

Article

Analysis of Decarbonisation and Energy Efficiency Improvement Through Mycelium, Hygromorphic Wood and Hemp

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Abstract

Decarbonising the building sector requires addressing both embodied carbon in materials and operational energy for indoor conditioning. This article critically reviews the potential of mycelium, hygromorphic wood and hemp as emerging natural materials for low-carbon construction, comparing them with conventional materials only within function-specific applications such as envelopes, insulation, non-load-bearing components and passive systems. Recent comparative literature shows that mycelium composites can reach thermal conductivities of 0.026–0.12 W/m·K and densities of 51–280 kg/m³; in wood–mycelium formulations, an average density of 167.5 kg/m³ and climate impact of 2.13 kg CO₂-eq/kg with a conventional electricity mix, reduced to 0.66 kg CO₂-eq/kg with renewable energy, have been reported. Hemp shows typical densities of 140–540 kg/m³, conductivities of 0.061–0.12 W/m·K, compressive strengths of 0.3–3.5 MPa and potentially negative climate performance of about –40 to –80 kg CO₂-eq/m³, compared with +300 to +400 kg CO₂-eq/m³ for conventional concrete. Hygromorphic wood is relevant not as insulation or a primary structural replacement, but as a passive actuation material for adaptive envelopes. Hemp is currently the most mature option, mycelium is promising for circular non-structural panels and insulation, and hygromorphic wood is an operational-modification strategy whose building-level energy benefits still require direct quantification. Cross-study comparisons should be interpreted as bounded ranges because composition, fabrication, testing and LCA (Life Cycle Assessment) system boundaries vary substantially across the literature.

Keywords: hygromorphic wood; mycelium; hemp; decarbonisation; energy efficiency; biomaterials; sustainable construction

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1. Introduction

Decarbonising the building sector requires action on both the embodied carbon of materials and the operational energy associated with indoor conditioning. In this context, biomaterials are of interest not only because of their low material intensity or renewable origin, but because of three combined mechanisms: biogenic carbon storage, lower manufacturing energy demand and hygrothermal capacity to moderate heating and cooling loads. The scope of this review is therefore function-specific: mycelium and hemp

are examined mainly as insulation, infill, non-load-bearing or envelope materials, while hygromorphic wood is examined as a passive actuation technology. Concrete and steel are used as conventional benchmarks for density, thermal bridges and embodied impacts, not as direct functional equivalents for all uses. This distinction is essential because values for density, thermal conductivity, strength and global warming potential vary with composition, fabrication process, testing method, service scenario, database selection and LCA (Life Cycle Assessment) system boundaries. (Cheng et al., 2024) [1]; (Alaux et al., 2024) [2]; (Hurst and O'Donovan, 2024) [3].

Interest in mycelium, hygromorphic wood and hemp has intensified over the last 10–15 years because they represent three complementary routes of innovation. Mycelium makes it possible to “grow” panels or blocks from lignocellulosic waste and convert agricultural by-products into low-footprint insulation or non-structural infill. Hygromorphic wood uses the hygroscopic anisotropy of wood to produce components that open, curve or shade without motors or electronic control. Hemp, especially in the form of hempcrete, is the most mature of the three families, with real applications in building envelopes, wall linings and prefabricated elements for low-emission envelopes. (Alaneme et al., 2023) [4]; (Candido et al., 2024) [5]; (Tong and Memari, 2025) [6]; (Reichert et al., 2015) [7]; (Peng et al., 2023) [8].

The objective of this work is to compare, using material and environmental performance criteria, where these three biomaterials can replace, complement or reduce the use of concrete, steel, ceramic materials and synthetic insulation in construction systems oriented towards climate neutrality. The analysis deliberately excludes carbon fibre and does not claim structural equivalence among all materials. The contribution of the article is to condense the most recent state of the art into a comparative framework centred on quantitative ranges, viable architectural uses, functional boundaries, uncertainty and real technical limitations. (Tong and Memari, 2025) [6]; (Volk et al., 2024) [9]; (Bošković and Radivojević, 2023) [10].

