Manufacturing of lightweight insulation foam from renewable henequen fibres

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8th International Conference on Multifunctional, Hybrid and Nanomaterials
Montpellier, France Europe
3-6 March 2025

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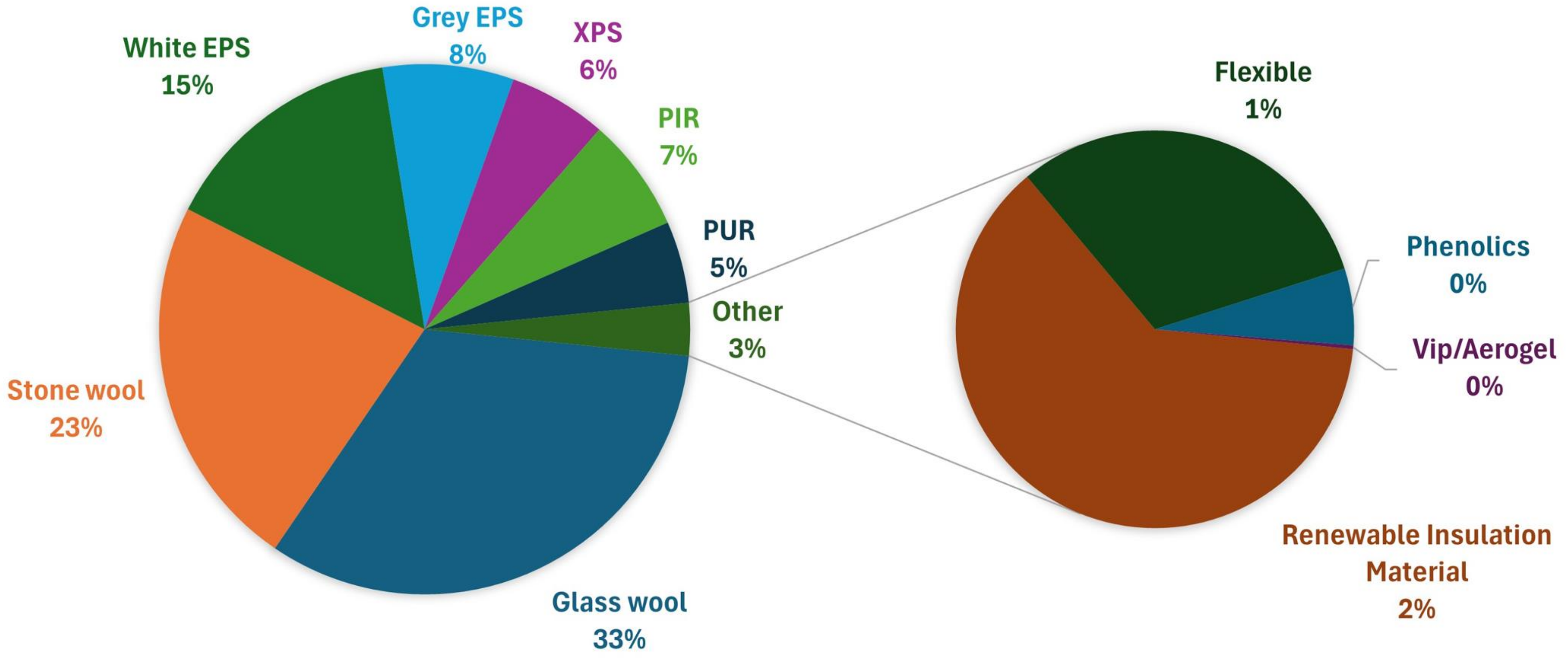
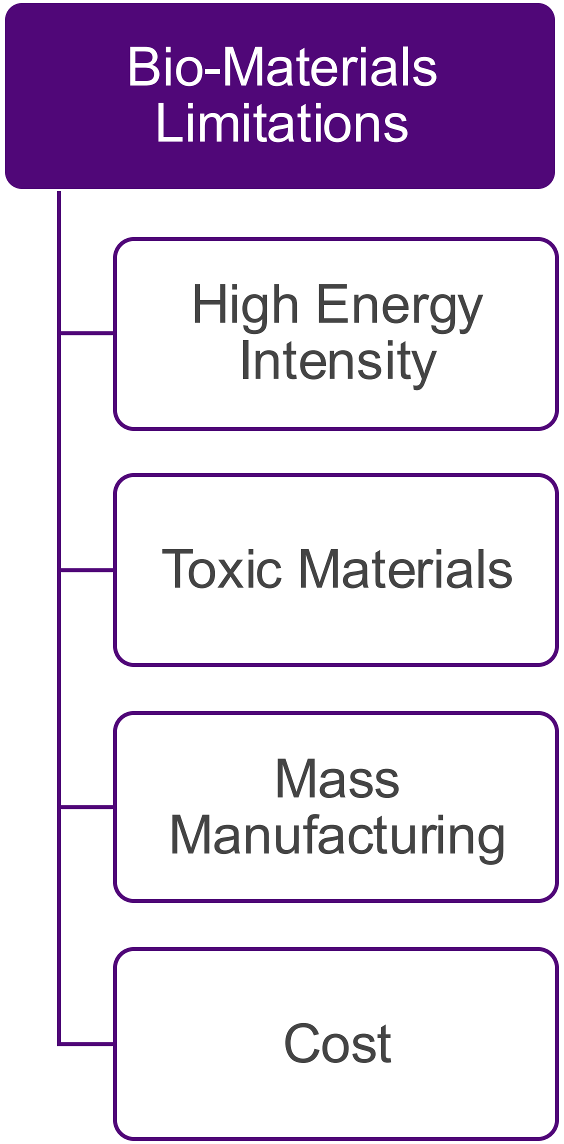
Introduction

Problem

- The building sector accounts for 37% of global CO_2 emissions.
- Current materials have high environmental costs and are difficult to recycle.
- Bio-based options have limitations





Design process - Principles

Principles

- Abundant & Underutilized Resources
- Eco-Friendly Processing
- Flame Resistant
- Scalable & Low-Energy

Process

- Develop sustainable, high-performance insulation
- Optimize thermal, mechanical & fire resistance properties
- Compare environmental impact with traditional materials

Intent of Study

Intent

- Develop a simple and scalable manufacturing process for lightweight fibrous networks form lignocellulosic henequen fibre.

Why henequen?

- Natural long fibre which is underutilised and in abundance
- Sustainability benefits during growth and harvesting

Research objectives

- Assess performance of designed foams in areas of:
  - Density & Porosity
  - Thermal Conductivity
  - Flame Resistance
  - Recyclability & Biodegradability
  - Life-Cycle Impact
- Assess viability in comparison to current solutions

Market Gap & Innovation

Gap in the market

- Ease of Manufacturing
- Easy Fibrillation
- Flame Retardant
- Sustainable
- 100% non-toxic foam

Investigation

- Mechanical Fibrillation via blending
- Chemical cross-linking
- Flame Retardant using Borax
- Xanthan Gum
- Use of abundant raw material

