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RESEARCH GROUP IN SUSTAINABLE CONSTRUCTION
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VSB TECHNICAL UNIVERSITY OF OSTRAVA

Multi-criteria development of lightweight hemp-shive composite panels incorporating gasified wood pellets for sustainable construction products

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Sustainability matters under European Construction Products Regulation: (EU) 2024/3110

For natural and bio-based construction products, sustainability must be demonstrated together with essential technical performance.

Green transition

- Life-cycle assessment and environmental performance become central evidence.
- Lower embodied carbon, efficient use of raw materials, and circularity gain strategic importance.

Digital transparency

- Traceability of raw materials and product data supports credibility and market access.
- Digital product information strengthens comparability, compliance and verified claims.

Natural raw materials (timber, hemp, cork, fibres, agricultural residues) → **Processing & manufacturing** → **Construction product** → **Technical + environmental evidence** (LCA · traceability · declared performance) → **Compliant market access**

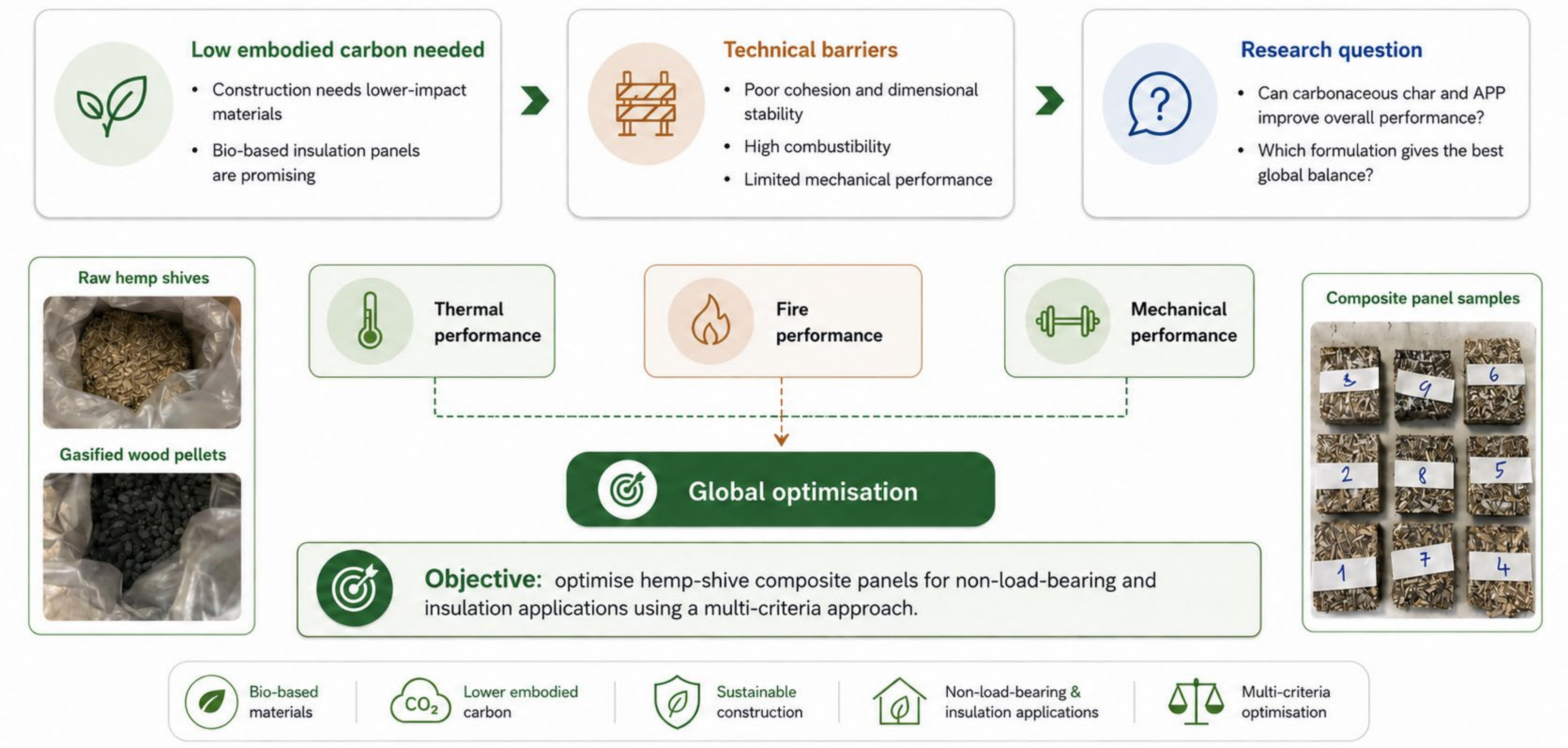
Essential technical characteristics to be demonstrated