2. State of the Art

Over a decade, mycelium has evolved from an experimental packaging material into a biofabrication platform for panels, lightweight bricks, acoustic elements and architectural prototypes. Recent reviews agree that its main advantage lies in the combination of circularity, low toxicity, biodegradability and good thermal performance; its main limitations remain mechanical variability, water absorption and lack of standardisation. In parallel, research has evolved from simple homogeneous mixtures towards mixed substrates, densification by pressing, integration with wood and LCA assessment at laboratory and industrial scales. (Alaneme et al., 2023) [4]; (Volk et al., 2024) [9]; (Alaux et al., 2024) [2]; (Livne et al., 2024) [11].

Hygromorphic wood has developed through a different route: not as a mass substitute for structural materials, but as a passive actuation technology embedded in the material itself. Research moved from prototypes of weather-sensitive skins to bilayers with higher geometric precision, metre-scale self-shaping elements and bioinspired shading systems monitored for more than one year on a real façade. Recent literature indicates that its architectural value does not lie in competing with steel or other materials in absolute strength, but in reducing the need for motorised ventilation or solar-protection mechanisms in specific adaptive envelope components; however, building-level energy savings remain insufficiently quantified. (Reichert et al., 2015) [7]; (Wood et al., 2018) [12]; (Grönquist et al., 2019) [13]; (Peng et al., 2023) [8]; (Cheng et al., 2024) [1].

Hemp, for its part, is the most consolidated line. Hempcrete has been the subject of sustained growth in research on formulation, application typologies, hygrothermal behaviour, life cycle analysis and in situ measurement. Recent literature confirms four

features: low density, reduced thermal conductivity, moisture-regulation capacity and very favourable carbon-balance potential, although with insufficient mechanical strength for conventional load-bearing functions. The most recent publications no longer ask whether hemp can function as infill or vapour-open insulation, but rather what combination of binder, thickness, prefabrication and finish maximises its environmental and construction performance. (Tong and Memari, 2025) [6]; (Memari et al., 2025) [14]; (Bošković and Radivojević, 2023) [10]; (Rivas-Aybar et al., 2023) [15].

3. Materials and Methods

A narrative-comparative review oriented towards construction and architectural applications was carried out, prioritising peer-reviewed journal articles published mainly between 2014 and 2026. Searches were conducted in Scopus, Web of Science, ScienceDirect and Google Scholar using combinations of the following Boolean strings: (“mycelium” OR “fungal biomaterial”) AND (“building material” OR “construction” OR “insulation”) AND (“thermal conductivity” OR “mechanical properties” OR “life cycle assessment”); (“hempcrete” OR “hemp-lime” OR “hemp-based”) AND (“building envelope” OR “thermal performance” OR “carbon footprint”); (“hygromorphic wood” OR “hygroscopic actuation” OR “adaptive shading”) AND (“building” OR “façade” OR “envelope”). Studies were retained when they provided at least one of the following groups of data: physical, thermal or mechanical properties; life cycle analysis or carbon footprint; architectural demonstrators or in situ tests; and evidence of scaling or construction feasibility. Exclusion criteria were duplicate records, purely chemical or biological studies without a construction application, unavailable full-text papers without quantitative material or environmental data, and studies in which the reported component was not relevant to buildings. The search process was therefore conducted and reported as a targeted narrative-comparative review rather than as a full systematic review or meta-analysis. The reporting of databases, search strings and eligibility criteria is intended to make the literature-selection logic transparent without implying a formal systematic review screening workflow. This methodological framing was adopted because the reviewed literature combines laboratory tests, architectural prototypes, LCA studies and field case studies that do not share a common effect size or a sufficiently homogeneous reporting basis for pooled quantitative synthesis.

