

FROM FIELD RESIDUE TO BIO-BASED PANELS: INDUSTRIAL HEMP SHIVES IN PARTICLEBOARD AND FIBREBOARD PRODUCTION – A COMPREHENSIVE REVIEW

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ABSTRACT

Industrial hemp cultivation generates large quantities of stems and shives (hurd) that remain underutilised despite their attractive characteristics as a renewable lignocellulosic resource. In recent years, hemp shives have been increasingly explored as a partial or full substitute for wood particles and fibres in particleboards, medium-density fibreboards (MDF) and related panel products. This review synthesises the current state of knowledge on the use of industrial hemp stems and shives in bio-based wood panels, covering raw material properties, pre-treatments, panel manufacturing parameters and resulting performance. Particular attention is given to the influence of particle granulometry, density profile, adhesive type (UF, MF including UF/MF blends, pMDI and emerging bio-based binders) and processing conditions on mechanical properties, dimensional stability, thermal and hygric behaviour. The review compares hemp-based and conventional wood-based panels in terms of bending strength, internal bond, screw withdrawal resistance, water absorption and thickness swelling, as well as thermal conductivity and moisture buffering capacity relevant to building applications. Environmental and techno-economic aspects, including resource availability, lightweight design and potential for circular construction, are also briefly discussed. Finally, the paper identifies critical research gaps related to long-term durability, fire performance, interface optimisation between hemp particles and novel binders, upscaling from laboratory to industrial production, and standardisation of testing protocols for hemp-based panels. These gaps are used to outline future research directions and innovation pathways needed to fully valorise industrial hemp stems and shives as a reliable feedstock for next-generation bio-based particleboards and fibreboards.

Key words: industrial hemp; hemp shives; bio-based panels; particleboard; fibreboard; MDF; lignocellulosic composites; moisture buffering; thermal insulation

INTRODUCTION

Wood-based panels such as particleboard (PB), medium-density fibreboard (MDF) and related engineered products are among the most widely used materials in furniture manufacture, interior fittings and building applications. Their global production has grown steadily over the last decades; for particleboard alone, output increased by about 31% from 77.15 million m³ in 2010 to 100.74 million m³ in 2019, driven by strong growth in furniture and construction markets (Fehrmann *et al.*, 2023). At the same time, the sector faces increasing pressure from limited forest resources, competition with solid wood and pulp industries, and stricter environmental regulations on formaldehyde emissions and carbon footprints. These trends have intensified the search for alternative, renewable lignocellulosic feedstocks and more sustainable adhesive systems for panel production.

Industrial hemp (*Cannabis sativa* L.) has emerged as a promising candidate in this context. Hemp is a fast-growing annual crop with relatively low agronomic inputs and good adaptability to temperate climates. After harvesting seeds or fibres, large quantities of stems remain as a by-product. Decortication of the stems yields long bast fibres and short, woody inner fragments

known as shives or hurds. While bast fibres have received considerable attention for use in textiles, composites and reinforcement in polymer matrices, hemp shives are still often treated as a low-value residue, used mainly for animal bedding, mulching or low-grade absorption materials (Stevulova *et al.*, 2014; Osman *et al.*, 2025). Their valorisation in wood-based panels would add value to the hemp production chain and diversify the raw material base of the panel industry. Beyond panels based purely on hemp shives, flax shive and hemp hurd residues have also been shown to be suitable alternative raw materials for three-layer particleboards bonded with low levels of pMDI, achieving mechanical properties that meet or exceed ANSI requirements compared with conventional wood-residue boards (Sam-Brew & Smith, 2017).

Hemp shives combine several attributes that make them attractive for particleboard and fibreboard manufacture. They are composed mainly of cellulose, hemicelluloses and lignin, similar to wood, but typically exhibit lower bulk density and a highly porous microstructure. Chemical modification studies have shown that appropriate treatments can tailor their morphology, surface chemistry and thermal stability, improving compatibility with inorganic and organic binders (Stevulova *et al.*, 2014). In addition, the high internal porosity of shives is beneficial for hygrothermal and acoustic performance, which is especially relevant for panels aimed at building insulation or interior climate regulation (Maalouf *et al.*, 2015; Sinka *et al.*, 2019). Similar combinations of relatively low density, high open porosity and favourable thermal conductivity have been reported for hemp hurds and hemp-based concretes and composites designed for building envelopes, wall plugs and insulating elements (Balčiūnas *et al.*, 2013; Sassoni *et al.*, 2014; Walker & Pavia, 2014; Viel *et al.*, 2019).

