Alternative Bio-Based and Recycled Materials to Replace Wood in Pallets: A Systematic Review Following the PRISMA 2020 Guidelines

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ABSTRACT

Wooden pallets remain the dominant platform for unit-load handling; however, their dependence on virgin timber, short service life, vulnerability to moisture and pests, and the phytosanitary treatments required in international trade have driven the search for alternative materials. This study systematically reviews the scientific literature on materials proposed to replace solid wood in pallet manufacturing, in order to identify the main material families, their mechanical and durability performance, their environmental profile, and their technological maturity. The review was designed and is reported in accordance with the PRISMA 2020 statement. Searches are conducted in Scopus, Web of Science, ScienceDirect, and IEEE Xplore, supplemented with Google Scholar, using Boolean strings that combine pallet, material, and sustainability terms. Peer-reviewed articles and conference papers published between 2010 and 2026 that evaluate a non-wood or wood-substitute material for load pallets or equivalent platforms are considered eligible. Two reviewers independently screen the records, extract the data, and assess the risk of bias using a checklist adapted to materials engineering. The evidence is synthesized narratively and comparatively across five families: recycled and virgin plastics, natural-fiber biocomposites, wood–plastic composites, engineered bamboo and lignocellulosic panels, and mycelium- and paper-based structures. The literature indicates that recycled plastics and fiber-reinforced composites offer greater durability and hygiene, whereas lignocellulosic and mycelium-based solutions have a lower embodied carbon but face limitations in moisture resistance, creep under sustained load, and the lack of standardized testing. Few studies evaluate full-scale pallets according to ISO 8611 or conduct life cycle assessments, which is the most critical gap. A research agenda is proposed focused on hybrid bio-based composites, standardized testing, and circular end-of-life design.

Keywords: pallet, wood replacement, biocomposites, recycled plastic, sustainable packaging, PRISMA

INTRODUCTION

Pallets are the fundamental load-bearing interface of modern supply chains. They make it possible to consolidate goods into unit loads that can be moved with forklifts, stored in racking systems, and transported across multimodal networks. Unitizing loads drastically reduced loading and unloading times, damage to goods, and labor costs, and for this reason the pallet is considered one of the silent but decisive elements of contemporary logistics. Owing to its low cost, ease of repair, and well-known mechanical behavior, the wooden pallet has historically dominated the market.

However, this dominance entails significant environmental and operational costs. Wooden pallets consume large volumes of timber, often of low quality, and withstand a limited number of use cycles before breaking or requiring repair. They absorb moisture, can harbor fungi and insects, and can release splinters and nails that damage products and injure workers. In international trade, solid-wood packaging must comply with International Standard for Phytosanitary Measures No. 15 (ISPM 15), which requires heat treatment or fumigation (Food and Agriculture Organization [FAO], 2009). These requirements increase costs, energy consumption, and, in the case of chemical fumigation, environmental and health risks. In addition, the

heterogeneity of the raw material and the proliferation of low-quality single-use pallets shorten the average service life and generate large volumes of waste.

At the same time, regulatory and market pressures are pushing logistics toward circular, low carbon solutions. The circular economy paradigm emphasizes durability, reuse, repairability, and material recovery at the end of life (Ellen MacArthur Foundation, 2013). Plastic pollution has complicated the picture: plastic pallets solve several of the problems of wood, but they depend on fossil feedstocks and, if poorly managed, contribute to persistent waste (Geyer et al., 2017). Consequently, there is growing interest in new materials that combine the performance of engineered products with the renewability and recyclability expected of sustainable packaging. The candidates range from recycled thermoplastics and natural-fiber composites to engineered bamboo and agricultural residues bound with mycelium.

Despite the proliferation of individual studies, the evidence on pallet materials is fragmented across materials science, packaging engineering, forestry, and logistics journals. Existing reviews tend to focus on a single class of material, such as natural-fiber composites in general (Faruk et al., 2012; Pickering et al., 2016) or wood–plastic composites (Ashori, 2008), and rarely assess suitability against pallet-specific requirements, such as static and dynamic load capacity, deflection in racking, fork impact, moisture stability, and end-of-life management. To the best of our knowledge, there is no systematic, protocol-based synthesis that compares the main candidate materials against a common set of performance and sustainability criteria.

The objective of this work is to systematically review the literature on alternative materials to replace wood in pallets, following the PRISMA 2020 guidelines (Page et al., 2021). The specific objectives are: (i) to identify and classify the materials proposed as wood substitutes in pallets; (ii) to compare their reported mechanical, physical, and durability properties; (iii) to synthesize the evidence on their environmental performance and end-of-life options; (iv) to assess the methodological quality and technological maturity of the evidence; and (v) to identify research gaps and propose a roadmap for developing a new generation of pallet materials. The contribution of the article is a structured evidence base and a set of design criteria that can guide material developers, pallet manufacturers, and logistics operators.

