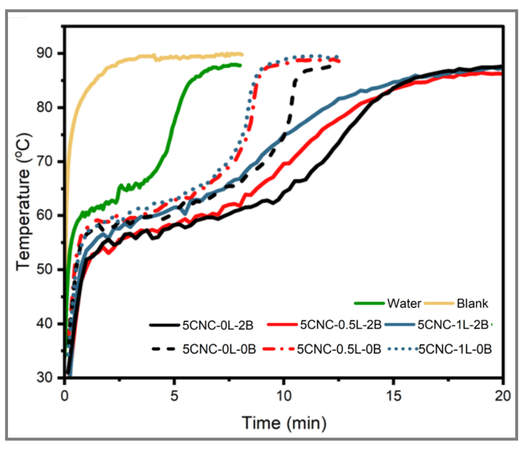


Lignin has a highly aromatic structure which contributes to the formation of thermally stable carbon-rich residues and increases the rate of carbonization.

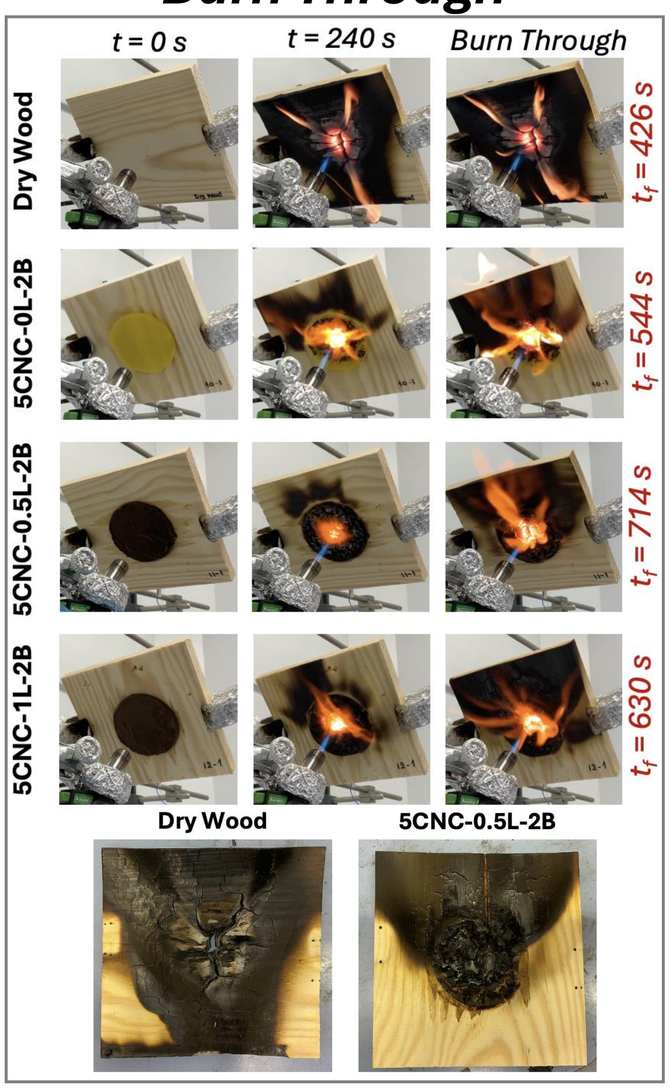
Rheological Behaviour



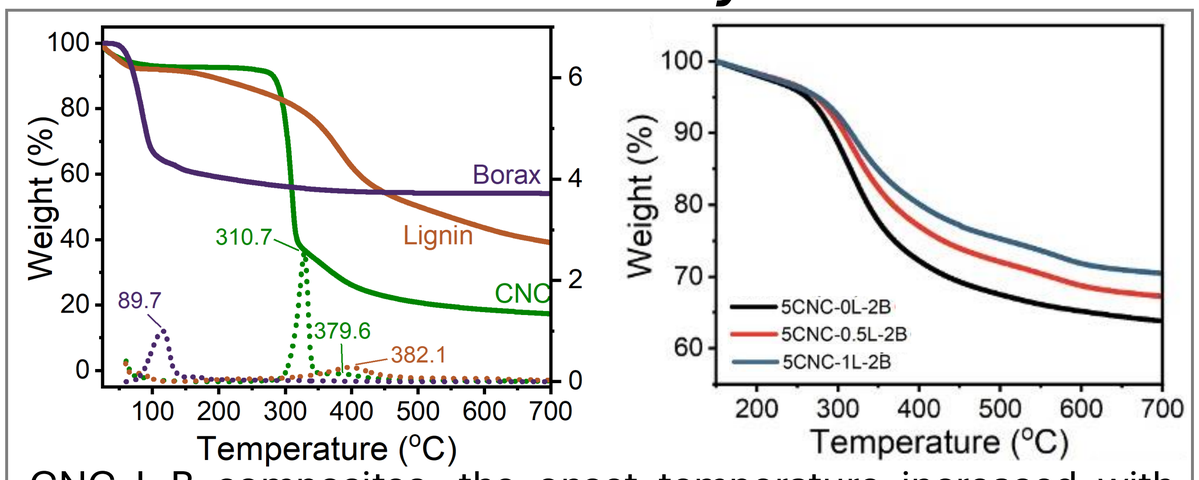
Water Retention



Burn Through

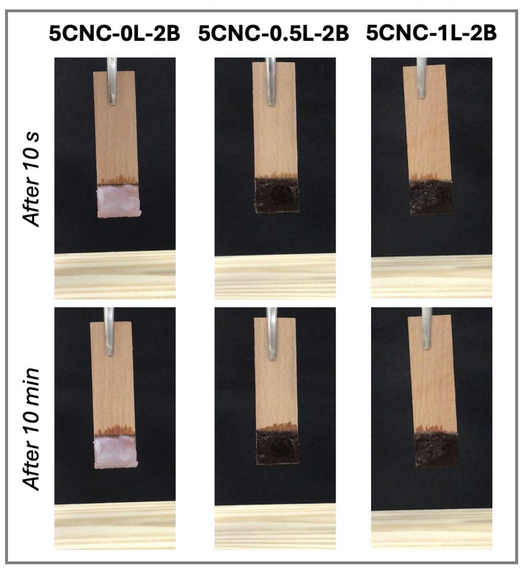


Thermal Analysis



CNC–L-B composites, the onset temperature increased with increasing lignin content, that lignin may interact with boric acid, thereby limiting its catalytic effect on CNC.

Adhesion on Wood



Conclusion

- Incorporating **moderate lignin content** significantly enhanced the **hydrogel's network structure** through increased hydrogen bonding, **resulting in smaller pore sizes** and higher **water retention** during combustion.
  - **Char yield** increased from **8.6% (neat CNC hydrogel) to 70.5% (CNC–Lignin–Borax hydrogel).**
  - **Burn-through time** extended to 12 minutes, which is **71% longer than uncoated wood**.
  - In vertical flammability tests, **burning duration decreased by 71%** (wet) and 32% (dry) with optimized lignin content.
- The retained water contributed to **cooling and oxygen dilution effects**, while the synergistic action of lignin and borax enabled the formation of a **dense glassy char layer**, acting as **a barrier to heat and oxygen.**

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