Over roughly the last decade and a half, a growing body of work has investigated hemp shives in panel-like products. Early studies considered binderless or low-resin panels from pretreated hemp shives, primarily targeting acoustic performance and demonstrating that suitable pre-treatment and pressing conditions can yield panels with favourable sound absorption coefficients (Brencis *et al.*, 2015). Maalouf *et al.* (2015) evaluated hemp–starch composite panels produced by bonding hemp shiv with wheat starch, with a focus on hygric properties and moisture buffering performance for building envelopes. Their results showed that such panels could achieve moderate mechanical integrity while providing very high moisture buffering values compared to conventional lining materials, underlining the potential of hemp shive panels for passive indoor humidity regulation.

More recent research has moved towards structural or semi-structural applications and systematic optimisation of panel design. Fehrmann *et al.* (2023) studied ultra-low-density hemp hurd particleboards (ULHPB) with densities of 213–309 kg·m⁻³, considering the combined influence of particle granulometry, adhesive type (bio-epoxy, phenol-resorcinol-formaldehyde and MDI) and panel composition on physical and mechanical performance. Their work highlighted the strong effect of particle size distribution and adhesive system on bending strength, internal bond and dimensional stability, and showed that MDI-bonded boards in particular can deliver significantly improved properties compared with other formulations. In a series of studies, Savov and colleagues have demonstrated the feasibility of producing hemp shive panels that approach or meet conventional particleboard requirements. One study on one-layer panels with varying UF/MF amino resin content (8–14%) – using an adhesive system composed of 90% urea–formaldehyde and 10% melamine–formaldehyde – showed that hemp shive boards can reach very good bending and internal bond strength, and particularly high edge screw withdrawal resistance, suggesting good suitability for furniture frame constructions (Savov & Hristodorova, 2023).

Complementary work on the effect of panel density on staple withdrawal strength further confirmed the critical role of density in fastener-holding performance of hemp shive boards (Hristodorova *et al.*, 2023).

Building on these laboratory-scale results, Savov *et al.* (2025) recently explored the structural optimisation of lightweight three-layer panels composed of a hemp shive core and hemp fibre face layers. By varying the panel density and face-layer content, they identified configurations that satisfy the mechanical requirements for P2 particleboards (EN 312) and approach MDF benchmarks for dry-use applications, although thickness swelling remained above standard MDF limits. Their study clearly demonstrated the potential of hemp shive–fibre panels as sustainable alternatives to conventional wood-based panels in furniture manufacturing, while also revealing the challenge of achieving sufficient dimensional stability in the presence of highly hygroscopic particles.

Parallel research streams have examined hemp stalks and shives in other panel-like and sandwich structures. Boccarusso *et al.* (2021) developed hybrid carbon/hemp sandwich panels using hemp bi-grid cores produced in a continuous process, showing attractive energy absorption and impact performance. Gallina *et al.* (2025) investigated semi-industrial preparation of flexible panel rolls based on micronized hemp stalks and bicomponent thermoplastic fibres, achieving high hemp contents (up to 80%) with promising thermal and sound insulation properties. Islam *et al.* (2025) designed polymer composite sandwich panels with hemp fabric skins and various core materials, demonstrating the viability of hemp-based skins in multi-material panel systems. Although these studies are not strictly wood-based panels in the traditional sense, they underline the versatility of hemp residues in engineered panel products and help define performance envelopes relevant to certain applications (e.g., lightweight cores, acoustic or thermal functions).