The comparative analysis was structured around four families of indicators: materialised product properties, hygrothermal envelope performance, decarbonisation potential and degree of architectural applicability. To avoid false equivalences, three levels of comparison were separated: intrinsic properties (density, thermal conductivity and compressive strength), functional envelope performance (thermal resistance or the thickness required to reach a target U-value), and environmental indicators reported per kilogram, cubic metre or square metre. A single universal LCA unit was not imposed when source studies used incompatible boundaries; instead, Table 1 provides a bounding sensitivity analysis for 1 m² of envelope with $U = 0.20 \text{ W/m}^2\text{K}$ where the available thermal data allow such a calculation. This criterion is methodologically necessary because the literature on embodied carbon and embodied energy presents notable heterogeneities in databases, manufacturing assumptions, system boundaries and end-of-life scenarios; a recent study shows that 30% of embodied-energy and embodied-carbon data differ by more than 20% between sources. (Hurst and O'Donovan, 2024) [3].

Table 1. Bounding sensitivity analysis from reported conductivity and GWP ranges. Normalisation is illustrative for 1 m² of an envelope component with a target U-value of 0.20 W/m²·K where applicable; values are not formal product-level LCAs.

Bounding Comparison/Functional Assumption	Sensitivity Range/Interpretation
Hemp $\lambda = 0.061\text{--}0.12$ W/m·K; U = 0.20 W/m ² ·K	Required thickness $\approx 0.305\text{--}0.600$ m; this supports envelope/infill use, not structural substitution.
Hempcrete GWP = -40 to -80 kg CO ₂ -eq/m ³	For the above thickness range, indicative climate balance ≈ -12 to -48 kg CO ₂ -eq/m ² , before boundary-specific corrections.
Mycelium $\lambda = 0.026\text{--}0.12$ W/m·K; U = 0.20 W/m ² ·K	Required thickness $\approx 0.130\text{--}0.600$ m; variability is dominated by substrate, density and processing.
Mycelium GWP = $0.3668\text{--}2.13$ kg CO ₂ -eq/kg; density = $51\text{--}280$ kg/m ³	Broad indicative envelope range $\approx 2.4\text{--}358$ kg CO ₂ -eq/m ² if extreme values are combined; this should be read as a sensitivity envelope rather than a product claim.
Wood–mycelium composite, $\lambda \approx 0.06$ W/m·K, density 167.5 kg/m ³ , GWP = $0.66\text{--}2.13$ kg CO ₂ -eq/kg	At U = 0.20 W/m ² ·K, indicative impact $\approx 33\text{--}107$ kg CO ₂ -eq/m ² ; renewable electricity materially improves the lower bound.
Synthetic insulation $\lambda \approx 0.032$ W/m·K; density ≈ 35.7 kg/m ³ ; GWP ≈ 4.39 kg CO ₂ -eq/kg	At U = 0.20 W/m ² ·K, thickness ≈ 0.160 m and indicative impact ≈ 25 kg CO ₂ -eq/m ² .
Mineral wool $\lambda \approx 0.04$ W/m·K; density ≈ 78.3 kg/m ³ ; GWP ≈ 1.09 kg CO ₂ -eq/kg	At U = 0.20 W/m ² ·K, thickness ≈ 0.200 m and indicative impact ≈ 17 kg CO ₂ -eq/m ² .
Concrete $\lambda = 1.7\text{--}2.0$ W/m·K; U = 0.20 W/m ² ·K	Required thickness $\approx 8.5\text{--}10.0$ m; this confirms that concrete is not a functional insulation comparator.
Fixed-temperature vs. ambient/diurnal mycelium growth	>70% lower production energy is process-specific and cannot be generalised without electricity-mix and boundary data.