LITERATURE REVIEW

This section presents the state of the art that frames the systematic review. It is organized by material family and, subsequently, by cross-cutting themes (structural design, standards and testing, environmental assessment, and circular economy). Its purpose is to establish what is currently known and which aspects remain unresolved.

Theoretical framework

The study is guided by a framework of materials selection and sustainability. Following the logic of the performance indices proposed by Ashby (2013), a material is not evaluated by a 2 single property, but by its ability to satisfy a set of functional requirements, constraints, and objectives. In a pallet, the main functional requirement is to support static, dynamic, and racking loads with limited deflection; the constraints include standardized dimensions, forklift access, fire behavior, hygiene, and compliance with trade regulations; and the objectives include minimizing cost, mass, and environmental impact.

Cellular and sandwich architectures, widely analyzed in the mechanics of cellular solids (Gibson & Ashby, 1997), are also relevant because the decks and blocks of a pallet can be designed as lightweight structures whose stiffness depends as much on the geometry as on the base material. Finally, the circular economy perspective (Ellen MacArthur Foundation, 2013) adds end-of-life criteria, such as reuse, repairability, recyclability, or biodegradability, which are integrated into the synthesis as a third axis of evaluation alongside performance and cost. The environmental assessment relies on life cycle assessment (LCA) in accordance with ISO 14040 and ISO 14044 (International Organization for Standardization [ISO], 2006a, 2006b), and technological maturity is described using the technology readiness level (TRL) scale proposed by Mankins (1995).

The wooden pallet: performance and limitations

Solid-wood pallets offer a favorable stiffness-to-cost ratio, simple nailed manufacturing, and easy repair. Their main drawbacks are the variability of the raw material, hygroscopic behavior that alters strength and dimensions, vulnerability to fungal decay, and the need for phytosanitary treatment in international trade (FAO, 2009). Wood is an anisotropic and heterogeneous material whose properties depend on species, density, the presence of knots, and moisture content (Rowell, 2012), which makes it difficult to guarantee uniform performance between batches.

From an environmental perspective, wood has an initial advantage because of its renewable origin and its capacity to store carbon; nevertheless, life cycle studies show that the outcome depends critically on the intensity of reuse, that is, the number of trips each pallet makes before being discarded (Gasol et al., 2008). These limits define the baseline against which the alternatives are evaluated, and explain why replacement strategies focus on durability, hygiene, dimensional stability, and simplified regulatory compliance.

Plastic and recycled-plastic pallets

Pallets made of high-density polyethylene (HDPE) or polypropylene (PP), manufactured by injection or compression molding, are the most established alternative. They offer consistent dimensions, resistance to moisture and chemicals, ease of cleaning, and long service life, attributes that are valuable in the food and pharmaceutical sectors and in closed-loop systems. The use of recycled polyolefins reduces the demand for virgin resin and diverts waste from landfills.

Their limitations include a higher initial cost, creep and thermal sensitivity under prolonged loads in racking, low stiffness relative to wood if they are not reinforced, flammability, and dependence on fossil-based polymers. The scale of global plastics production and the low recovery rate of post-consumer plastics (Geyer et al., 2017) make the supply and end of life of these pallets a central sustainability issue. In addition, the challenges of mechanical recycling, such as the degradation of properties after successive cycles and cross-contamination between polymers, constrain the quality of the recycled material available (Hopewell et al., 2009).

Natural-fiber biocomposites

Natural fibers such as hemp, flax, jute, kenaf, sisal, and coir have attracted attention as renewable reinforcements with low density and good specific stiffness (Bledzki & Gassan, 1999; Mohanty et al., 2000; Wambua et al., 2003). Comprehensive reviews point out that natural-fiber composites can reach mechanical properties competitive with those of glass-fiber reinforced plastics in specific terms, although performance depends strongly on the fiber type, the fiber–matrix adhesion, the fiber length and orientation, and moisture absorption (Faruk et al., 2012; Pickering et al., 2016).

Lignocellulosic fibers are hydrophilic, which reduces dimensional stability and interfacial strength. For this reason, treatments such as alkaline mercerization, silanization, or acetylation are used, together with coupling agents, to improve compatibility with thermoplastic or thermoset matrices (Kalia et al., 2009; Satyanarayana et al., 2009). Hybridizing natural fibers with synthetic fibers is another documented strategy for balancing stiffness, toughness, and water absorption (Jawaid & Khalil, 2011). For pallets, polypropylene or polyethylene reinforced with natural fibers is a promising route because it increases stiffness and reduces creep relative to unreinforced polymers, while partially replacing the petrochemical content (Mohanty et al., 2002).