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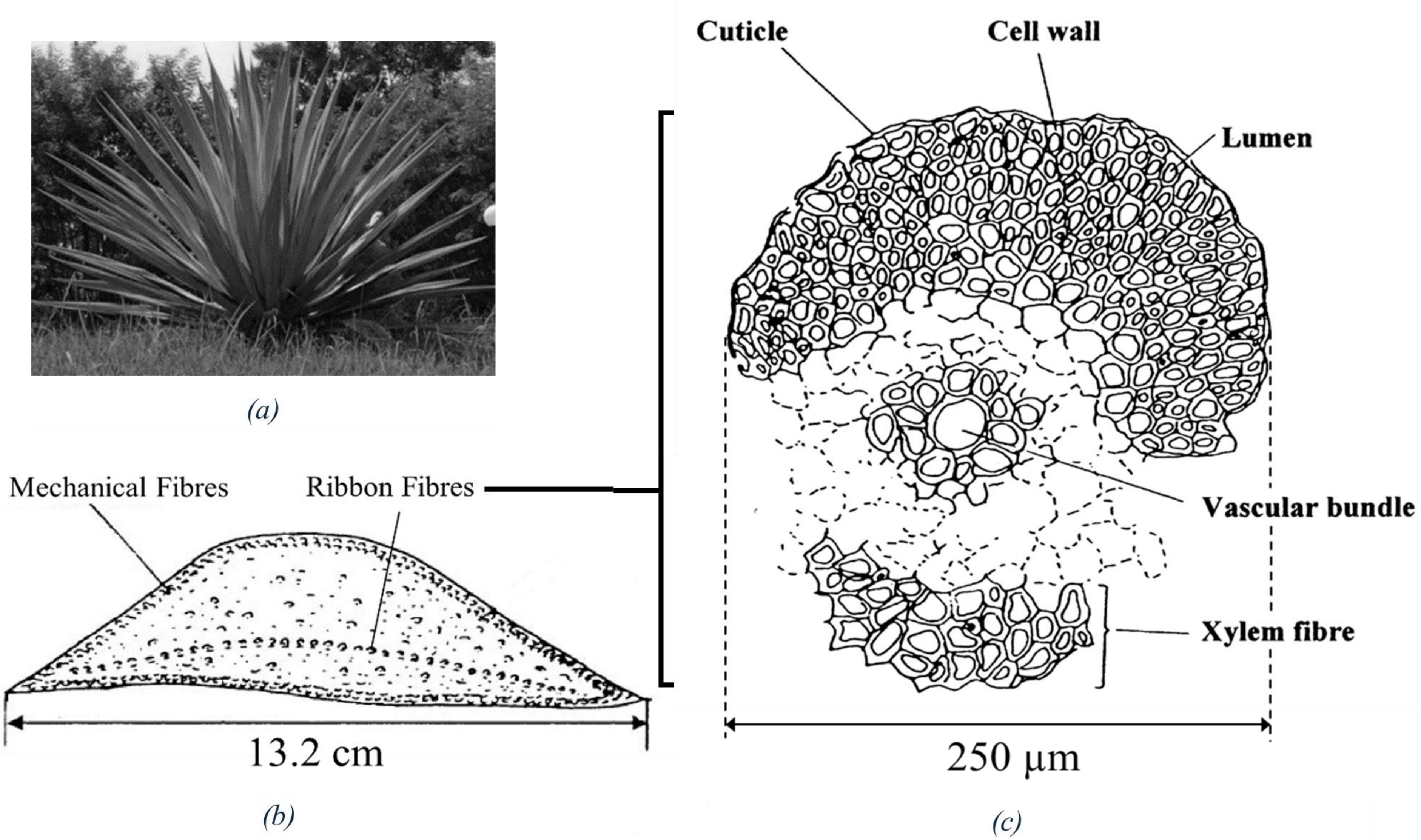
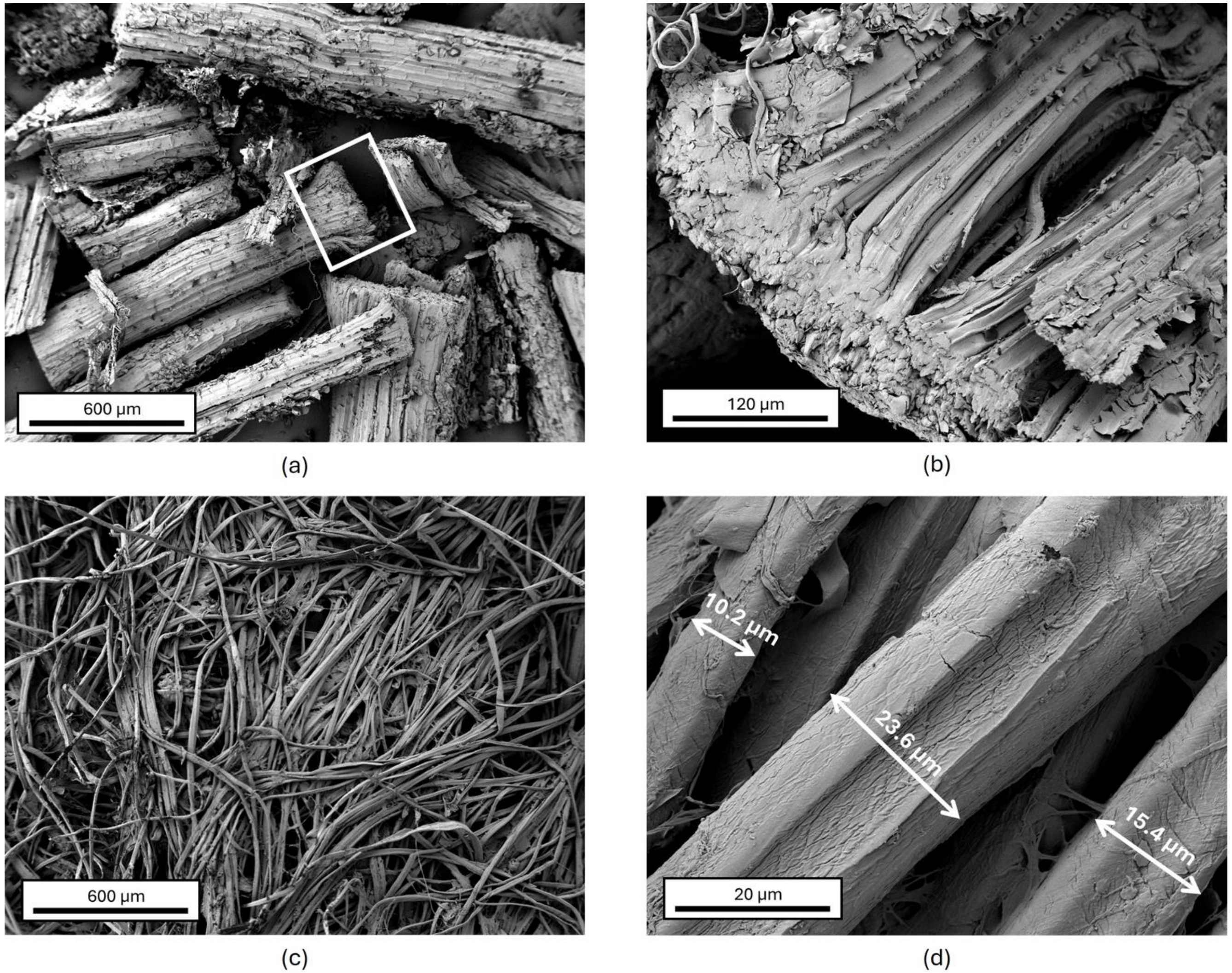
Henequen Fibre Structure



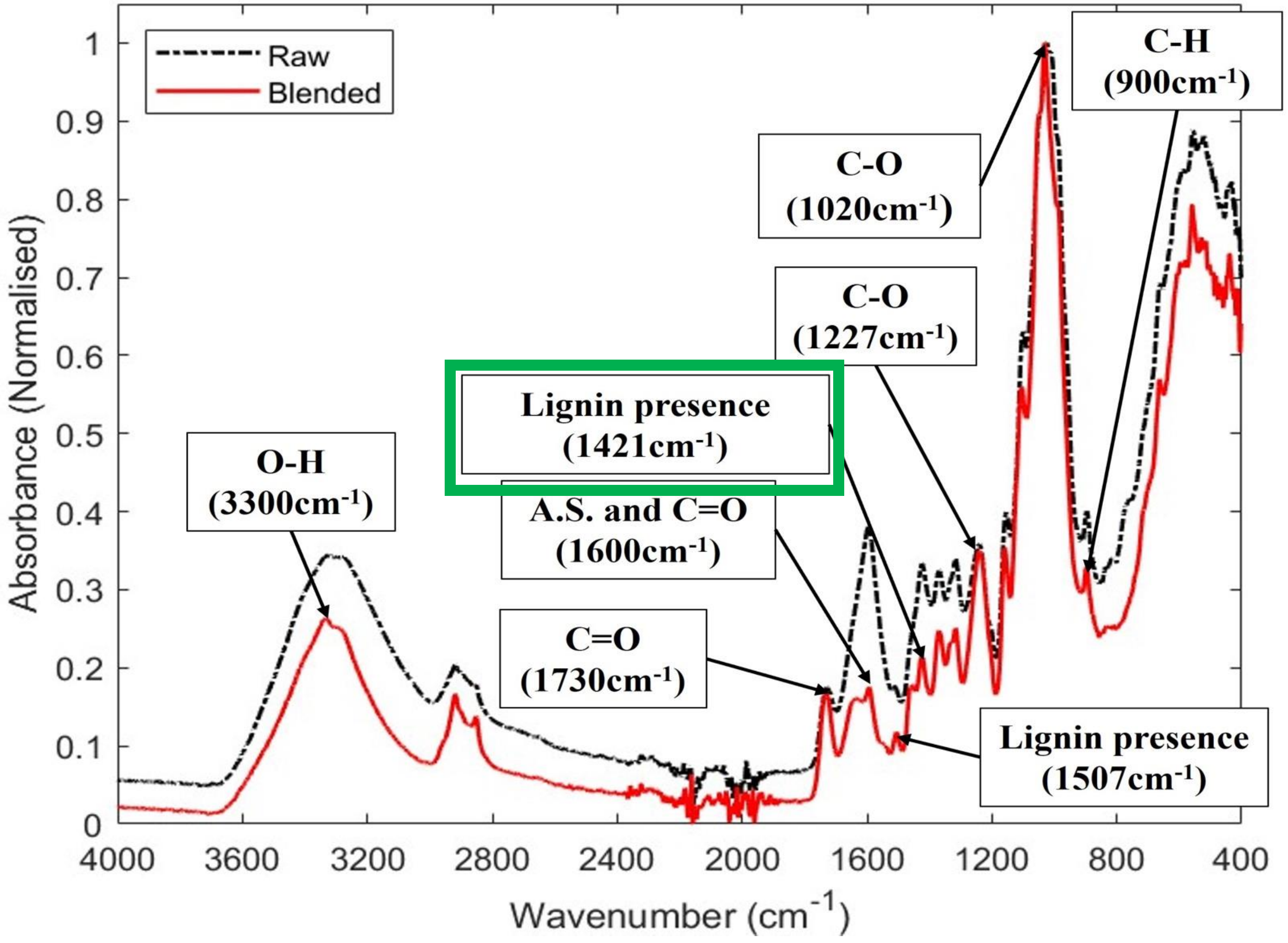
Bisanda E, Ansell MP. Properties of sisal-CNSL composites. Journal of Materials Science. 1992;27:1690-700.

Fibrillation

- Breaks fibre bundles into smaller ‘fibrils’ that branch out
- Allows for greater physical fibre-fibre interaction – fibres mechanically ‘lock together’
- Effective strategy to deliver stability of fibre network -> Interlocking prevents relative displacement of fibres



Simple Fibrillation Strategy using Blender



FTIR shows:

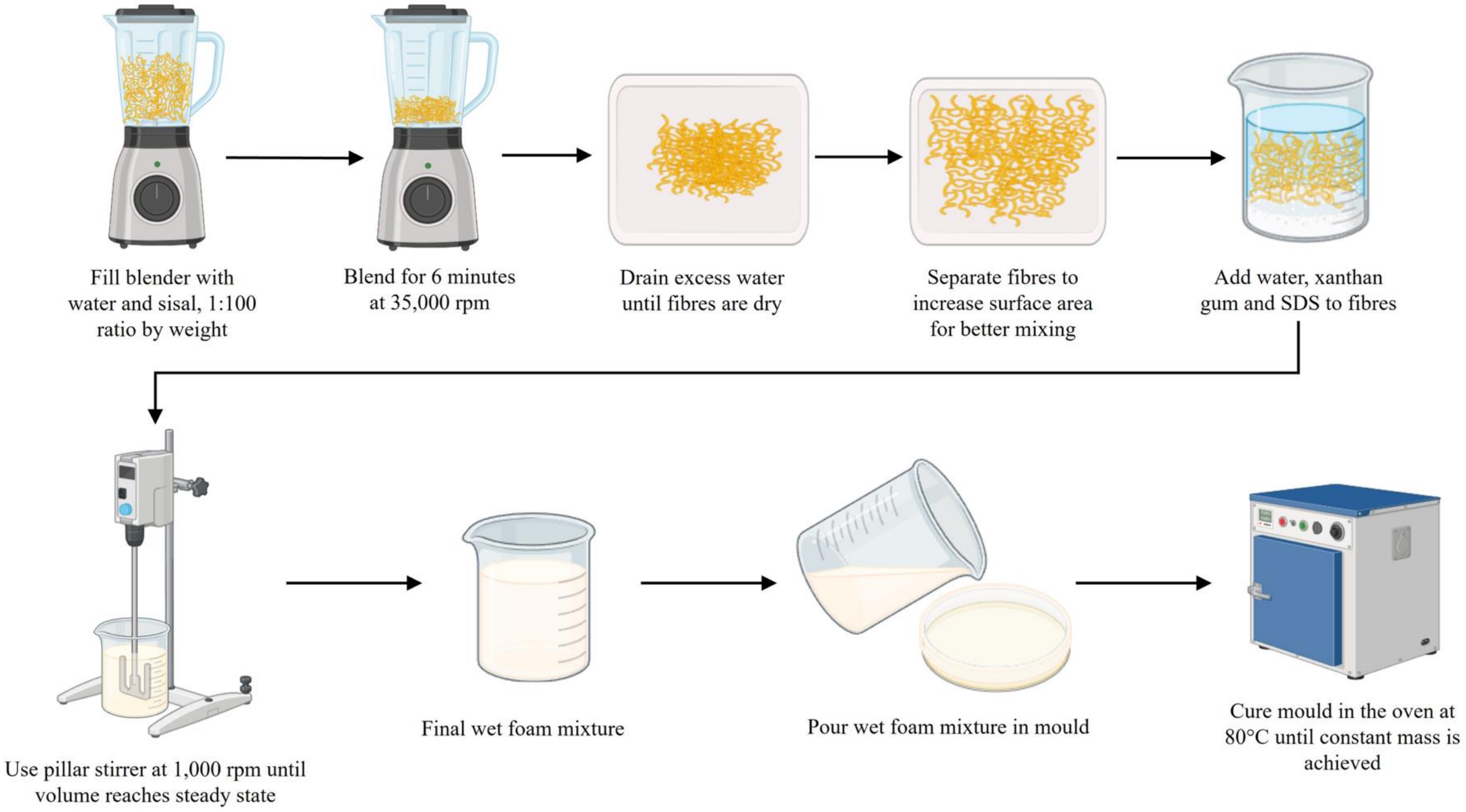
- Reduction (loss) of lignin
- Preservation of Hemicellulose

Blender observed to repeatably alter fibre geometry:

- Diameter Reduction: **381 µm → 21 µm (94.5%)**
- Length Reduction: **5.1 cm → 2.9 cm (45%)**
- Aspect Ratio Increase: **130 → 1400 (1076%)**

Foam 1 – Xanthan Gum Stabilised

Xanthan gum (a common food additive) used as binder for cellulose fibre foam)

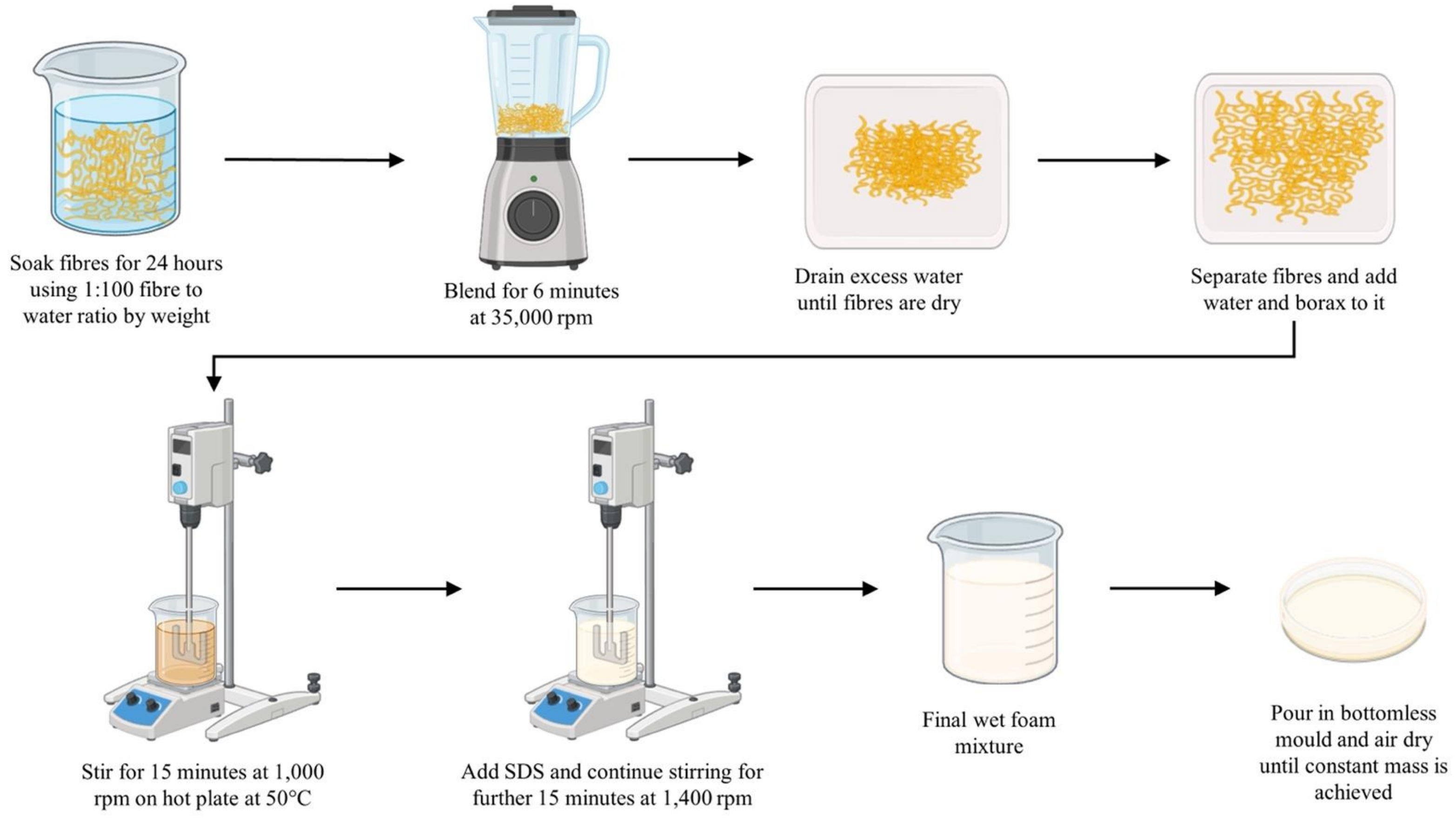


This foam is:

- Non-Toxic
- Easily Accessible
- Has not been explored for such uses
- Effective at very low concentrations of xanthan gum (0.5wt%)

Foam 2 – Borate Stabilised Foam

Addition of borate can help to stabilise cellulose fibre network (chemical interaction and cross-linking).



This foam is:

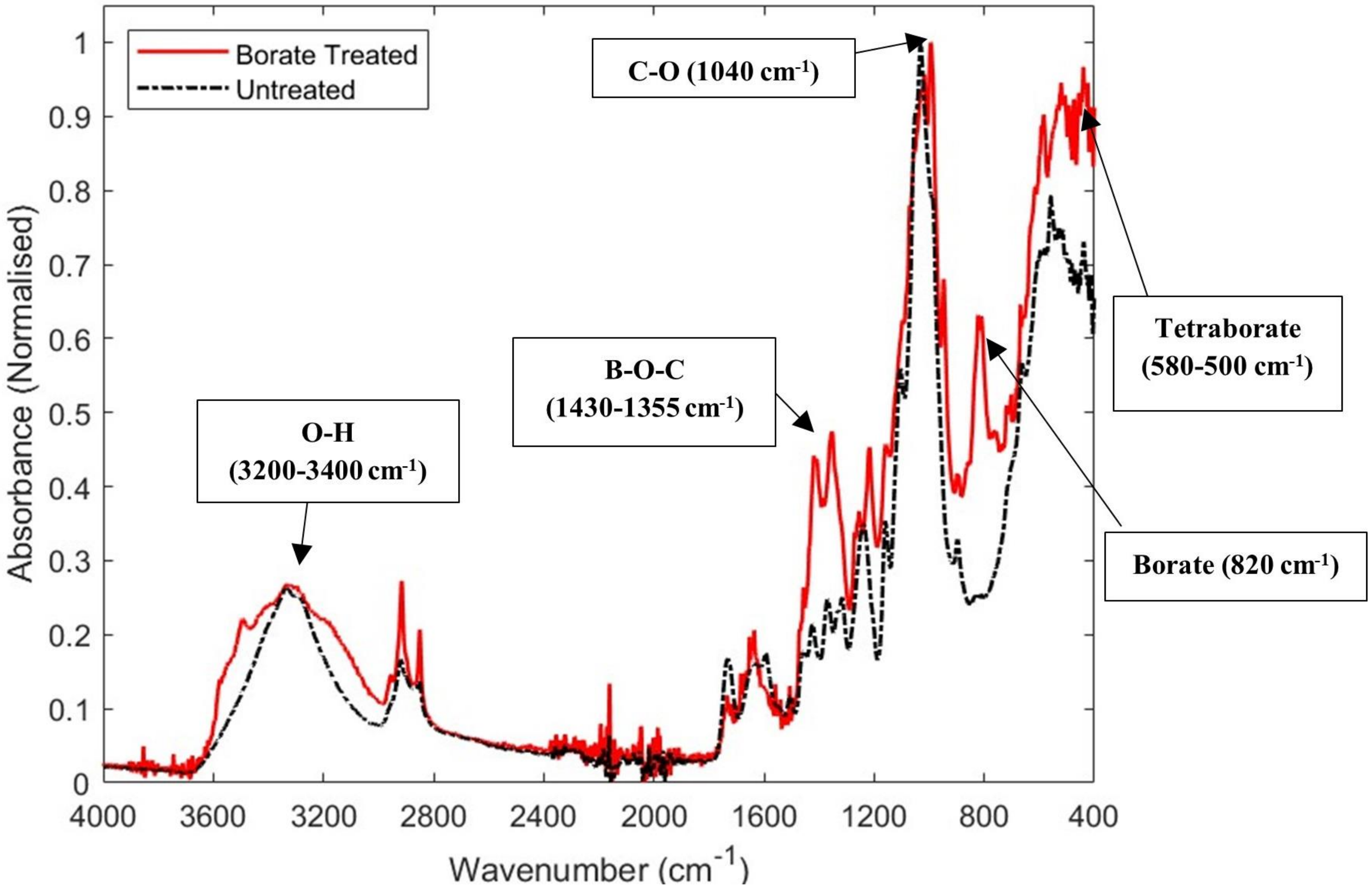
- Relatively safe/cheap
- Provides benefit at very low borax concentrations (1.5 – 2 wt%)
- Added to fibre solution prior to foaming process with minimal heating (~50^{o}C)