4. Results and Discussion

The quantitative evidence shows a function-specific pattern rather than a single hierarchy. Hemp is the biomaterial closest to the market and to real building applications; mycelium is the one with the greatest potential for circularity and impact reduction if its production process is decarbonised; and hygromorphic wood offers a distinctive passive actuation strategy for adaptive envelopes, although its building-level energy savings are not yet quantified with the same robustness as its mechanical responsiveness. The key point is not to choose a single “winning” material, but to assign each one to the construction role where its balance between performance, durability and carbon is most favourable. (Tong and Memari, 2025) [6]; (Candido et al., 2024) [5]; (Livne et al., 2024) [11]; (Cheng et al., 2024) [1].

Table 1 brings together the most consistent technical values for the three natural materials. In all three cases, lightness is a decisive advantage over concrete and ceramics; nevertheless, mechanical strength is competitive only in densified mycelium and, partially, in hybrid solutions. In hemp and mycelium, the function most robustly supported by the evidence is that of insulation, infill or non-load-bearing components. In hygromorphic wood, the central property is not compression but reversible curvature and programmable hygroscopic sensitivity. (Tong and Memari, 2025) [6]; (Candido et al., 2024) [5]; (Livne et al., 2024) [11]; (Peng et al., 2023) [8]. (Table 2).

Table 2. Synthesis sources: (Tong and Memari, 2025) [6]; (Candido et al., 2024) [5]; (Livne et al., 2024) [11]; (Jin et al., 2024) [16]; (Peng et al., 2023) [8]; (Nasr et al., 2023) [17].

Material	Representative Density	Thermal Conductivity λ	Dominant Mechanical Performance	Technical-Construction Interpretation
Mycelium	$51\text{--}280$ kg/m ³ ; 167.5 kg/m ³ in wood–mycelium composite	$0.026\text{--}0.081$ W/m·K; 0.06 W/m·K in comparative design; 0.12 W/m·K in Pleurotus/straw system	Up to $2.5\text{--}5.9$ MPa in hot-pressed formulations	Suitable for insulation, lightweight panels, infills, sandwiches and non-load-bearing moulded pieces
Hygromorphic wood	0.47 g/cm ³ in Scots pine bilayers	$0.10\text{--}0.31$ W/m·K for wood depending on species/direction	Reversible actuation by humidity; greater sensitivity in $200/400$ μ m bilayer with 0.6% iMC	Suitable for shading, passive ventilation, kinetic panels and self-shaping of curved pieces

Material	Representative Density	Thermal Conductivity λ	Dominant Mechanical Performance	Technical-Construction Interpretation
Hemp	140–540 kg/m ³ in reviewed formulations; 250–500 kg/m ³ as a frequent use range	0.061–0.12 W/m·K; 0.05–0.15 W/m·K in general review	0.3–3.5 MPa as a typical non-load-bearing block	Suitable for infill walls, linings, prefabricated elements, roofs and vapour-open envelopes

When these biomaterials are compared with conventional materials, the comparison is meaningful only if the functional role is specified. Concrete and steel remain primary load-bearing materials; hempcrete and most mycelium composites are considered here primarily as envelope, insulation, infill or non-load-bearing systems, while hygromorphic wood is considered as an adaptive shading or ventilation component. Within that restricted scope, the broad property contrast is clear. The structural concrete analysed in the hempcrete review has densities of 2200–2400 kg/m³, conductivities of 1.7–2.0 W/m·K and compressive strengths of 20–40 MPa, while ceramic brick has, in a recent review, a dry density close to 1980 kg/m³ and a conductivity of 0.41 W/m·K. Steel maintains a density of 7850 kg/m³ and conductivities of around 44.5–54.7 W/m·K, which explains its thermal bridges if they are not properly interrupted. The synthetic insulation materials compared by Candido et al. [5] have an average λ of 0.032 W/m·K and an average density of 35.7 kg/m³; mineral wools, $\lambda \approx 0.04$ W/m·K and density ≈ 78.3 kg/m³. (Tong and Memari, 2025) [6]; (Nasr et al., 2023) [17]; (Candido et al., 2024) [5]; (Martins et al., 2016) [18]. (Table 3).