On the adhesive side, most hemp shive panel studies to date have relied on conventional thermosetting resins, particularly urea-formaldehyde (UF), melamine-formaldehyde (MF), phenol-formaldehyde (PF), phenol-resorcinol-formaldehyde (PRF) and polymeric diphenylmethane diisocyanate (pMDI) (Fehrmann *et al.*, 2023; Savov and Hristodorova, 2023; Osman *et al.*, 2025). However, growing regulatory pressure on formaldehyde emissions and the broader decarbonisation agenda have stimulated efforts towards bio-based binding systems. Recent work on plywood panels has demonstrated that lignocellulosic and tannin-based adhesive formulations can partially or fully replace fossil-derived resins while maintaining satisfactory mechanical performance (Papadopoulou *et al.*, 2024). In parallel, sodium silicate-based systems have been investigated for wood–hemp composites tailored for additive manufacturing, showing that hemp hurd can be incorporated into inorganic binder matrices while balancing extrudability, strength and cost (Tanikella *et al.*, 2025). These developments are highly relevant for hemp shive panels, where the combination of alternative lignocellulosic raw materials and bio-based or low-emission binders is essential for producing genuinely “bio-based panels”.

Despite this increasingly rich literature, the knowledge on industrial hemp shives in wood-based panels remains fragmented. Many studies focus on specific niche applications (e.g., moisture buffering panels, ultra-low-density boards, sandwich cores), use different testing standards or target properties, and are often limited to laboratory-scale production under very specific conditions. Systematic comparisons with conventional particleboard, MDF and fibreboard products are still relatively rare, especially regarding screw and staple withdrawal, thickness swelling, long-term creep and fatigue, and fire performance. In addition, the interplay

between particle granulometry, panel structure (single-layer vs multi-layer), density profiles and advanced binder systems has not yet been fully explored.

The present paper addresses these gaps by providing a comprehensive review of the valorisation of industrial hemp stems and shives in bio-based wood panels, with a particular focus on particleboards, fibreboards and MDF-type products. The review first summarises the key physical, chemical and hygrothermal properties of hemp shives and stems relevant to panel manufacture, including the effects of chemical and physical pre-treatments. It then analyses the main panel manufacturing routes (single- and multi-layer boards, sandwich structures, binderless and low-density boards), adhesives and process parameters reported in the literature, highlighting their influence on mechanical, physical, thermal and acoustic properties relative to current standards and benchmark wood-based panels. Environmental and techno-economic aspects, such as resource availability, energy demand and prospects for circular construction, are briefly discussed.

A central aim of this review is to identify and articulate research gaps that must be addressed to enable the large-scale, reliable use of industrial hemp shives in next-generation bio-based panels. Particular attention is paid to open questions concerning long-term durability and ageing, fire and emission behaviour, optimisation of the particle–binder interface (particularly for novel bio-based adhesives), process upscaling from laboratory to industrial conditions, and the need for harmonised testing and classification frameworks tailored to hemp-based panels. These gaps, highlighted throughout the paper and synthesised in the final section, form the basis for proposing future research directions and innovation pathways towards fully valorised hemp shive particleboards and fibreboards.

STATE OF THE ART ON INDUSTRIAL HEMP SHIVES IN WOOD-BASED PANELS

Industrial hemp (*Cannabis sativa* L.) generates large quantities of stems, from which bast fibres are separated and a woody core remains as shives (hurds). These shives often account for 60–80% of the stalk mass and are still underutilised, typically used for low-value products such as bedding or mulch (Brencis *et al.*, 2015; Savov *et al.*, 2025). Chemically, hemp shives contain about 40–45% cellulose, 20–25% hemicelluloses and 20–25% lignin, with low ash content, which is comparable to hardwoods commonly used in particleboards and fibreboards (Stevulova *et al.*, 2014). Their bulk density is much lower than wood, around 90–120 kg·m⁻³, and the microstructure is highly porous and hygroscopic. This combination of wood-like chemistry and lightweight, porous anatomy explains both the potential and the challenges of using hemp shives in wood-based panels.