1. Structural integrity Mechanical performance and robustness	**2. Fire safety** Reaction to fire and fire resistance
3. Hygiene & health Low-emission and safe material behaviour	**4. Safety in use** Reliable performance in service
5. Acoustic performance Sound insulation and comfort	**6. Thermal performance** Energy efficiency and insulation capacity
7. Outdoor emissions Environmental impact during the life cycle	**8. Sustainable resources** Resource efficiency, reuse and recyclability

Sustainability supported by measurable technical performance, traceability and life-cycle evidence.

Research motivation and novelty

Developing lightweight bio-based panels for sustainable construction



Materials, formulations and panel manufacturing

Inputs, experimental design and processing. Target nominal density 300 kg/m^3.

Taguchi L9 experimental design (3 factors × 3 levels)

Factor	Levels		
Gasified wood pellets (wt.%)	5	10	15
MUF resin (wt.%)	8	12	16
APP (wt.%)	3	5	7

3 reference panels without gasified wood pellets and APP

Target density ≈ 300 kg/m^3

Exp.	Gasified wood pellets	MUF	APP	Raw HS
1	5	8	3	84
2	5	12	5	78
3	5	16	7	72
4	**10**	**8**	**5**	**77**
5	10	12	7	71
6	10	16	3	71
7	15	8	7	70
8	15	12	3	70
9	15	16	5	64

Three additional panels without gasified wood pellets and APP were produced using 8, 12 and 16 wt.% MUF. They provide a baseline but are not part of the screening ANOVA.