Table 3. Synthesis sources: (Tong and Memari, 2025) [6]; (Candido et al., 2024) [5]; (Nasr et al., 2023) [17]; (Martins et al., 2016) [18].

Conventional Material	Density	λ	Mechanical/Functional Performance	Comparative Comment Against Biomaterials
Structural concrete	2200–2400 kg/m ³	1.7–2.0 W/m·K	20–40 MPa	Much better in load-bearing capacity, much poorer in insulation and notably worse in GWP compared with hemp
Structural steel	7850 kg/m ³	44.5–54.7 W/m·K	200–300 MPa typical yield strength	Excellent structurally, critical in thermal bridges
Ceramic/fired brick	~ 1980 kg/m ³	~ 0.41 W/m·K	3–10 MPa in masonry/compared prisms	Better inertia than insulation; clearly denser than hemp and mycelium
Synthetic insulation	~ 35.7 kg/m ³	~ 0.032 W/m·K	Insulating function, non-structural	Better λ than mycelium and hemp, but more fossil-based and less biodegradable
Mineral wool	~ 78.3 kg/m ³	~ 0.04 W/m·K	Insulating function, non-structural	Direct competitor of mycelium in envelope use

The environmental comparison is favourable for several bio-based options but remains boundary-sensitive. For hempcrete, the review by Tong and Memari reports GWP between -40 and -80 kg CO₂-eq/m³, while conventional concrete is placed at $+300$ to $+400$ kg CO₂-eq/m³. In Serbia, Bošković and Radivojević showed that the most favourable life cycle scenario for a hemp–lime wall reached -9.696 kg CO₂-eq, while the least favourable rose to $+10.165$ kg CO₂-eq, showing that the material is not “automatically” carbon-negative: it depends on binders, transport, waste and end of life. In hemp boards, Rivas-Aybar et al. [15] obtained -2.302 kg CO₂-eq/m², with a 164% improvement when replacing grid electricity with solar energy, reaching -6.07 kg CO₂-eq/m²; in addition, electricity consumption in post-processing accounted for 45% of emissions. (Tong and Memari, 2025) [6]; (Bošković and Radivojević, 2023) [10]; (Rivas-Aybar et al., 2023) [15].

In mycelium, environmental behaviour also depends strongly on manufacturing energy. Volk et al. [9] reported 0.3668 kg CO₂-eq/kg for a lightweight hemp-based MBC at laboratory scale in Germany. In the wood–mycelium composite of Candido et al. [5], the impact was 2.13 kg CO₂-eq/kg with the national electricity mix and 0.66 kg CO₂-eq/kg with renewables, compared with 1.09 kg CO₂-eq/kg for mineral wools and 4.39 kg CO₂-eq/kg for average synthetic insulators. Alaux et al. [2] confirmed that, in climate-change terms,

mycelium is promising compared with plastic insulation, but does not necessarily outperform all existing materials, and estimated that including the remaining life stages increases GHG emissions by around 10%. Electricity was identified as the main hotspot. (Volk et al., 2024) [9]; (Candido et al., 2024) [5]; (Alaux et al., 2024) [2].

The reduction in embodied energy in mycelium can be especially intense if the cultivation process is modified. Livne et al. [11] showed that growth at room temperature or under diurnal cycles can save more than 70% of production energy while maintaining equivalent thermal and mechanical properties; in addition, fixed-temperature growth accounted for 73% of embodied energy and more than 40% of process CO₂ emissions. This finding is decisive for its industrial viability: the main challenge for mycelium is not so much the biocomposite itself, but the energy mode used to produce it. (Livne et al., 2024) [11]. (Table 4).

Table 4. Synthesis sources: (Tong and Memari, 2025) [6]; (Bošković and Radivojević, 2023) [10]; (Rivas-Aybar et al., 2023) [15]; (Candido et al., 2024) [5]; (Volk et al., 2024) [9]; (Alaux et al., 2024) [2]. The hygromorphic wood row retains explicit caution because no homogeneous LCA directly comparable with the other two materials was identified in the studies retrieved.