Raw material characteristics, pre-treatment and their implications

Anatomically, hemp stems consist of an outer ring of bast fibres and an inner woody core; shives are formed from parenchyma and xylem tissues with thin walls and large lumens (Stevulova *et al.*, 2014). The resulting particles are very light, compressible and water-absorbing. For panel production this means that, at a given board density, a larger volume fraction of voids and cell lumens is present compared with wood particles, which favours thermal and acoustic performance but complicates resin distribution and dimensional stability.

Mechanical processing and fractionation are therefore crucial. Shives from industrial decortication lines have broad particle size distributions, with a large share of coarse particles above 2–4 mm and a mix of fines and short bast fibres. Studies on ultra-low-density hemp hurd particleboards showed that particle size distribution strongly affects density profile, internal bond and bending performance; mixes with a dominant coarse fraction provided better mechanical properties than very fine fractions, which tended to increase thickness swelling and resin demand (Fehrmann *et al.*, 2023). In structural three-layer concepts, coarse shives are mainly used in the core, while defibrated stalks with a higher proportion of small particles and fibres are used in the faces, leading to denser, smoother surfaces (Savov *et al.*, 2025).

Chemical and thermo-chemical treatments have been applied to tailor shive behaviour. Alkaline treatments with NaOH or Ca(OH)₂, and chelating agents such as EDTA, partially remove hemicelluloses, pectins and extractives, increase cellulose crystallinity and improve thermal stability and compatibility with both organic and inorganic binders (Stevulova *et al.*, 2014). Hydrothermal and steam-explosion treatments promote partial depolymerisation of hemicelluloses and softening of lignin, enabling binderless self-bonding under hot-pressing and improving dimensional stability (Brencis *et al.*, 2015). In hemp–starch composites, additional silane-based surface treatments enhanced adhesion and modified moisture sorption and moisture-buffering behaviour (Maalouf *et al.*, 2015).

In summary, hemp shives are chemically suitable as wood substitutes, but their high porosity and hygroscopicity demand careful control of granulometry, moisture and pre-treatment. This provides a foundation for lightweight, hygrothermally active panels, but also defines the constraints for achieving PB/MDF-class mechanical and durability performance.

Adhesive systems and interface issues

Most structural hemp-shive panels studied to date rely on conventional thermosetting resins. One-layer hemp-shive particleboards with 8–14% urea–formaldehyde/melamine–formaldehyde (UF/MF) blends and densities around 650 kg·m⁻³ have been shown to meet or exceed EN 312 P2 requirements for bending strength, stiffness and internal bond, while offering very high screw withdrawal resistance compared with wood particleboards (Savov & Hristodorova, 2023). Panels with about 10% total resin content appear to offer an optimal compromise between mechanical properties, dimensional stability and formaldehyde content. For high-density boards bonded with 10% melamine–formaldehyde (MF), increasing density from 600 to 900 kg·m⁻³ almost doubled staple withdrawal resistance, emphasising the strong role of densification in fastener-holding performance (Hristodorova *et al.*, 2023).

In ultra-low-density boards (≈213–309 kg·m⁻³), polymeric MDI has emerged as the most effective binder. Comparing MDI, phenol-resorcinol-formaldehyde (PRF) and bio-epoxy, Fehrmann *et al.* (2023) found that MDI-bonded hemp hurd particleboards exhibited higher bending strength, stiffness, screw withdrawal resistance and dimensional stability, and could satisfy thickness-swelling limits for moisture-resistant particleboards despite their very low density. This is attributed to the high reactivity of isocyanate groups with hydroxyls in the cell wall and the ability of low-viscosity MDI to penetrate the porous shive structure.

Alongside these synthetic systems, bio-based and hybrid binders are gaining attention. Hemp–starch composite panels with wheat starch as the sole binder provide fully bio-based, low-density boards with modest mechanical performance but excellent moisture-buffering capacity

and favourable thermal conductivity for building linings (Maalouf *et al.*, 2015). Hybrid pMDI formulations for plywood, in which part of the wheat flour is replaced by agricultural residues including defatted hemp seeds, have shown that bio-fillers can be incorporated into isocyanate adhesives without sacrificing shear strength or thermal stability (Papadopoulou *et al.*, 2024). This concept is relevant for hemp-shive PB/MDF, where both raw material and a portion of the adhesive can be derived from agricultural biomass. These hemp-based systems align with broader developments in self-binding and natural binder concepts for formaldehyde-free hot-pressed lignocellulosic boards, where lignin softening, carbohydrate plasticisation and hydrogen bonding are exploited instead of synthetic amino resins (Hubbe *et al.*, 2018).