Borate Cross-Linking & Chemical Validation

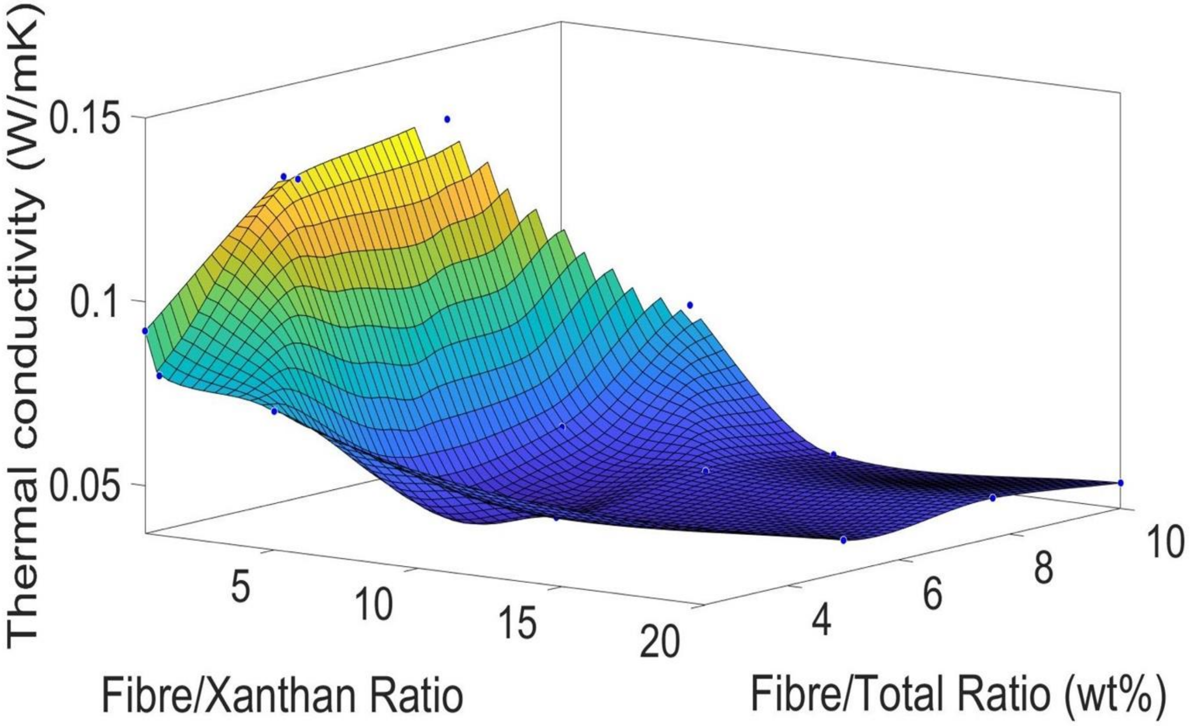
- **Chemical Cross-Linking in Borate Foam**: New **B–O–C peak (1355-1430 cm^{-1})** indicates Formation of borate linkage

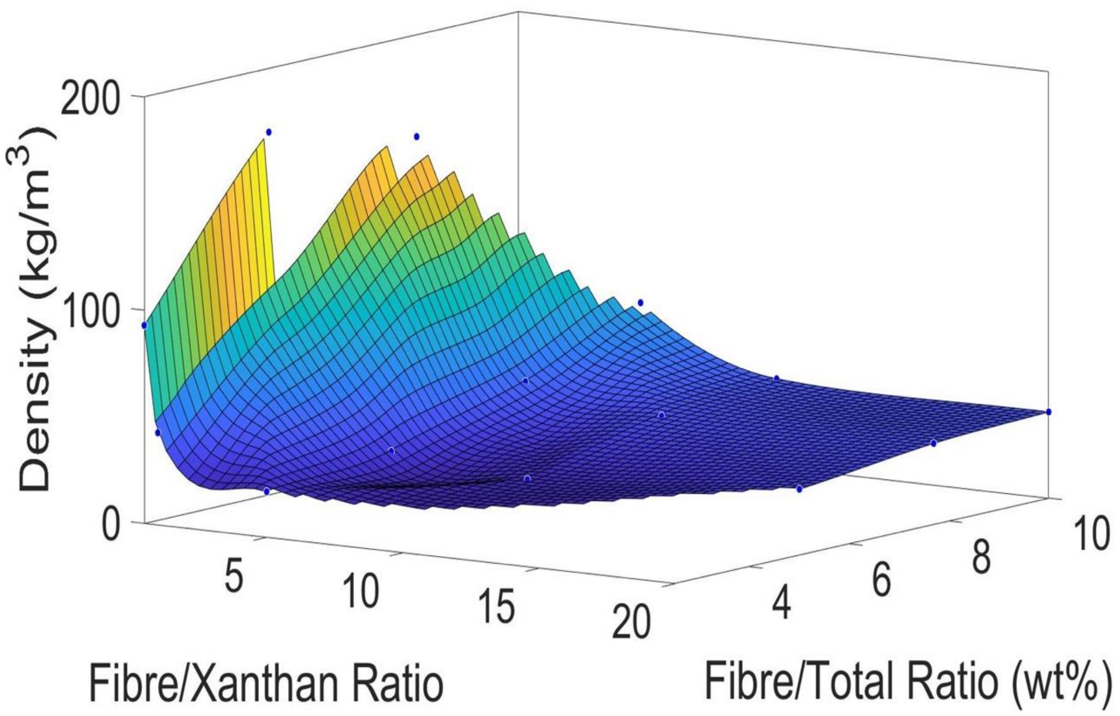
- Residual **borate (820 cm^{-1}) & tetraborate (580-500 cm^{-1})** observed

- Synergistic with delivery of flame resistant properties from borate.

