PacifiCan-MMRI Accelerating Circular Economy (ACE) TechBrief Report

Project title: Enhancing the Antimicrobial Properties of Biowaste-based Cellulose Aerogels

Industry partner(s): The German Aerospace Center (DLR), Advanced BioCarbon 3D Ltd.

Researchers: S. Yeo, K. Vojnits, M. Zhao, B. Goncalves, D. Costa, K. Ganesan, B. Milow, and S. Pakpour

Introduction & Background:

Aerogels are a unique class of solid material, consisting of over 90% air with an extremely low density and high porosity. Cellulose aerogels are of particular interest, resulting from their biodegradable nature, sustainable source material, and biocompatibility. As of March 31st, 2025, there were 1,755 articles on Scopus with the words "cellulose" and "aerogel" in the title. Recent advances have been made to functionalize these aerogels, with applications in food packaging[1], water remediation[2-3], wound dressing[4], and drug delivery[5,6]. Cellulose aerogels can be further enhanced with antimicrobial properties[2,4,7-12] and derived from biowaste sources including agricultural residues[7-9] and forestry debris[10-12], contributing to a circular economy. As such, there is notable opportunity to transform biowaste into functionalized aerogels, with a variety of tailored applications. However, challenges remain in the scalability of aerogels, due to high production costs and overall time constraints.

The aim of this project is to develop cellulose aerogels with antimicrobial properties from agricultural residues for use in insulation and filtration. This process will be optimized at the lab scale to achieve specific qualities, including degree of polymerization, crystallinity, purity, and rheological properties in an aqueous-based solvent medium. Density, porosity, specific surface area, pore volume, pore size distribution, and thermal conductivity will be characterized. Aerogel production and characterization is completed at DLR, taking advantage of their expertise in biopolymers and their aerogel production facilitates. Completed aerogels are sent to UBCO for the addition of antimicrobial agents and antimicrobial activity assessment at the Biomedical Research Laboratory, for their skillset in microbiological studies and antimicrobial susceptibility testing. Our Canadian industry partner, ABC3D, provided agricultural residues for aerogel generation.

We are grateful for our additional collaborators: geniaLab®(Germany), Forschungszentrum Jülich GmbH (Germany), and the Indian Institute of Technology Roorkee (India).

Relevance to Circular Economy:

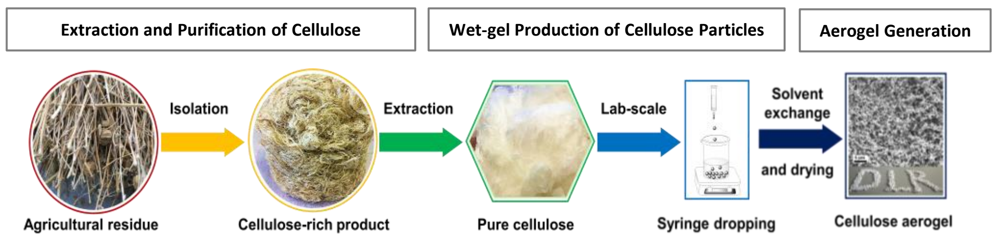
In 2022, Canada conducted its first Waste Management Survey, revealing that 350,000 tonnes of organic waste originated from agricultural residues, forestry debris, and woody biomass[13]. When left to accumulate in landfills, organic materials produce substantial volumes of methane, a potent green house gas[14]. As a result, Canada takes great initiative to divert these materials to compositing facilities, however, this technique is not without its own challenges[15,16]. In favor of a circular economy, where the production of waste is minimized and resource efficiency is maximized by promoting reuse, recycling, and regeneration, such organic materials can be broken down into its constituent components including cellulose, hemicellulose, and lignin, to be repurposed[16-18]. One such application is cellulose aerogels, benefited by the diversity in downstream applications across industries.

Methodology:

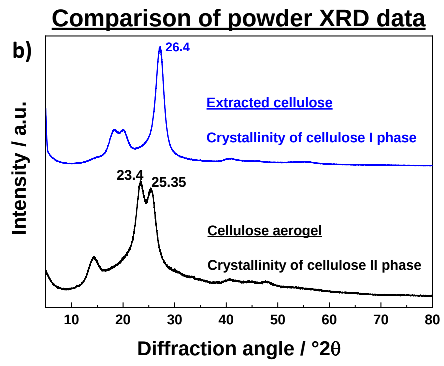
Cellulose was extracted from hemp-based agricultural waste by first grinding it into raw, ground fibers. These fibers underwent alkali hydrolysis followed by bleaching to remove hemicellulose and lignin, respectively, yielding pure cellulose **(Figure 1a)**. Afterwards, dissolution of cellulose fibers is conducted in a NaOH/urea mixture, followed by a sole freeze-thaw event. Gelation was accomplished by dropping single droplets of cellulose solution into an acetic acid/deionized water bath to form spherical beads, which are washed with deionized water until neutral. Solvent exchange with EtOH was performed, and supercritical CO_2 drying was used to generate aerogels. Antimicrobial properties were applied through the immersion of aerogels into 0.2M $ZnCl_2$ for 1 hr followed by 30 mins of drying under ambient conditions, efficacy was assessed against Gram-negative and Gram-positive bacteria using the standard plate count assay **(Figure 2a)**.