In inorganic and hybrid systems, magnesium-based binders and sodium silicate have been combined with hemp shives to produce non-combustible wall materials. Magnesium oxychloride–hemp composite panels achieve competitive mechanical and thermal performance with very low embodied carbon, especially when chemically modified shives are used to reduce detrimental interactions with the alkaline binder (Stevulova *et al.*, 2014; Sinka *et al.*, 2019).

Across all binder families, the shive–binder interface is critical. Pre-treatments that change surface chemistry, polarity and roughness directly affect wetting, resin uptake, cure kinetics and the formation of mechanical or covalent bonds. However, systematic, comparative studies on pre-treatment–binder combinations are still rare. Most adhesive systems have been optimised empirically for specific densities and target properties, leaving substantial uncertainty about the general design rules for high-performance hemp-shive PB/MDF with reduced fossil and formaldehyde content.

Manufacturing concepts and processing windows

Hemp-based particleboards and fibreboards are generally produced on equipment developed for wood-based panels, with some adaptations. One-layer hemp-shive boards are manufactured by drying, resin blending, mat forming and hot-pressing. Due to the low bulk density of shives, mats are thick and highly compressible, and their formation requires careful control of air flow and drop height to avoid segregation of heavy and light fractions. Hot pressing at ≈ 160 °C with multi-stage pressure schedules and relatively long press factors is commonly used to ensure full cure and consolidation (Savov & Hristodorova, 2023; Hristodorova *et al.*, 2023).

Three-layer panel concepts exploit the different roles of shives and fibre-rich fractions. Savov *et al.* (2025) developed lightweight hemp shive–fibre panels with shives in the core and defibrated stalks or hemp fibres in the faces. By varying overall density (400 – 600 kg·m⁻³) and face-layer share, they identified designs around 500 – 550 kg·m⁻³ and roughly 40% face fraction that satisfy mechanical criteria for P2 particleboards and approach MDF performance for dry use, while remaining substantially lighter than standard boards. These panels can be produced on conventional three-layer particleboard lines using separate core and face forming and metal stops to control thickness.

In the ultra-low-density range, Fehrmann *et al.* (2023) showed that particle size, resin content and pressing conditions interact strongly. Boards with higher compaction and optimised granulometry performed better than low-density boards with increased resin content, underscoring that densification and mat structure are at least as important as adhesive dosage.

Lamination with thin skins (aluminium, hardboard, Kraft liner) greatly improves bending properties of such boards, enabling their use as sandwich cores rather than stand-alone panels.

Beyond flat-pressed boards, air-lay thermobonding processes have been used to produce flexible biocomposite panel rolls from micronised hemp stalks and bicomponent PP/PE fibres, with hemp contents up to 80%. These semi-industrial rolls exhibit low thermal conductivity and effective sound attenuation, and can be unrolled and cut on site as insulation layers (Gallina *et al.*, 2025). Other studies have shown the feasibility of sandwich panels with hemp fabric skins and various cores, as well as hybrid carbon/hemp grid cores produced in continuous processes (Islam *et al.*, 2025; Boccarusso *et al.*, 2021). Although not all of these concepts fall under classical PB/MDF, they illustrate the versatility of hemp residues in panel-type products.

Altogether, the manufacturing “toolbox” now includes one-layer and three-layer boards, ultra-light cores, thermobonded mats and advanced sandwich structures. However, robust processing windows that account for realistic variability in hemp feedstock, moisture and binder systems are still under development, and most results come from laboratory or pilot-scale studies.