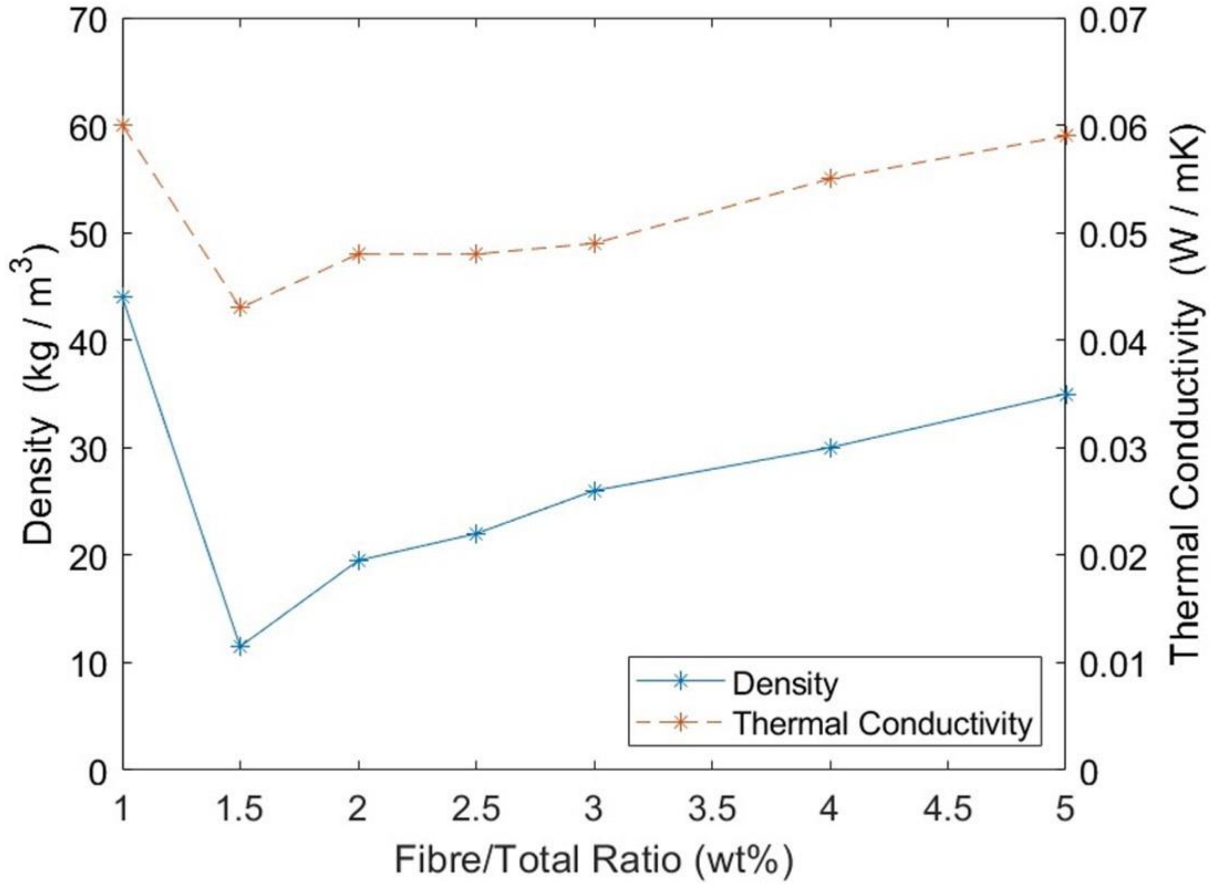


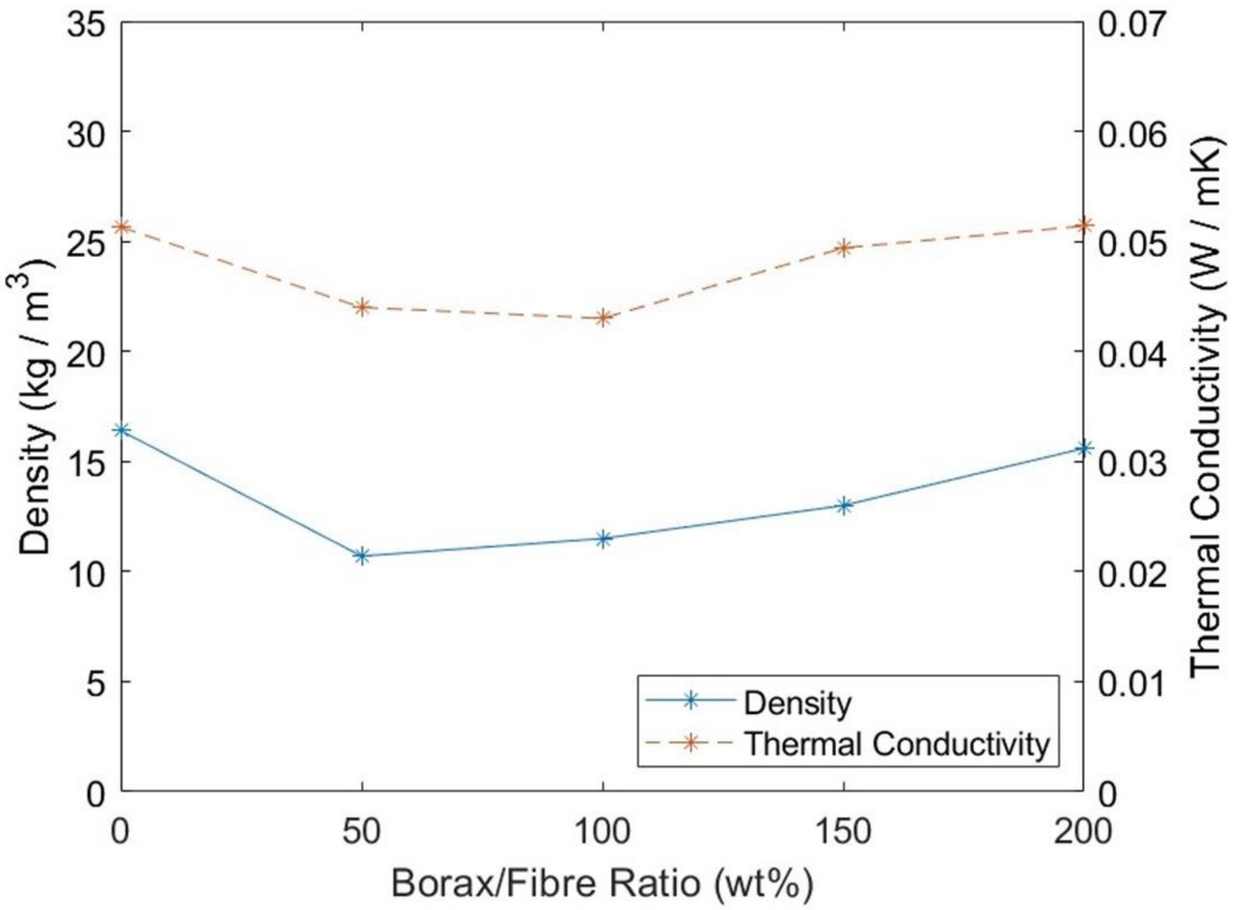
Optimising Thermal Resistance I





Optimising Thermal Resistance II





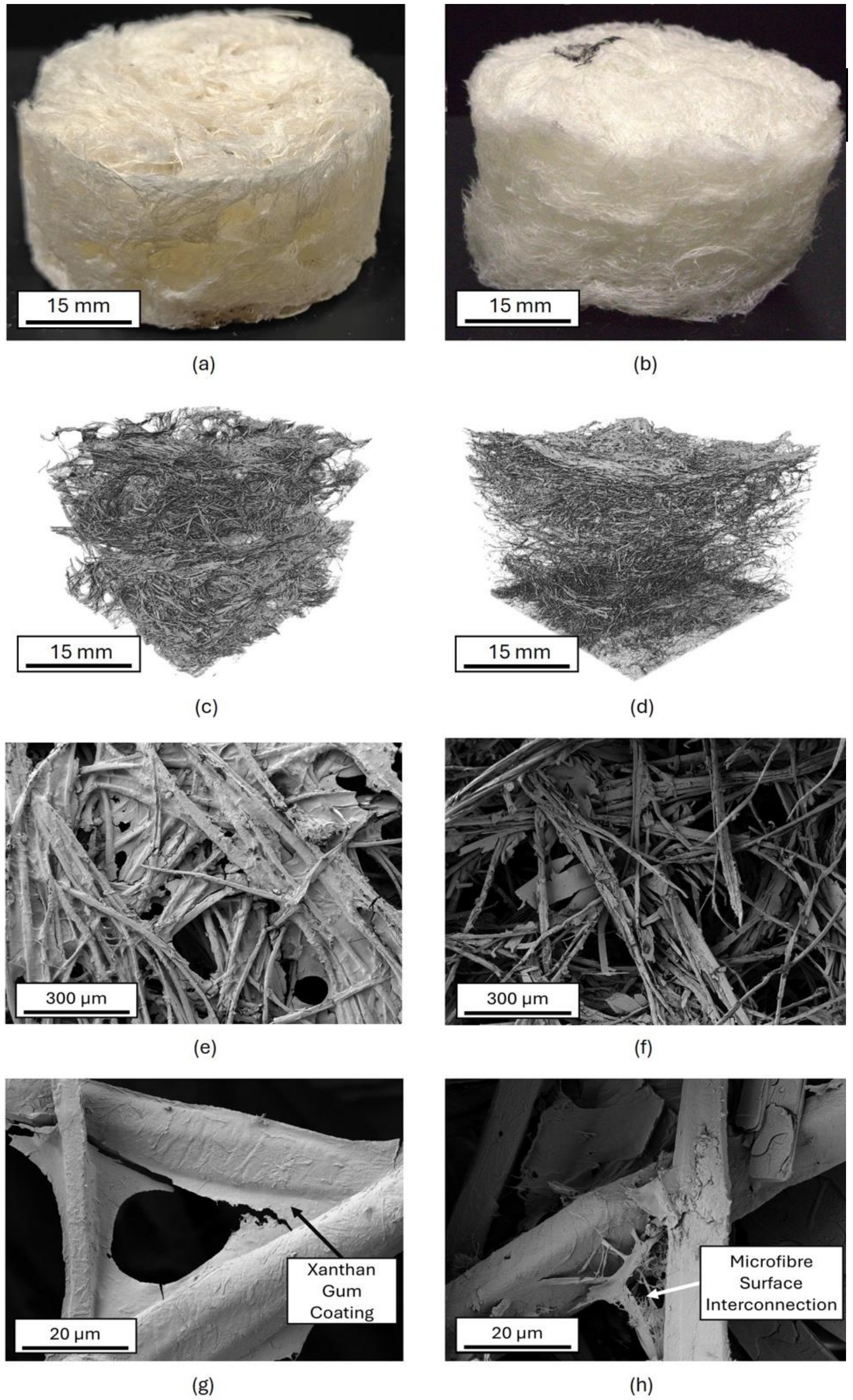
Structure – Density & Porosity

Foam Morphology & Porosity:

- CT scans confirm a **randomly oriented fibrous network**

- 94.4% porosity
- Fibres are coated and physically adhered by a gum layer
- Thin film at intersections stabilizes the structure

- 94.3% porosity
- Fibres physically linked forming branched junctions
- No binding agent required



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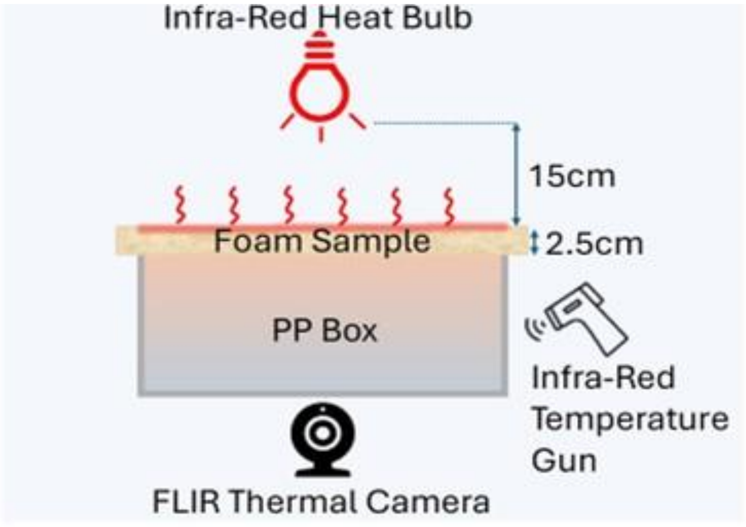
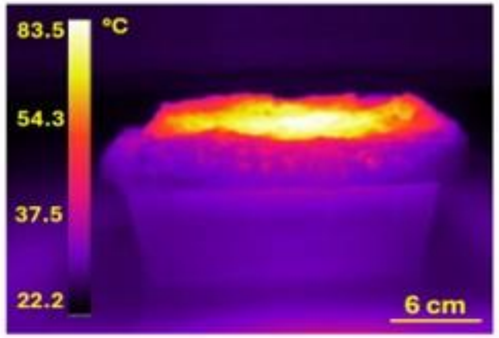
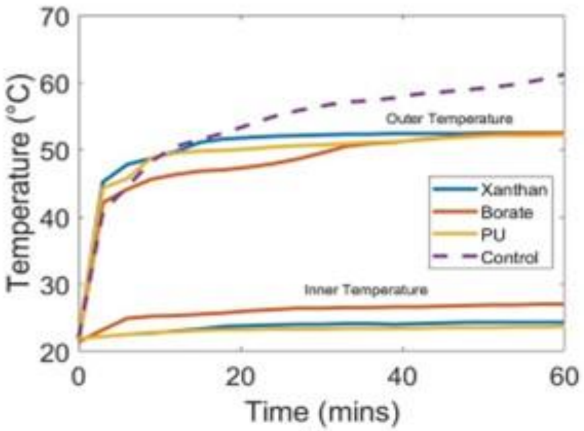
Thermal Imaging



(a)



(b)



(c)