Results & Discussion:

a)



b)



c)

Physical Properties of Aerogels	
% wt. Cellulose	6%
Bead Size (mm)	3.08±0.23
Skeletal Density (g·cm^{-3})	1.52
BET Specific Surface Area (m^2·g^{-1})	414
Tapping Density (g·cm^{-3})	0.18
Porosity (%)	87.87
Pore Volume (cm^3·g^{-1})	2.65
Pore Distribution (nm)	10-100
Pore Size (nm)	24.22
Crystallinity of Aerogel	Cellulose II

Figure 1. a) Schematic diagram of cellulose extraction from agricultural residues (hemp) followed by syringe dropping method for aerogel bead formation. **b)** XRD of extracted hemp cellulose and hemp cellulose aerogels. **c)** Physical properties of hemp-based cellulose aerogels.

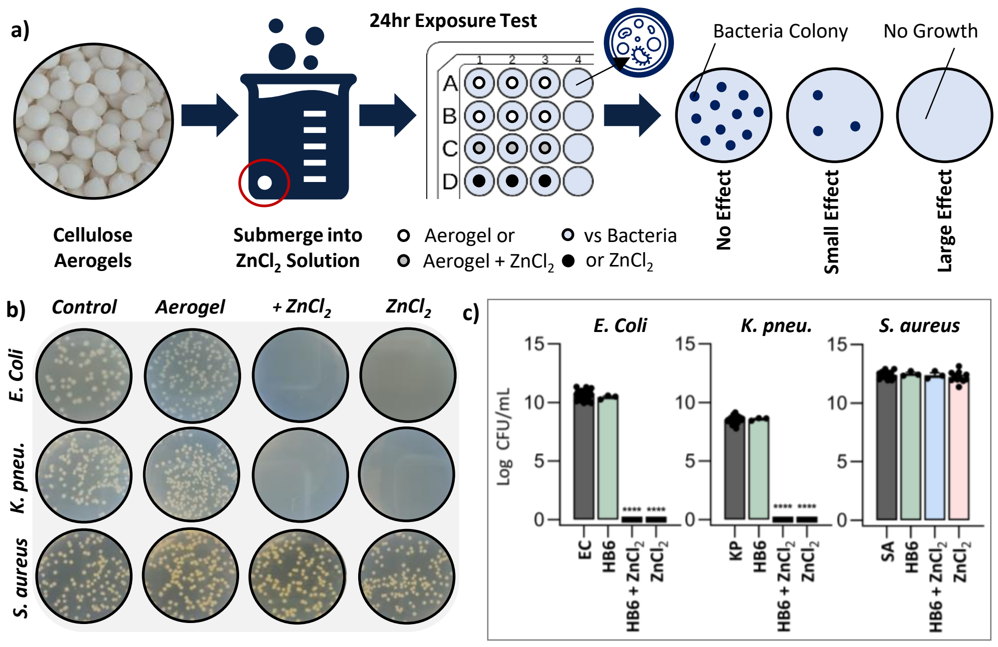


Figure 2. a) Addition of antimicrobial $ZnCl_2$ (0.2M) to hemp-based cellulose aerogels (HB6) through immersion technique, followed by antimicrobial susceptibility testing by standard plate count assay. **b)** Test plates for each condition and microorganism. **c)** Log CFU/mL results from colony counts.

Hemp-based cellulose aerogels (HB6) were 3mm in size and of cellulose II crystallinity, with a skeletal density of 1.52 g·cm^{-3} and porosity of 87.87% **(Figure 1b,c)**. Pore volume was 2.65 cm^3·g^{-1} with a pore size of 24.44 nm and pore distribution between 10-100 nm. BET specific surface area was 414 m^2·g^{-1}, and tapping density 0.18 g·cm^{-3}. HB6 aerogels were not antimicrobial against any of the tested bacteria, including *E. coli* (EC), *K. pneumoniae* (KP), and *S. aureus* (SA) **(Figure 2b,c)**. However, following antimicrobial treatment with $ZnCl_2$, HB6 gained antimicrobial efficacy against *E. coli* and *K. pneumoniae* but not *S. aureus.* In summary, pure cellulose was successfully extracted from hemp-based agricultural residue and repurposed into cellulose aerogels with desirable physical properties, and while not initially antimicrobial, it is clear antimicrobial activity can be applied through the immersion method.

Conclusion & Next Steps:

It is evident that agricultural residues can be repurposed into cellulose aerogels with desirable properties to support a circular economy, with the added benefit of functionalization with antimicrobial activity with $ZnCl_2$, effective against *E. coli* and *K. pneumoniae*. The next step is to explore additional antimicrobial agents, highlighting the need to address *S. aureus* resistance. Future work includes the potential to test other microorganisms, including other bacterial species, fungi, or viruses.

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