Panel performance and benchmarking against conventional PB/MDF

Mechanical and physical tests show that hemp-shive panels can, under appropriate conditions, match or surpass conventional wood-based panels for several key indicators. Medium-density one-layer hemp-shive boards with roughly 10% UF/MF resin and $650 \text{ kg}\cdot\text{m}^{-3}$ density generally meet or exceed EN 312 P2 limits for bending strength, stiffness and internal bond (Savov & Hristodorova, 2023). Three-layer hemp shive–fibre boards with optimised architecture also fulfil these requirements and approach MDF benchmarks for dry-use panels (Savov *et al.*, 2025). Related work on mixed wood–hemp and flax-shive particleboards further confirms that hemp hurds can serve as effective low-density core material when bonded with low dosages of pMDI, producing panels that conform to ANSI specifications and exceed the performance of wood-residue boards at similar densities (Sam-Brew & Smith, 2017).

Fastener-holding capacity is a particular strength. Experimental data show that both screw and staple withdrawal resistances in hemp-shive panels are often substantially higher than in wood particleboards of comparable density, especially from the edge zones. In MF-bonded boards, increasing density from 600 to $900 \text{ kg}\cdot\text{m}^{-3}$ more than doubled staple withdrawal, and even the lowest-density hemp panels outperformed industrial wood particleboard references for this property (Hristodorova *et al.*, 2023). This is highly relevant for furniture applications with stapled or screwed joints.

Water absorption and thickness swelling are more challenging because of the high hygroscopicity of hemp shives. Nonetheless, resin content, binder type and panel density significantly improve performance. Savov & Hristodorova (2023) observed that increasing UF/MF content from 8 to 14% halved thickness swelling after 24 h and that hemp-shive boards showed lower water absorption and thickness swelling than wood-particleboard controls at the same resin level. Panels with 14% resin met the EN 312 P3 thickness-swelling limit for boards in humid conditions. In ultra-low-density boards, MDI-bonded hemp hurd panels achieved thickness swelling within moisture-resistant limits, whereas PRF- and epoxy-bonded boards did not (Fehrmann *et al.*, 2023).

Low-density hemp composites bonded with starch or thermoplastics exhibit very low thermal conductivities ($0.07\text{--}0.13 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and very good sound absorption and attenuation,

placing them in the range of wood-fibre insulation boards and mineral wool (Maalouf *et al.*, 2015; Gallina *et al.*, 2025). Hemp–starch panels in particular display “excellent” moisture-buffering values according to NORDTEST classification, indicating strong potential as interior linings that stabilise indoor humidity (Maalouf *et al.*, 2015).

Fire performance, long-term durability and emission behaviour are less well documented. Mineral-bound hemp composites show good fire resistance, but formal fire classifications for UF/MF-bonded hemp-shive PB/MDF are scarce. Studies indicate that E1 formaldehyde emission class is achievable at moderate resin contents, but comprehensive VOC profiles and long-term emission data are lacking (Savov & Hristodorova, 2023). Long-term creep, fatigue and biological durability under realistic service conditions have hardly been addressed.

In summary, the existing performance data position hemp-shive PB/MDF as promising alternatives to conventional panels for many interior applications, particularly furniture and interior linings, but they also reveal missing information on long-term and fire-related behaviour that is needed for wider adoption.

Environmental and techno-economic aspects

Hemp cultivation offers several environmental advantages: rapid growth, low input requirements and significant CO₂ uptake. When used in panels, hemp shives contribute biogenic carbon and reduce dependency on forest resources. LCA studies on hemp-based components and thermal insulators show substantial reductions in embodied carbon compared with conventional systems, with significant net CO₂ uptake over the cultivation and product life cycle (Zampori *et al.*, 2013). When used in panels, hemp shives contribute biogenic carbon and reduce dependency on forest resources. LCA studies on hemp-based components and thermal insulators show substantial reductions in embodied carbon compared with conventional systems, with significant net CO₂ uptake over the cultivation and product life cycle (Zampori *et al.*, 2013). For example, a magnesium–hemp composite wall panel with a U-value of 0.18 W·m⁻²·K⁻¹ has been reported to emit roughly six times less CO₂-equivalents per square metre than comparable masonry or aerated-concrete systems with mineral wool insulation (Sinka *et al.*, 2019). Semi-industrial hemp-stalk panel rolls with up to 80% biomass content further reduce fossil resource use by replacing part of the polymeric insulation with agricultural residues (Gallina *et al.*, 2025). More generally, ecological-footprint and life-cycle studies on conventional particleboard processes and interior wood products underline the dominant influence of raw material sourcing and resin systems on the overall environmental profile, providing a relevant benchmark for future hemp-based PB/MDF (Saravia-Cortez *et al.*, 2013; Cobut *et al.*, 2015).