Environmental Indicator	Mycelium	Hygromorphic Wood	Hemp	Conventional Materials
Emissions/GWP	0.3668 kg CO ₂ -eq/kg in lightweight MBC; 0.66–2.13 kg CO ₂ -eq/kg in wood–mycelium depending on electricity mix	Insufficient comparable quantitative LCA evidence in the studies retrieved; potential advantage lies in wood base and actuator-free operation, not yet in a quantified product-level LCA	–40 to –80 kg CO ₂ -eq/m ³ in hempcrete; –9.696 to +10.165 kg CO ₂ -eq depending on scenario; –2.30 to –6.07 kg CO ₂ -eq/m ² in hemp board	Concrete: +300 to +400 kg CO ₂ -eq/m ³ ; synthetic insulators: 4.39 kg CO ₂ -eq/kg; mineral wool: 1.09 kg CO ₂ -eq/kg
Electricity as hotspot	Very high relevance	Not applicable in an analogous way	High in board processing and binders	High in intensive industrial materials
Recyclability/end of life	Reusable, compostable or recoverable; sensitive to LCA standards	Reusable; bio-based; low technical complexity	Recyclable, biodegradable and potentially reusable as biogenic aggregate	Lower biodegradability; variable recycling
Biodegradability	High	High	High	Low or none in plastics and cementitious materials

To reinforce the quantitative reading without overstating precision, Table 4 replaces single percentage differences with bounded sensitivity ranges. The calculations normalise thermal performance, where possible, to 1 m² of envelope with a target U-value of 0.20 W/m²·K. The resulting values are illustrative because the source studies differ in density, manufacturing process, electricity mix, allocation, service life, cradle-to-gate or cradle-to-grave boundaries and end-of-life assumptions. (Tong and Memari, 2025) [6]; (Candido et al., 2024) [5]; (Memari et al., 2025) [14]; (Livne et al., 2024) [11]. (Table 1).

In terms of building energy efficiency, hemp is the material with the most directly transferable evidence within envelope applications. The in situ measurement of a refurbished dwelling with a hempcrete wall yielded R-16.93 for a total thickness of 11.75 inches, that is, approximately R-1.45 per inch. The authors concluded that this value is more than ten times higher than that of a regular concrete wall of the same thickness, 5.6 times higher than the original wall of the dwelling and 1.3 times higher than the hypothetical case with conventional batt insulation. This does not mean that hemp has the lowest absolute λ on the market or that it replaces structural concrete, but rather that its vapour-open wall system can compete very favourably when assessed as an integrated non-load-bearing envelope solution. (Memari et al., 2025) [14].

For mycelium, evidence on energy efficiency is promising but more dependent on system design. Jin et al. [16] showed a minimum λ of 0.12 W/m·K in Pleurotus/straw

composites and concluded that sandwich panels for façades and roofs with a thickness of 240 mm could meet class A requirements in the hot-summer/cold-winter Chinese climate. By contrast, Candido et al. [5] warn that, although the wood–mycelium composite with renewables can have lower GWP per kilogram than conventional insulations, its higher conductivity and relatively high density require greater thickness and more mass to achieve the same thermal performance. Mycelium, therefore, should not be judged only by λ , but by its balance between available thickness, circularity and embodied carbon. (Jin et al., 2024) [16]; (Candido et al., 2024) [5].

Hygromorphic wood contributes to adaptive envelope operation through a different route: passive response to humidity. Cheng et al. [1] demonstrated a bioinspired hygromorphic shading system operating on a real façade for more than one year, without external energy supply and with daily and seasonal response capacity. The same research acknowledges, however, that direct quantification of the improvement in indoor climate was left for future work. This point is important: today it can be stated with evidence that hygromorphic wood can avoid actuator energy in the component itself and simplify control logic; it still cannot be stated with the same precision how many kWh/m²·year it saves in complete buildings in a generalisable way. (Cheng et al., 2024) [1].