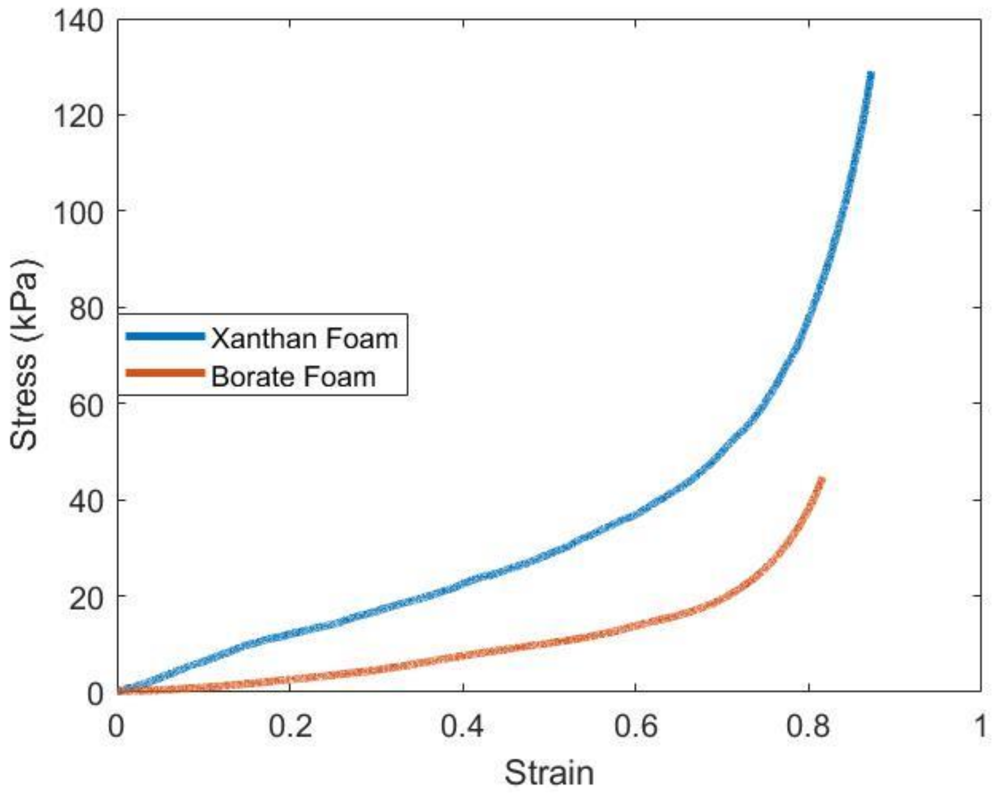
All foams demonstrate an improvement over control / insulating performance.

New design foams are comparable in performance to current PU solutions

Material	Outer Temperature (°C)	Temperature in box (°C)
Xanthan	83.5	27.3
Borate	52.5	27.0
PU Foam	54.1	24.9
Control	-	61.2

Mechanical Performance

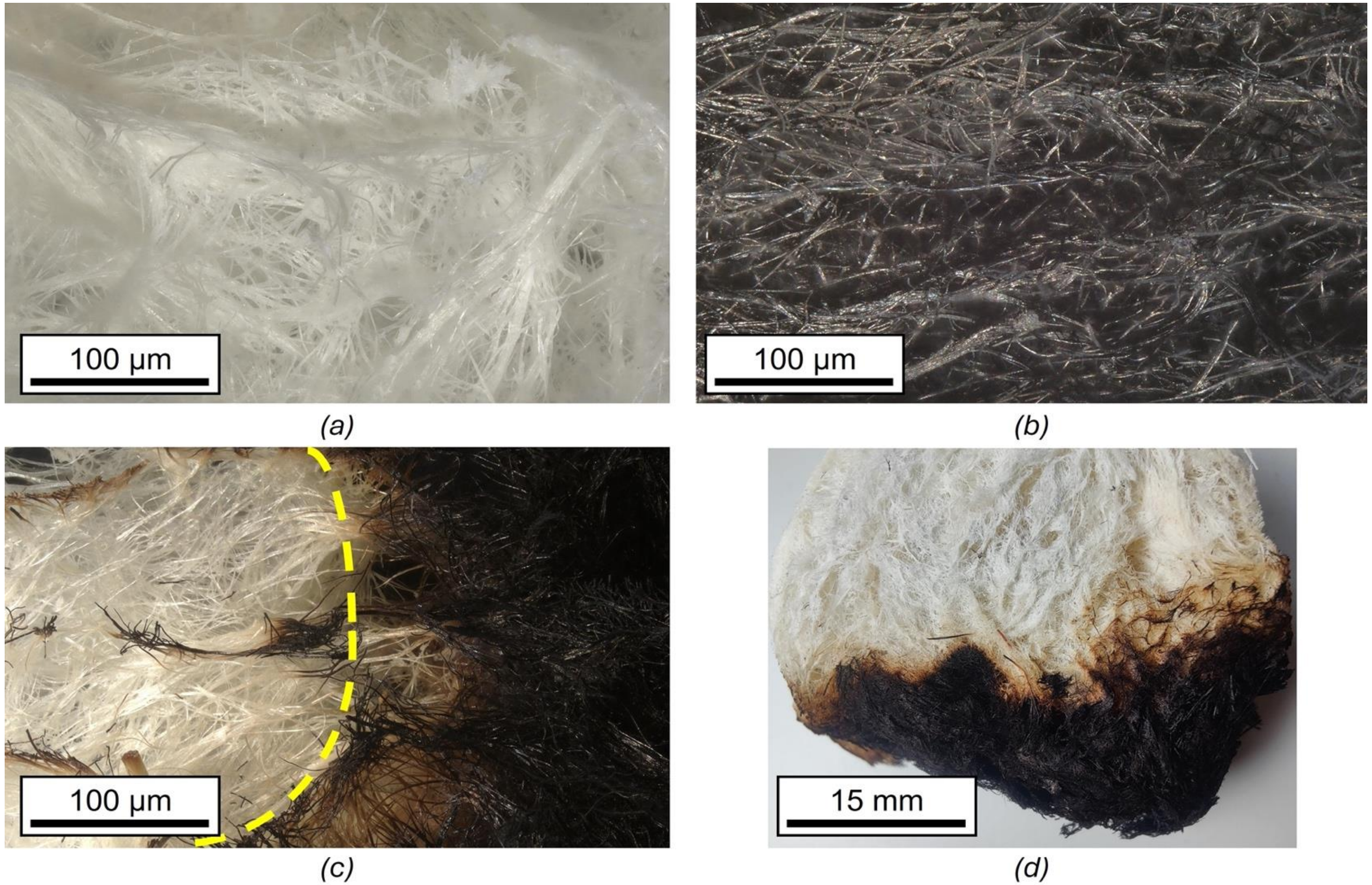
- **Two Distinct Deformation Phases:**
  - Elastic Regime: Initial fibre rearrangement and bending.
  - Strain Stiffening: Increased resistance due to fibre buckling.
    - Densification Effect: New fibre-fibre contacts form under large strains, increasing resistance.
- **Key Observations:**
  - Xanthan Foam: Higher stiffness (56.4 kPa) due to mechanical bonding.
  - Borate Foam: Lower stiffness (19.4 kPa) with chemical cross-linking.
  - Both foams exceed BS ISO 21844 (7 kPa at 10% strain).



Flame Resistance - Borates

Borate:

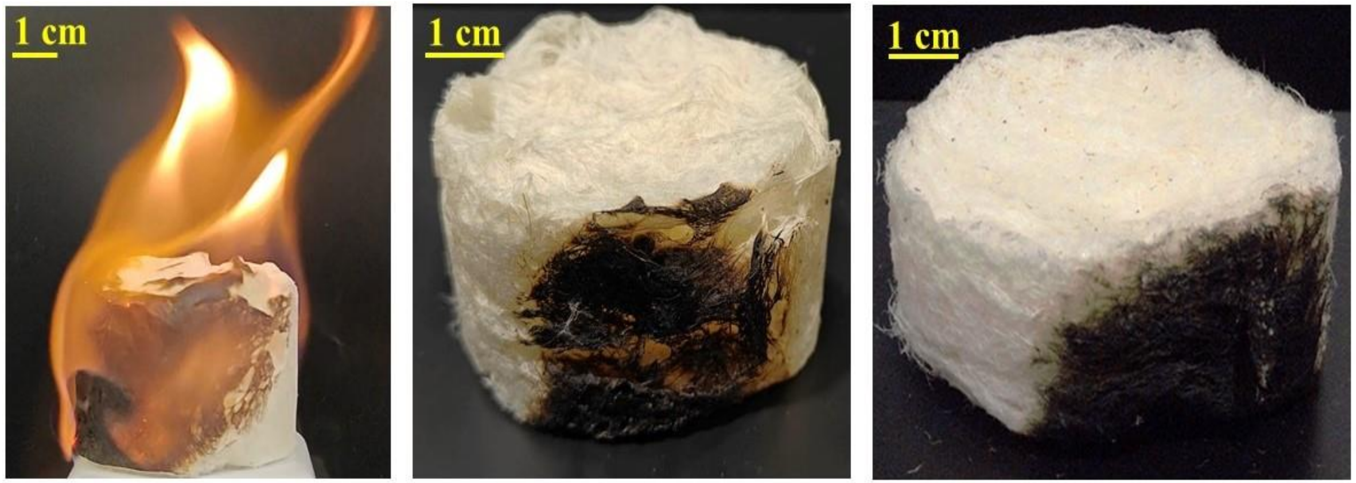
- Addition serves **dual purpose** - can be used to deliver both
  - flame resistance
  - stabilisation for foam design
- Natural sodium salt
- Effective at small concentrations (1.5-2 wt%)
- Homogenizes well