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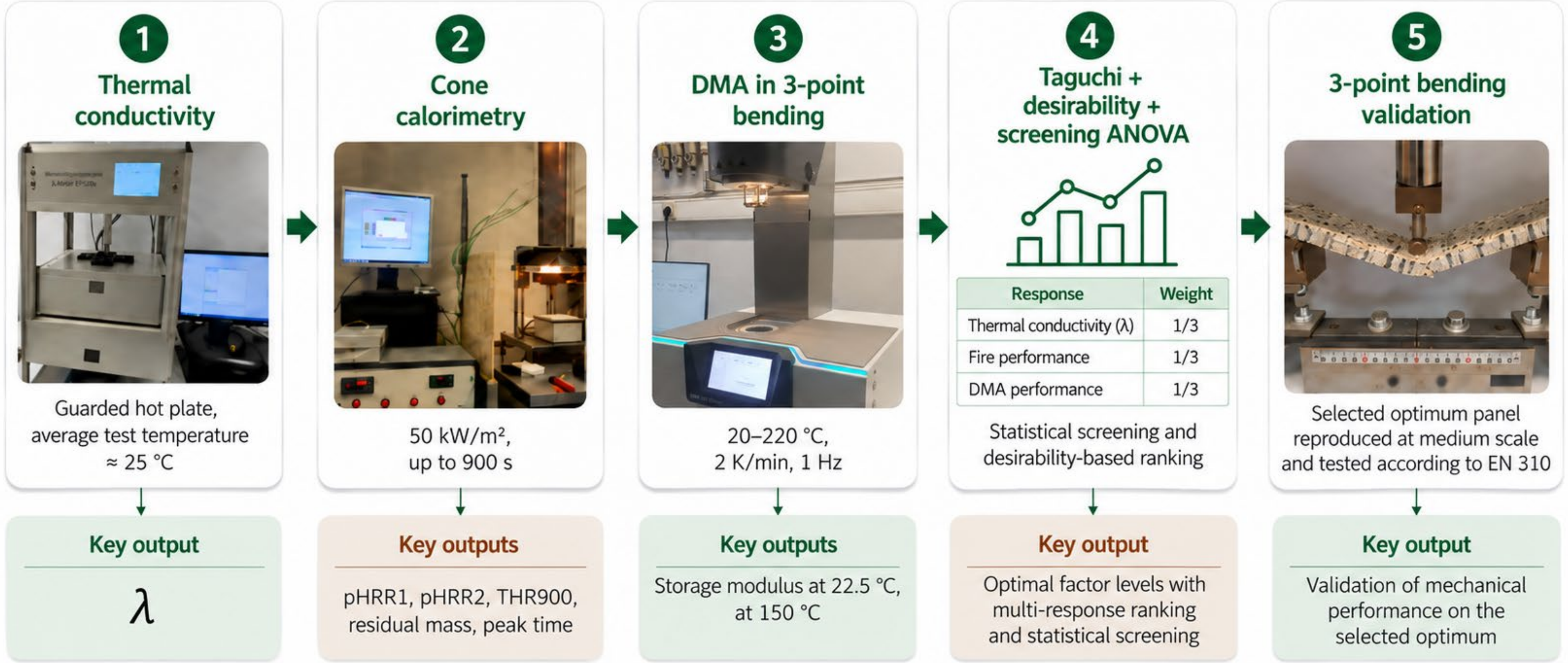
Experimental Programme and response variables