At the same time, techno-economic studies highlight several constraints. Raw-material variability, seasonal availability and competition with existing uses can affect price and supply security of hemp shives (Savov *et al.*, 2025). Adhesive costs are significant, especially when MF or MDI are used to achieve moisture resistance. Process adjustments are needed to handle low-density shives in forming and dosing systems, but capital investments can be relatively modest when existing PB/MDF infrastructure is used. The ability of hemp boards to deliver equal or better performance at lower density suggests that, at the product level, transport and handling costs can be reduced and environmental gains are achievable even if process energy per kilogram is similar to wood-based boards.

Overall, hemp-based panels fit well into the narrative of circular and low-carbon construction materials, but more detailed techno-economic and life-cycle analyses are required for PB/MDF-class products, including end-of-life options such as mechanical recycling or bio-based disposal.

Research gaps and problem statement

Despite rapid development in recent years, the research landscape on hemp-shive wood-based panels remains fragmented and oriented towards laboratory case studies. Several gaps emerge clearly from the state of the art and define the problem space for further work.

First, material characterisation and product standardisation are incomplete. Basic data on chemical composition and bulk density exist, but there is no harmonised description of hemp shive granulometry, sorption behaviour and variability across cultivars and processing routes. Panels are tested against existing wood-based standards that do not fully reflect the multifunctional, lightweight and laminated nature of many hemp-based products.

Second, the interaction between pre-treated shives and new generations of bio-based and hybrid binders is poorly understood. High-performance hemp panels currently rely mainly on UF/MF and pMDI, yet societal and regulatory drivers call for lower formaldehyde emissions and reduced fossil carbon. Systematic studies that combine different pre-treatments of shives with starch, protein, lignin, tannin and hybrid pMDI systems, under unified panel designs and testing protocols, are largely lacking. Without such work, it is difficult to design hemp-based PB/MDF that simultaneously satisfy mechanical, durability and emission requirements.

Third, long-term durability, fire performance and indoor air impacts remain underexplored. Existing data are dominated by short-term tests (24 h water uptake, bending, internal bond). There is very limited information on panel behaviour under cyclic humidity and temperature, long-term creep or fatigue, resistance to mould and decay under real indoor exposure, and response to fire according to established building classifications. For materials that are promoted specifically for green buildings and interior applications, this constitutes a critical knowledge gap.

Fourth, upscaling and process robustness pose open challenges. Most promising results have been achieved with carefully selected and conditioned raw materials under laboratory or pilot conditions. Industrial hemp shives, however, vary widely in particle size, moisture and contamination. There is a need for process maps and in-line quality-control tools that ensure consistent panel properties under realistic variability and that demonstrate robust performance on existing PB/MDF lines or on dedicated continuous processes.

Finally, integration into circular and modular building and furniture systems is still in its infancy. Potential advantages of hemp-based panels – high bio-based content, low embodied carbon, moisture buffering – will only fully materialise if products are designed for disassembly, reuse and recycling, and if they are evaluated at system level (walls, furniture modules, building envelopes) rather than as isolated materials.

The central problem statement that arises from this review can therefore be formulated as follows: industrial hemp shives have been shown to be a technically viable feedstock for a wide range of wood-based panel products, and can deliver competitive or superior performance in many respects, yet the lack of standardised raw-material characterisation, limited understanding of shive–binder interfaces for next-generation adhesives, incomplete knowledge of long-term and

fire behaviour, and unresolved upscaling and circular-design issues currently hinder their transition from promising laboratory materials to reliable, widely used industrial products.