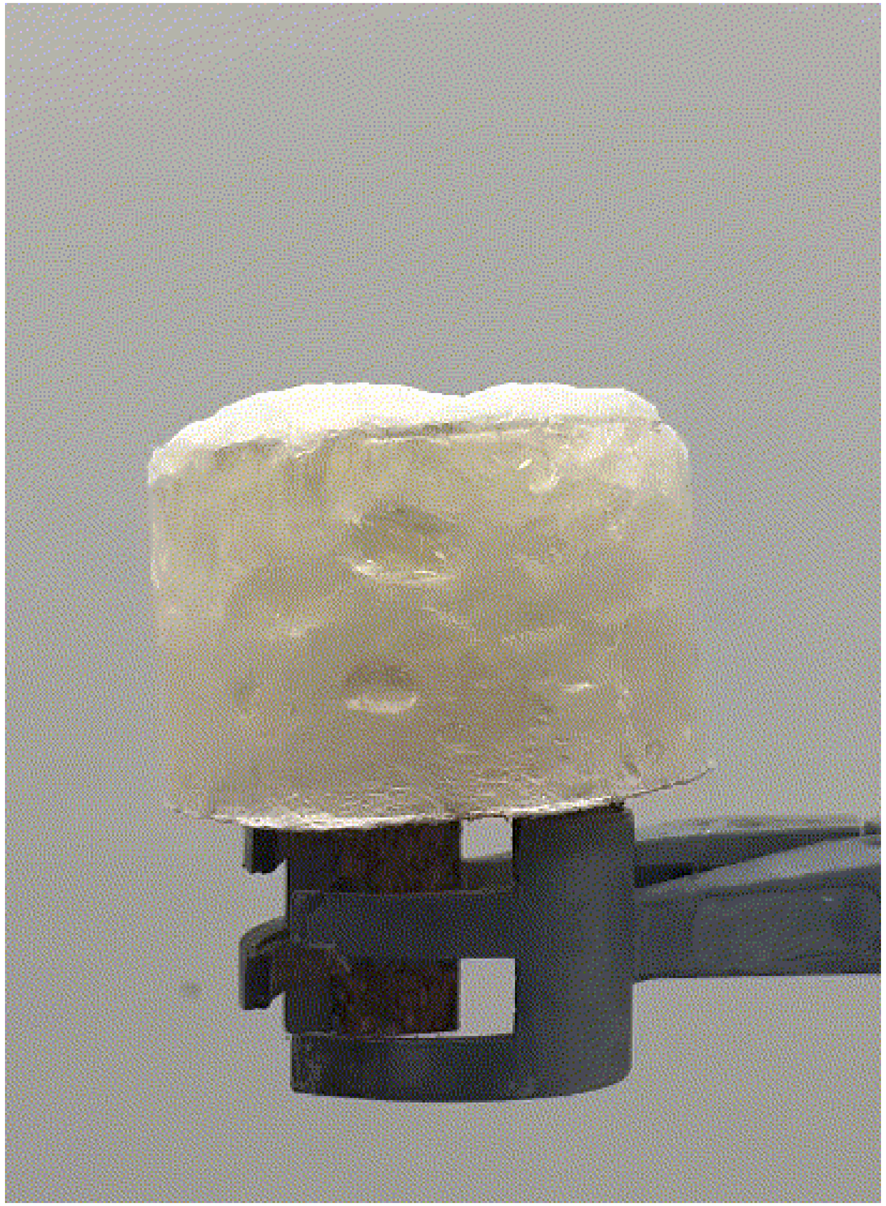
Flame Resistance - LOI

Results:

- Limiting Oxygen Index (LOI) Test (ASTM D2863)
- LOI Value: 29.5% → Classified as "Self-Extinguishing" (LOI >28%).



(a) (b) (c)



Comparison with Other Porous Materials

Density

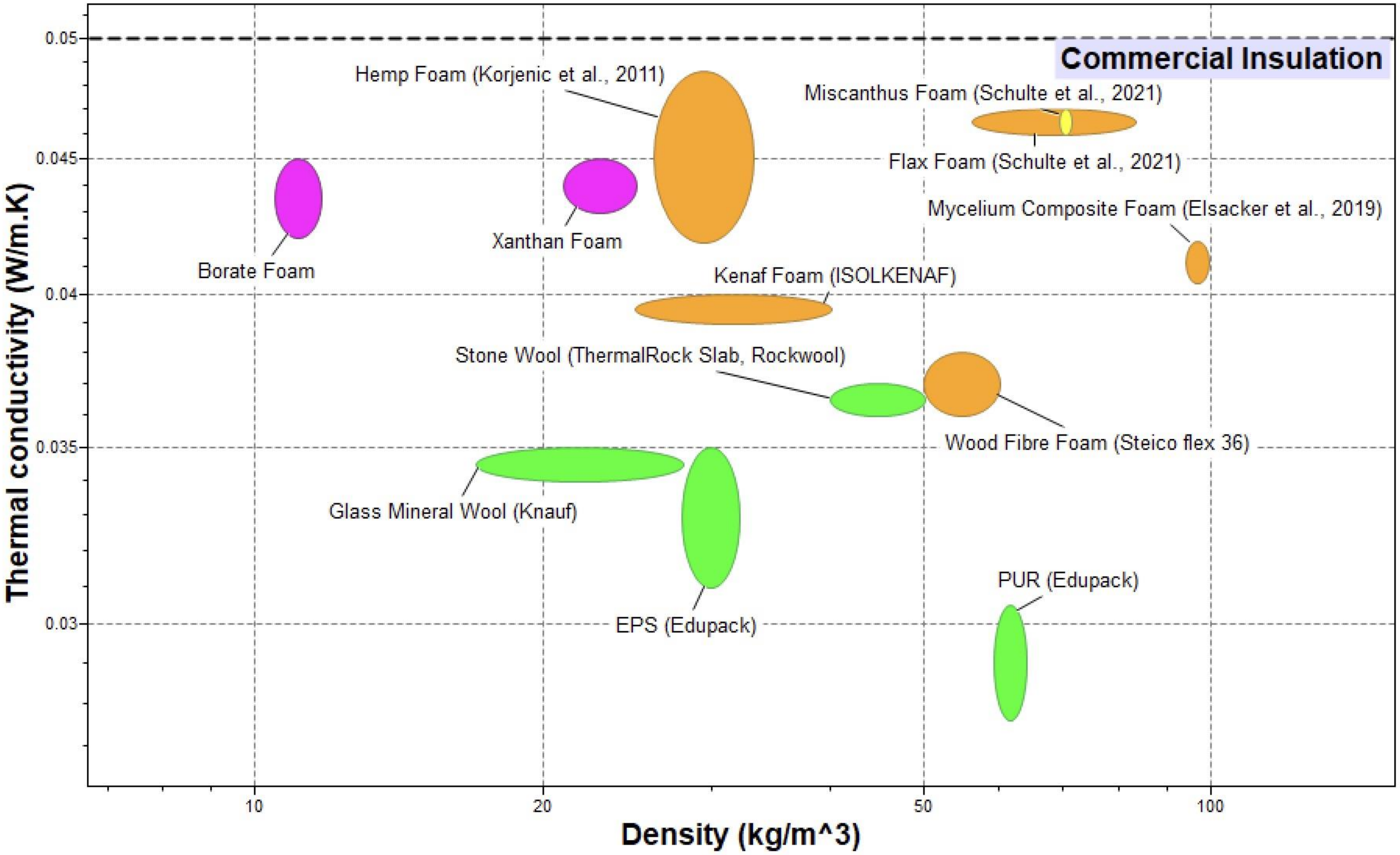
Lower than fossil-fuel and lignocellulosic insulation

→ **Resource-efficient**

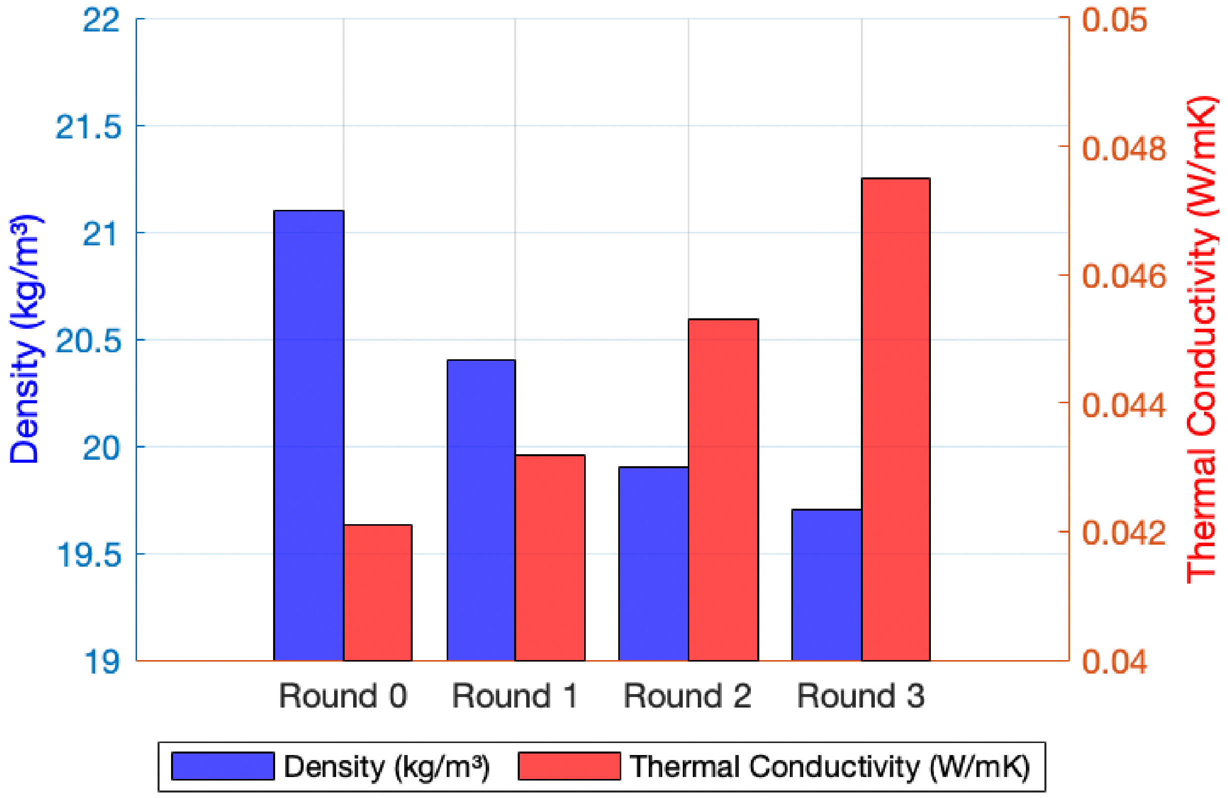
Thermal performance

Slightly poorer than **mineral wool & EPS**

Comparable to **bio-based insulation**



Recyclability



Xanthan foam can be recycled successfully: density and thermal conductivity were retained in 3 cycles.