Testing and multi-response optimisation

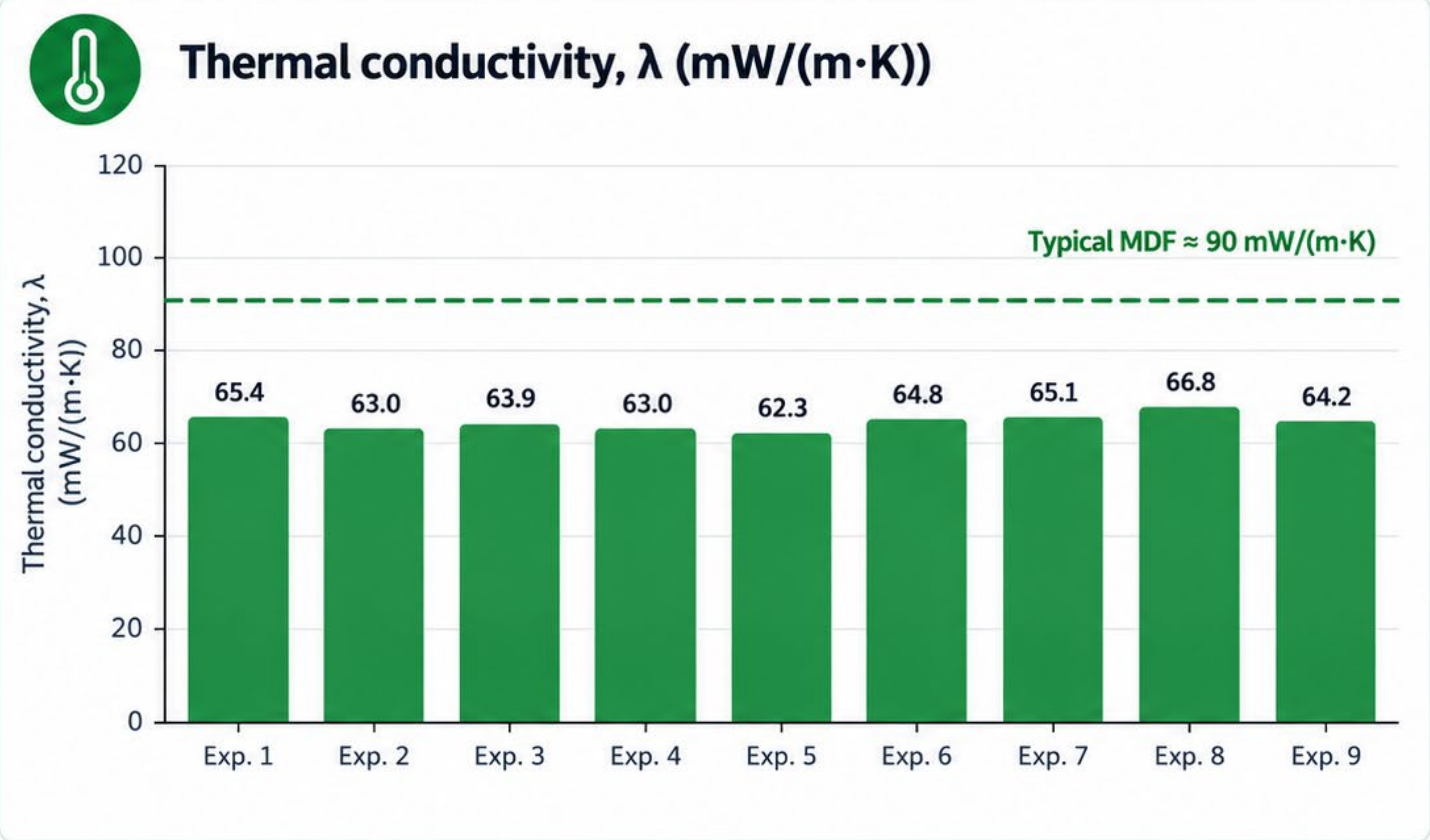


Response	Weight
Thermal conductivity (λ)	1/3
Fire performance	1/3
DMA performance	1/3

Decision: lower λ, pHRR and THR are better; higher residue, peak time and thermomechanical retention are better. ANOVA and equal-weight CDI (1/3 + 1/3 + 1/3) are applied to thermal, fire and DMA responses to identify the optimum formulation, which is then reproduced at medium scale for EN 310 three-point bending validation.

Thermal and fire reaction performance

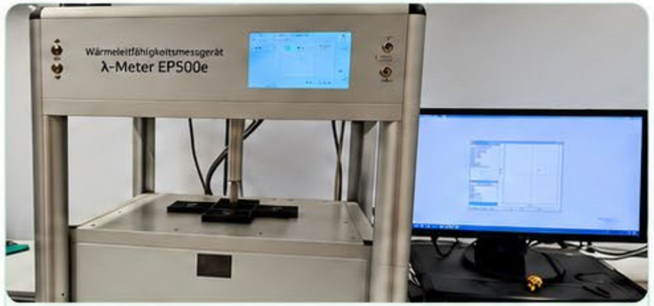
Main results



λ range
62.33 – 66.77 mW/(m·K)

Best thermal value
Exp. 5 = 62.33 mW/(m·K)

All formulations remained below the MDF reference.