Addressing these gaps through coordinated materials, process and system-level research is a prerequisite for fully valorising hemp stems and shives in future bio-based particleboards, fibreboards and multifunctional panel systems.

CONCLUSIONS

This review has examined the valorisation of industrial hemp stems and shives as lignocellulosic feedstock for bio-based particleboards, fibreboards and related panel products. The evidence shows that hemp shives, traditionally regarded as a low-value by-product, can act as a technically sound and functionally attractive alternative or complement to wood particles. Chemically they are close to hardwoods, but their low bulk density, high porosity and pronounced hygroscopicity distinguish them from conventional raw materials. These features favour the development of lightweight, thermally and acoustically efficient panels, yet simultaneously pose challenges for dimensional stability and biological durability. Mechanical and thermo-chemical pre-treatments, such as granulometry optimisation and alkaline or hydrothermal treatments, have proven effective in tailoring shive morphology and surface chemistry and in improving compatibility with both organic and inorganic binders.

Regarding adhesive systems and manufacturing concepts, conventional thermosetting resins – UF, MF, UF/MF blends and particularly pMDI – already enable hemp-shive boards to reach or exceed the mechanical performance of standard particleboards for furniture applications. Medium-density one-layer and three-layer hemp panels with amino resin contents on the order of 8–12%, typically around 10%, meet EN 312 P2 requirements and offer excellent screw and staple withdrawal resistance, while ultra-low-density MDI-bonded boards can achieve moisture-resistant thickness swelling when granulometry and pressing parameters are carefully optimised. At the same time, emerging bio-based and hybrid binders, such as starch-based systems, bio-filled pMDI and magnesium oxychloride, expand the application spectrum towards fully bio-based, hygrothermally active or fire-resistant panels. One-layer and three-layer flat-pressed boards, ultra-light cores, air-laid thermobonded rolls and advanced sandwich structures together illustrate the versatility of hemp residues as components in modern panel technologies.

From a performance and sustainability perspective, the main strengths of hemp-shive panels are their combination of high fastener-holding capacity, good bending properties at moderate densities and, in low-density formats, outstanding hygrothermal and acoustic behaviour. Medium-density PB/MDF-type products are suitable for furniture and interior fit-out, whereas low- and ultra-low-density formats are more appropriate for insulation layers, sandwich cores and functional linings. With suitable binders and formulations, water absorption and thickness swelling can match or surpass those of conventional particleboards. Environmental and techno-economic analyses indicate that hemp-based panels fit well into a circular bioeconomy: hemp cultivation sequesters CO₂, industrial processing generates concentrated shive streams that can be readily valorised, and several LCA studies report substantially lower carbon footprints for hemp-based wall and insulation systems compared with conventional solutions. Nevertheless, issues of raw-material variability, the cost and availability of high-performance binders and competition with established, low-cost wood-based PB/MDF remain important barriers to wider market penetration.

Crucially, this review has identified several research gaps that must be addressed for industrial hemp shives to transition from promising laboratory feedstock to widely used industrial raw material. There is, first, a clear need for standardised raw-material characterisation and dedicated product classes, including hemp-specific granulometry, sorption data and test protocols for multifunctional, lightweight and laminated panels. Second, the interface between pre-treated shives and novel bio-based or hybrid binders is still poorly understood, and systematic, comparative studies on pre-treatment–binder combinations for PB/MDF-class applications are largely missing. Third, data on long-term durability, fire performance and comprehensive emission profiles under realistic service conditions are scarce, particularly for panels intended for interior linings and furniture. Fourth, upscaling and process robustness in the face of raw-material variability require better-defined processing windows and in-line quality control. Finally, the potential of hemp-based panels in circular design, including recyclability, design for disassembly and integration into holistic low-carbon building and furniture systems, remains underexplored. Addressing these issues through coordinated research that links raw material, binder systems, processing, performance and system-level application will be essential for industrial hemp stems and shives to evolve from secondary agricultural residue into a strategic feedstock for next-generation bio-based panels.

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