Recycling achieves

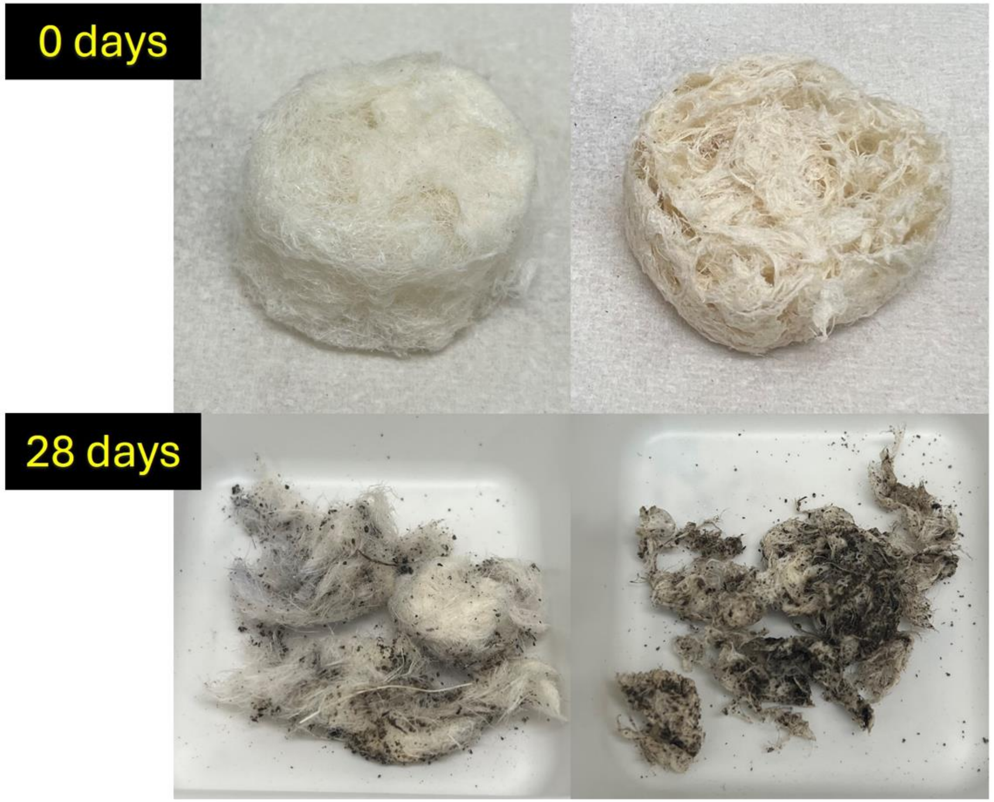
- Minimising waste and energy consumption
- Minimising carbon footprint
- Maintaining similar results to the original foam

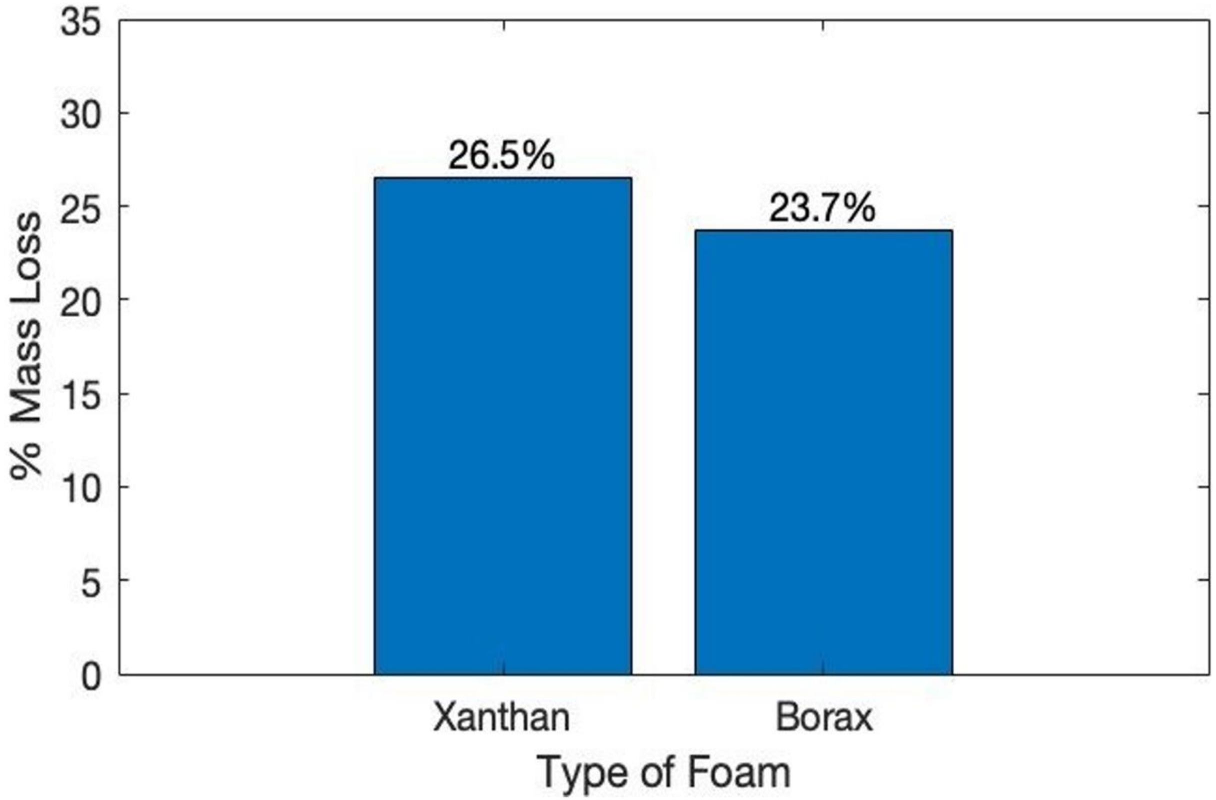
	Initial	Round 1	Round 2	Round 3
Density (kg/m3)	21.1	20.4	19.9	19.7
Thermal Conductivity (W/mK)	0.0421	0.0432	0.0453	0.0475

Biodegradability

Biodegradability shows promising results:

- Xanthan Foam loses 26.5% of its mass
- Borate Foam loses 23.7% of its mass

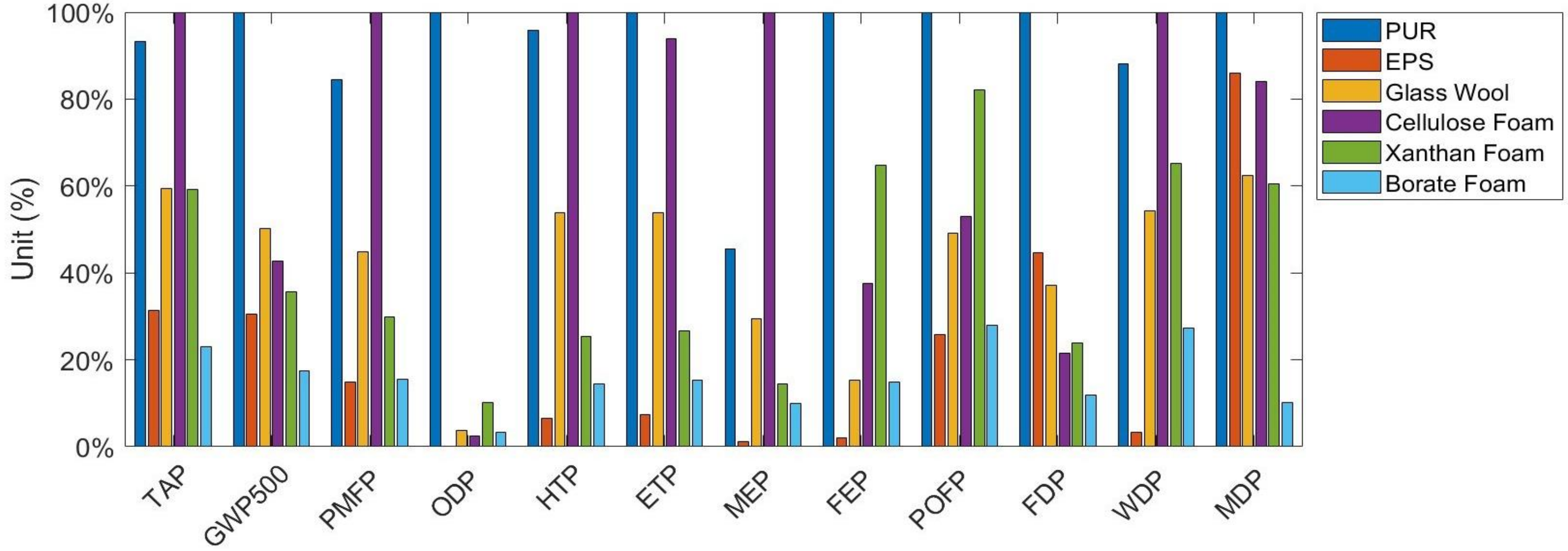




Life Cycle Assessment

- Borate Foam: 3.81 kg CO_2 / functional unit
- Xanthan Foam: 7.62 kg CO_2 / functional unit
  - Main contributors: 🚜 Diesel (30-55%) ⚡Electricity (30-50%)
- Glass Wool Comparison: lower impact overall but higher freshwater eutrophication & water use

- PUR Foam Comparison
  - Lower toxicity (HTP, ETP) (up to 90%)
  - Lower global warming potential (80% Borate)
  - Lower fossil fuel depletion (90% Borate, 80% Xanthan)
  - Lower water use (90% Borate, 40% Xanthan)



Key Takeaways

Combination of materials and methods as potential building blocks of high-performing foams for thermal insulation applications

Interlocking fibres

- Reduced Density
- Increased Porosity
- Stabilised foam

Borax

- Safe
- Cheap
- Crosslinking-stable foam structure
- Flame Retardancy

Xanthan Gum

- Easily Accessible
- Effective binder – low concentration
- Non-toxic
- Previously not used in construction

Thank you!

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Supported by:

- Royal Society: International Exchanges Scheme 2020 (Grant No.507 IES/R1/201026)
- CONAHCYT: Ciencia Básica 2017–2018 (Grant No.509 A1-S-8864)