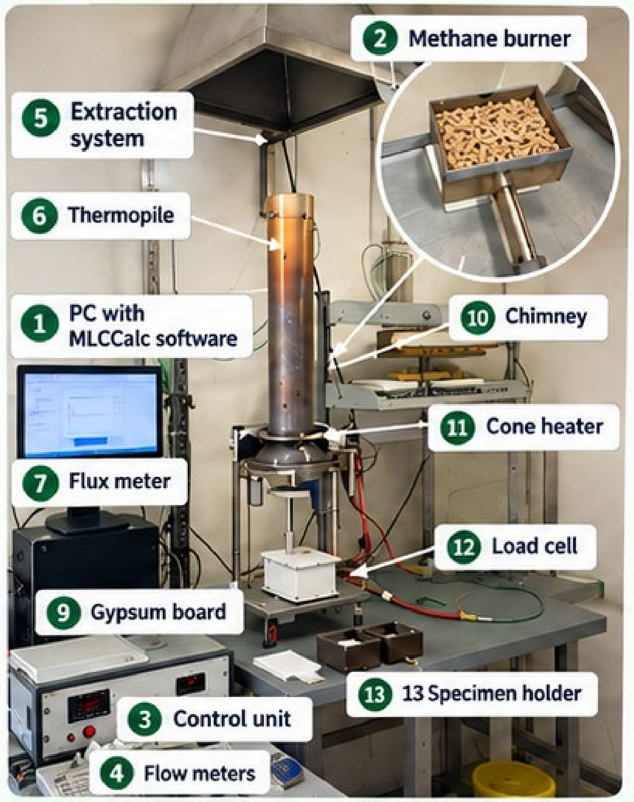


Thermal conductivity measurement equipment
Hot plate apparatus (λ-Meter EP500e) used for evaluating the thermal conductivity of the hemp-gasified wood pellets panels.

Thermal and fire reaction performance

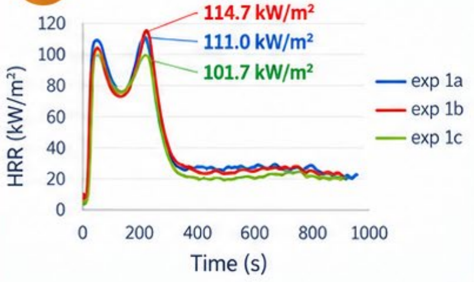
Main results

Cone calorimeter setup

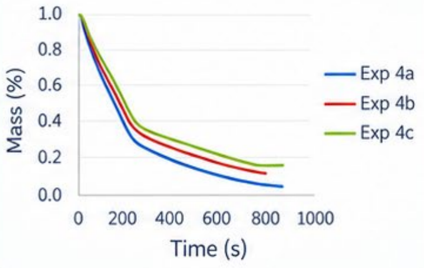


Test sequence (representative example)

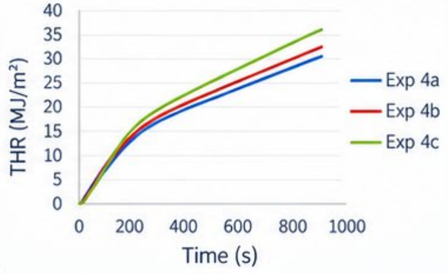
Heat release rate (Experiment 1)



Mass evolution (Experiment 4)



Total heat release (Experiment 4)



Key results (across test campaign)

pHRR1
64.4 – 88.3
kW/m²

pHRR2
75.4 – 116.6
kW/m²

THR900
21.6 – 32.2
MJ/m²

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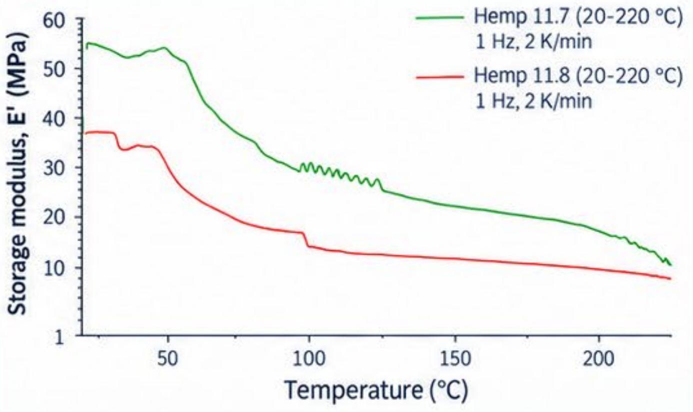
DMA Methodology and thermomechanical response