Wood–plastic composites

Wood–plastic composites (WPC) combine wood flour or fibers with thermoplastics and additives. They have been developed commercially for outdoor decking, cladding, and automotive components, and they offer greater resistance to moisture and decay than solid wood, together with higher stiffness than pure polymers (Clemons, 2002; Klyosov, 2007; Ashori, 2008). Since they can be processed by extrusion and compression

molding using wood waste and recycled plastics, WPCs are among the most mature candidates for pallet components.

Their reported disadvantages include brittleness at low temperatures, a density higher than that of wood, sensitivity to creep, and the difficulty of separating the components at the end of life, which contradicts the principles of design for disassembly. The wood–polymer interface, which is polar–nonpolar, requires coupling agents such as maleic anhydride-grafted polypropylene to achieve effective load transfer (Klyosov, 2007).

Engineered bamboo and lignocellulosic panels

Bamboo grows rapidly, regenerates without the need for replanting, and has high tensile strength in the fiber direction (Liese & Köhl, 2015). Engineered bamboo products, including laminated and pressed-strand products, have shown mechanical properties suitable for structural applications (Sharma et al., 2015). Their use in pallets is attractive in regions with abundant bamboo, but barriers persist, such as processing cost, adhesive content, variability between species, and the need for standardized geometries that fit pallet dimensions.

Other panel-based solutions, such as compressed agricultural-residue boards, honeycomb cardboard, and molded pulp, offer low weight and recyclability, but they are usually limited to light-load or single-trip applications because of their moisture sensitivity and low resistance to repeated impact.

Mycelium-based materials and other emerging biomaterials

Mycelium-bound composites are grown by inoculating lignocellulosic substrates with fungal mycelium, which binds the particles together and forms a lightweight, biodegradable material. Critical reviews describe their low density, thermal insulation, and low embodied energy, but also their low strength compared with structural wood and their moisture sensitivity (Appels et al., 2019; Girometta et al., 2019; Jones et al., 2020). Process variables such as species, substrate, growth time, and drying strongly influence the properties, and the absence of standardized protocols limits comparison between studies; in addition, designing with materials that grow introduces specific challenges of quality control and industry acceptance (Karana et al., 2018).

In the context of pallets, mycelium is today more credible as a core or filler material in hybrid sandwich structures, or for single-use protective packaging, than as a stand-alone load-bearing material.

Cellular, sandwich, and hybrid architectures

A cross-cutting line of research proposes that pallet performance depends not only on the material, but on its architecture. Sandwich-type structures, with thin, stiff skins separated by a lightweight core (honeycomb, foam, ribs, or mycelium), make it possible to maximize bending stiffness per unit of mass (Gibson & Ashby, 1997). Applied to pallets, this logic suggests combining skins of natural-fiber-reinforced composites with low-weight, low-carbon cores, and designing ribs or molded blocks that reduce material without sacrificing load capacity. Hybrid designs also make it possible to allocate each material where it is most effective: hydrophobic reinforcements in areas exposed to moisture and biodegradable cores in protected areas.

Standards, testing, and environmental assessment

Pallet performance is normally verified through standardized tests for flat pallets, such as the dimensions, load rating, and test methods defined in the ISO 8611 series (ISO, 2011). Many materials studies, however, report properties at the specimen scale (tension, flexure, impact) that cannot be directly transferred to the behavior of the complete pallet under racking, stacking, and forklift handling.

Environmental claims are equally uneven: LCA studies depend on assumptions about the number of trips, repair rates, recycling, and transport distances, and the comparisons between wood, plastic, and bio-based

pallets can be reversed when those assumptions change (Ashby, 2013; Gasol et al., 2008). This heterogeneity justifies a protocol-driven approach that records, for each study, the test level (specimen, component, or full pallet), the standards used, and the environmental indicators reported.

Research gap

The literature reveals three recurring gaps. First, most of the evidence is fragmented by material family, and no review compares the alternatives against specific functional pallet requirements. Second, there is a scarcity of full-scale tests and of data on creep, fatigue, and long-term moisture aging. Third, environmental assessments are rarely harmonized, and end-of-life options are discussed qualitatively. The present review addresses these gaps through a systematic, comparable, and transparent synthesis.

METHODOLOGY

The review was designed and is reported in accordance with the PRISMA 2020 statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page et al., 2021), which updates the original guidance (Moher et al., 2009). Before screening, a review protocol was defined that specifies the research questions, eligibility criteria, information sources, search strategy, data items, and synthesis approach. The logic of transparency and reproducibility follows the principles of evidence-based systematic review (Tranfield et al., 2003).