Applied maturity also differs clearly. In mycelium, the architectural literature records cases such as Hy-Fi, with more than 12 m in height and 10,000 mycelium bricks, the Growing Pavilion with 88 façade panels, and MycoTree as a compression spatial structure. In hygromorphic wood, the line from HygroSkin to the façade systems of the experimental livMatS building demonstrates a progressive step from pavilion and prototype towards a monitored envelope component. In hemp, the strongest evidence is not in iconic pavilions but in dwellings, prefabricated walls, refurbishment and real-wall tests, which, from the point of view of adoption, is more relevant than isolated formal spectacularity. (Almpani-Lekka et al., 2021) [19]; (Jin et al., 2024) [16]; (Memari et al., 2025) [14]; (Reichert et al., 2015) [7]; (Cheng et al., 2024) [1]. (Table 5).

Table 5. Synthesis sources: (Almpani-Lekka et al., 2021) [19]; (Reichert et al., 2015) [7]; (Grönquist et al., 2019) [13]; (Memari et al., 2025) [14]; (Jin et al., 2024) [16]; (Cheng et al., 2024) [1].

Material Line	Case/Evidence	Application Type	Relative Maturity Level
Mycelium	Hy-Fi; Growing Pavilion; MycoTree	Pavilions, façade panels, spatial compression	Medium–low: Convincing demonstration, standardisation still limited
Hygromorphic wood	HygroSkin; self-shaped curved structures; bioinspired façade monitored > 1 year	Shading, ventilation, kinetic panels, CLT or curved lamellae	Medium: High functional innovation, still with limited overall energy quantification
Hemp	Refurbished dwelling with in situ measurement; prefabricated blocks; hemp–lime walls	Walls, linings, roofs, lightweight prefabrication	Medium–high: Real applications and more robust field data

The technical and durability limitations are equally clear. In mycelium, water sensitivity, microbial degradation risk under persistent moisture, substrate- and species-dependent variability, fire behaviour and the need to standardise drying, pressing and protective finishes restrict current use to protected semi-structural or non-structural elements. In hygromorphic wood, hysteresis, fatigue under repeated humidity cycling, ultraviolet and exterior exposure, dimensional stability, connection detailing and long-term calibration of the response remain major bottlenecks. In hemp, compressive strength remains too low to compete with mineral or metal load-bearing systems; in addition, durability depends on binder chemistry, capillary water control, mould risk, fire detailing, drying before enclosure, maintenance of vapour-open finishes and end-of-life assumptions. For all three biomaterial families, service-life performance is not a secondary issue but a decisive condition for reliable carbon accounting: a low initial GWP can be offset by premature replacement, excessive coating maintenance or damage during

operation. These limitations do not invalidate the materials, but they do prevent them from being presented as universal substitutes. (Alaneme et al., 2023) [4]; (Bošković and Radivojević, 2023) [10]; (Peng et al., 2023) [8]; (Alaux et al., 2024) [2]; (Hurst and O'Donovan, 2024) [3].

5. Future Applications and Design Opportunities

The strongest short-term opportunity is functional hybridisation. A low-emission system can combine an optimised conventional primary structure, a hemp enclosure as a thermo-hygrometric layer, mycelium subcomponents for interior insulation or lightweight prefabrication, and hygromorphic wood in the exterior shading or ventilation layer. This strategy distributes each material where it generates the greatest value: hemp as a lightweight vapour-open mass and biogenic capture, mycelium as a low-energy circular infill, and hygromorphic wood as a route to reduce electromechanical complexity and potentially lower operational demand through motor-free adaptation. (Candido et al., 2024) [5]; (Tong and Memari, 2025) [6]; (Cheng et al., 2024) [1].