Three-point bending DMA for stiffness retention at elevated temperature

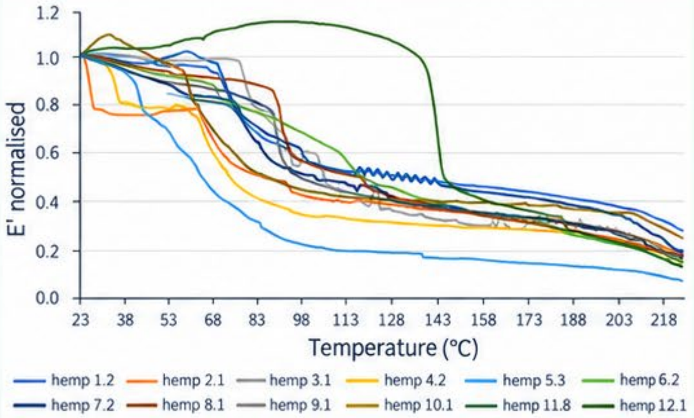
DMA setup and tested specimens

Three-point bending DMA at elevated temperature; cut specimens prepared from composite panels.

Measured storage modulus, E' vs. temperature



Normalised stiffness retention, $E'/E'_{23\,°C}$

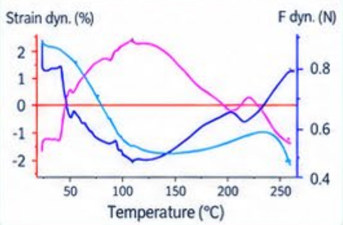


Test protocol

Test mode	3-point bending DMA
Temperature range	20 – 220 °C
Heating rate	2 K/min
Frequency	1 Hz

Key measured outputs

- Storage modulus E'(T) for selected formulations
- Normalised $E'/E'_{23\,°C}$ retention curves
- Representative force/strain response during heating



DMA adds valuable insight

- DMA reveals formulation-dependent thermomechanical stability and complements thermal and fire metrics in the multi-criteria optimisation.

Main limitation

- Marked stiffness degradation with temperature and variability between formulations remain key constraints for non-load-bearing applications.

Combined Desirability Index (CDI) methodology

Thermal, fire and thermomechanical responses combined

1 Normalization

All responses were normalised to a 0–1 range using min–max normalization:

$$n(x) = \frac{x - \min(x)}{\max(x) - \min(x)}$$

- $n(x) \in [0, 1]$ for all responses
- Enables comparison of responses with different units and ranges
- Used for both normalised and non normalised data

2 Global desirability equation

$$D = \frac{1}{3} D_{\text{fire}} + \frac{1}{3} D_{\lambda} + \frac{1}{3} D_{\text{DMA}}$$

Fire desirability (D_{fire})

$$\begin{aligned} D_{\text{fire}} = {} & 0.30[n(\text{PHRR}_1) + n(\text{PHRR}_2)] \\ & + 0.30[(1 - n(\text{PTime}_1)) + (1 - n(\text{PTime}_2))] \\ & + 0.20[(1 - n(\text{Residue}_1)) + (1 - n(\text{Residue}_2))] \\ & + 0.20[n(\text{THR}_1) + n(\text{THR}_2)] \end{aligned}$$

Thermal conductivity desirability (D_{λ})

$$D_{\lambda} = n(\lambda)$$

DMA desirability (D_{DMA})

$$D_{\text{DMA}} = 0.50(1 - n(E'_{22.5^{\circ}\text{C}})) + 0.50(1 - n(\text{Retention}_{150^{\circ}\text{C}}))$$

3 Weight summary

Group weights (global CDI)

Response group	Weight
Fire performance (D_{fire})	1/3
Thermal conductivity (D_{λ})	1/3
DMA performance (D_{DMA})	1/3

Within fire group (D_{fire})

Response (per test)	Weight
PHRR	0.30
PTime	0.30
Residue	0.20
THR	0.20

Within DMA group (D_{DMA})

Response	Weight
Storage modulus at 22.5 °C ($E'_{22.5^{\circ}\text{C}}$)	0.50
Retention at 150 °C	0.50

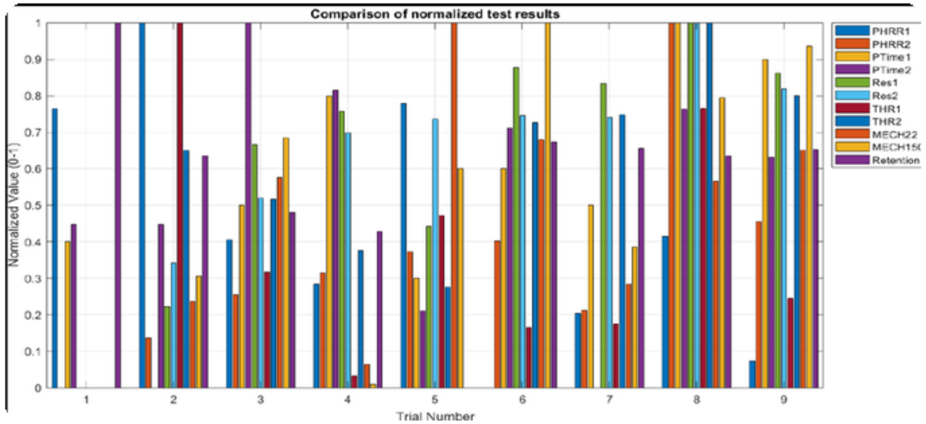
Lower D is Better: lower λ, pHRR and THR are better; higher residue, peak time PTime, $E'_{22.5^{\circ}\text{C}}$ and thermomechanical retention are better.

Combined Desirability Index (CDI) methodology

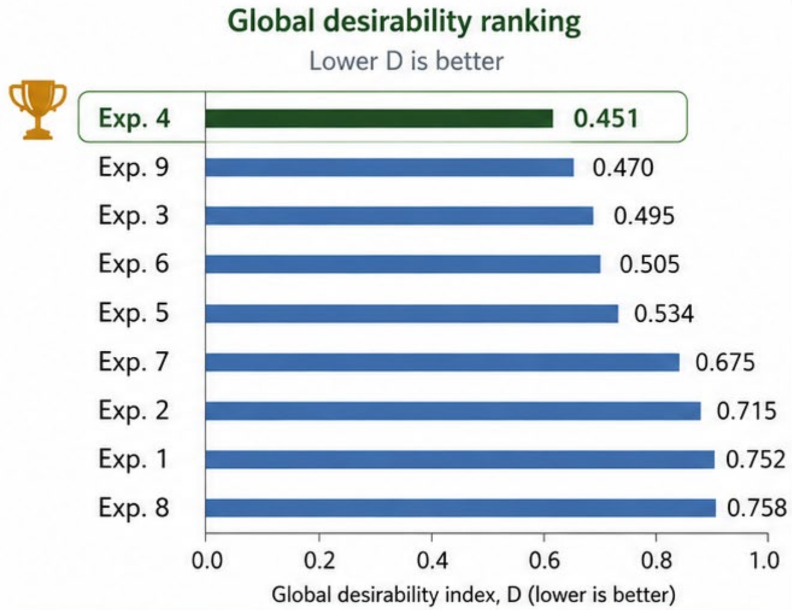
Thermal, fire and thermomechanical responses combined

Normalised response matrix

All measured responses scaled to 0–1 before combination

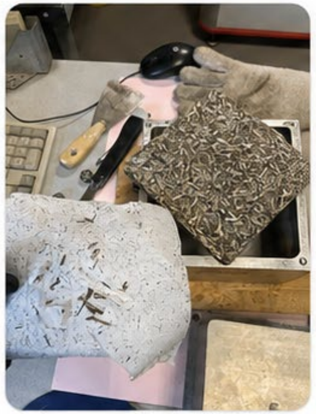


Purpose Screen the complete multi-response dataset and identify trade-offs between fire, thermal and thermomechanical behaviour.