In envelopes, three lines are especially promising. The first is the bio-substituted sandwich panel: a resistant wood or board face, a mycelium or hemp core and a detachable outer layer. The second is the prefabricated breathable façade with hempcrete in cassettes or blocks, where thermal performance and carbon reduction are already sufficiently demonstrated. The third is biomimetic hygromorphic shading, which can reduce electromechanical complexity in buildings with high solar exposure, although the building-level energy benefit must be quantified case by case. In all of them, industrialisation is a priority: without modularity, dimensional control and standardised testing, the climate promise will not become mass adoption. (Jin et al., 2024) [16]; (Memari et al., 2025) [14]; (Peng et al., 2023) [8]; (Cheng et al., 2024) [1].

For lightweight elements, the route with the greatest probability of success is hybrid prefabrication. Hemp can resolve the main volume of the envelope; mycelium, inserts or replaceable cores; and hygromorphic wood, local passive-control components. This scheme favours disassembly, repair and selective replacement. Mycelium, in particular, has a decisive advantage here: because it can be moulded and grown into complex shapes with low energy, it fits well in variable-geometry and low-load components. The most advanced line in this direction is that of reinforced or confined curved components, as explored by MycoCurva. (Özdemir et al., 2025) [20]; (Alaneme et al., 2023) [4].

Future research should prioritise six specific fronts: standardisation of comparable tests; systematic integration of renewable energy in biofabrication; water-repellent and fire-safe protection compatible with biodegradability; homogeneous LCA databases with explicit end of life and service life; long-term monitoring of moisture, ageing and maintenance; and joint assessment of embodied carbon and operational savings at building scale. Without these methodological transitions, the decarbonisation discourse will remain stronger than the evidence for implementation. (Hurst and O'Donovan, 2024) [3]; (Alaux et al., 2024) [2]; (Livne et al., 2024) [11].

6. Conclusions

The results allow five specific technical conclusions to be established. First, hemp is currently the most mature option for low-carbon envelope systems: it combines densities of 140–540 kg/m³, λ of 0.061–0.12 W/m·K, usual compressive strength of 0.3–3.5 MPa and a climate balance that can range from –40 to –80 kg CO₂-eq/m³ in the studies reviewed; in a real building, a hempcrete wall reached R-16.93, that is, 5.6 times the original wall and 1.3 times a lining with conventional batt insulation. Second, mycelium is the biomaterial with strong potential for circularity and customised biofabrication; its best reported

thermal formulations reach 0.026 W/m·K, and the use of room-temperature growth can reduce production energy by more than 70%, but it remains penalised by moisture sensitivity, mechanical variability and the possible need for greater thickness than synthetic insulators. Third, hygromorphic wood does not compete as insulation or as a main load-bearing material; it is best interpreted as a passive operational-modification strategy, with evidence of actuator-free response for more than one year on a real façade but without a generalisable quantified value for annual building energy savings. Fourth, none of the three materials should be presented as a universal substitute for concrete or steel: their performance is high when they are assigned to infill, insulation, hygrothermal regulation, finishing or passive-adaptation functions, and decreases when conventional load-bearing capacity is required. Fifth, the best strategy for low-emission buildings is not monomaterial but hybrid: hemp for the thermo-hygroscopic volume of the envelope, mycelium for lightweight prefabricated components and hygromorphic wood for passive façade devices. In terms of a publication oriented to buildings, the current evidence supports a cautious thesis: these materials can contribute to reducing embodied carbon and electromechanical complexity in specific envelope and non-structural functions, but their viability depends on functional matching, durability, moisture and fire performance, service life and transparent LCA boundaries. (Tong and Memari, 2025) [6]; (Memari et al., 2025) [14]; (Bošković and Radivojević, 2023) [10]; (Candido et al., 2024) [5]; (Volk et al., 2024) [9]; (Alaux et al., 2024) [2]; (Livne et al., 2024) [11]; (Jin et al., 2024) [16]; (Peng et al., 2023) [8]; (Cheng et al., 2024) [1].

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