BEST OVERALL FORMULATION

Experiment 4 = 10 wt.% torrefied hemp + 8 wt.% MUF resin + 5 wt.% APP + 77 wt.% raw hemp shives



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Scale-Up to medium scale EN310 validation

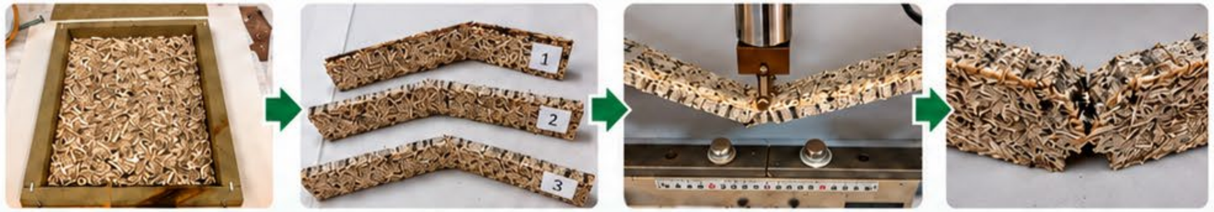
Thermal, fire and thermomechanical responses combined

2 Medium-scale manufacturing

- Weigh & mix
- ↓
- Press in medium-scale mould
- ↓
- Cool under pressure
- ↓
- Trim and cut specimens

MonTech LP 3000 press

From panel to test specimens



Larger sample production — Mould filled with gasified wood pellets mixture

Test specimens (EN 310) — Three 50 mm wide samples cut from the board

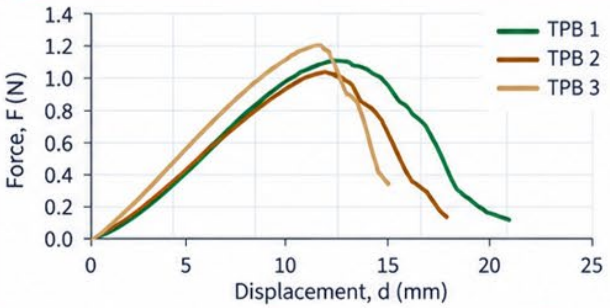
Three–point bending test — Support distance: 304 mm

Failed specimen — Typical fracture after maximum load

Test details (EN 310)

Support distance	304 mm
Loading rate	20 mm/min
Specimen thickness	12.46 – 12.70 mm
Width	46.93 – 48.80 mm
Length	335 – 336 mm

Force–displacement curves



Key results

Average F_{max}
1.075 N
$SD(F_{max}) = 0.072$ N

Average dF_{max}
13.29 mm
$SD(dF_{max}) = 1.306$ mm

MOE
10.17 N/mm²

MOR
0.63 N/mm²

Individual results

Sample	F_{max} (N)	dF_{max} (mm)
TPB 1	1.067	14.28
TPB 2	1.007	13.78
TPB 3	1.150	11.81

Interpretation

The optimum formulation achieved a technically balanced low-density board, but mechanical robustness remains the critical next step.

Application potential: Suitable for lightweight insulation and internal non-load-bearing boards; not suitable for structural use in its current form.

Conclusions

- Thermal conductivity remained within 62.33–66.77 mW/(m·K), confirming a credible lightweight-insulation range. The thermal optimum alone did not define the best global formulation.
- Gasified wood pellets and APP modified pHRR, THR and residual mass, but the response was not monotonic. Resin content, particle distribution and panel heterogeneity remained relevant interacting factors.
- Equal-weight integration of thermal, fire and DMA responses selected Experiment 4 as the best global compromise: 10 wt.% gasified wood pellets, 8 wt.% MUF resin, 5 wt.% APP and 77 wt.% raw hemp shives.
- Medium-scale three-point bending gave MOE = 10.17 MPa and MOR = 0.63 MPa. The present formulation is therefore appropriate for lightweight insulation or internal non-load-bearing lining, not structural or semi-structural use.
- The material is technically promising as a lightweight non-load-bearing product, but progression toward a construction product requires reproducible manufacturing and verified durability before structural or broad fire-safety claims are considered.

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