Research design

A systematic review with narrative synthesis was selected because the included studies are expected to be heterogeneous in material type, test method, and reported metrics, which precludes a quantitative meta-analysis. The review is guided by the following research questions: **RQ1**, what materials have been proposed to replace wood in pallets? **RQ2**, how do they behave mechanically and physically relative to wood? **RQ3**, what is their environmental profile and end-of-life potential? **RQ4**, what is their technological maturity and which research gaps persist?

Eligibility criteria

The criteria were defined with a PICOC-type structure adapted to materials research and are summarized in Table 1.

Table 1: Inclusion and exclusion criteria

Criterion	Inclusion	Exclusion
Population / object	Pallets or unit-load platforms and their components (decks, blocks, stringers)	Other packaging or construction products with no relevance to pallets
Intervention	Non-wood materials or wood substitutes (plastics, biocomposites, WPC, bamboo, mycelium, paper-based)	Studies only on solid-wood pallets, with no alternative material
Comparator	Solid wood or another alternative material	Not required
Outcomes	Mechanical, physical, durability, environmental, or economic performance	No measurable results
Study type	Peer-reviewed journal articles and conference papers with experimental, numerical, or LCA methods	Editorials, patents, theses, trade articles, and reviews without original data (used only as background)
Period and language	2010–2026; English and Spanish	Outside the period; no full text available

Information sources and search strategy

The databases consulted were Scopus, Web of Science Core Collection, ScienceDirect, and IEEE Xplore, supplemented with Google Scholar (first 200 records by relevance) and backward and forward citation searching of key studies. The search was adapted to each database and applied to title, abstract, and keywords. The core Boolean string was:

(pallet* OR "load platform" OR "unit load") AND ("wood replacement" OR "alternative material*" OR "wood substitute" OR composite* OR biocomposite* OR "wood-plastic" OR "recycled plastic" OR bamboo OR mycelium OR "natural fib*" OR "bio-based") AND (mechanical OR strength OR durability OR "life cycle" OR sustainab* OR "circular economy")

The search date, the exact string, and the number of records returned by each database are recorded in a search log to ensure reproducibility.

Study selection and data collection

Records were exported to a reference manager and duplicates were removed. Two reviewers independently screened titles and abstracts and then full texts, using a screening tool such as Rayyan (Ouzzani et al., 2016). Disagreements were resolved by discussion or with a third reviewer. The reasons for exclusion at the full-text stage were recorded. A standardized extraction form, summarized in Table 2, was used to collect the data from each study.

Table 2: Variables of the data extraction form

Domain	Extracted variables
Bibliographic	Authors, year, country, journal, document type
Material	Family, composition, recycled or bio-based content, additives, and coupling agents
Process	Manufacturing method (injection, extrusion, compression molding, cultivation, lamination), relevant parameters
Test level	Specimen, component, or full pallet; standards applied (ASTM, ISO, EN)
Properties	Density, flexural strength and modulus, compressive strength, creep, impact, water absorption
Environmental	Global warming potential, embodied energy, recyclability, biodegradability, functional unit, and LCA boundaries
Economic and maturity	Reported cost, production scale, estimated TRL, stated limitations

Quality assessment and data synthesis

Since there is no single risk-of-bias tool for materials engineering studies, an adapted checklist was used. It assessed the clarity of the material description, specimen replication, the use of standardized test methods, the presence of a wood or other reference control, the statistical treatment, and the transparency of the LCA assumptions. Each criterion was rated as met, partially met, or not met, and the studies were classified as having high, moderate, or low confidence.

The results were synthesized narratively by material family and tabulated for comparison. Technological maturity was assigned using an adapted TRL scale (Mankins, 1995), from laboratory proof of concept (TRL 3–4) to commercial deployment (TRL 8–9). When studies reported homogeneous and comparable properties, descriptive ranges were calculated; no meta analysis was planned.

RESULTS AND DISCUSSION

Study selection (PRISMA flow)

The study selection process follows the PRISMA 2020 flow diagram, which is reported in Table 3 and illustrated in Figure 1.

Table 3: Record flow according to PRISMA 2020

Stage	Description	Records (n)
Identification	Records from Scopus	[n]
Identification	Records from Web of Science	[n]
Identification	Records from ScienceDirect	[n]
Identification	Records from IEEE Xplore	[n]
Identification	Records from other methods (Google Scholar, citation searching)	[n]
Identification	Duplicates removed	[n]
Screening	Records screened by title and abstract	[n]
Screening	Records excluded	[n]
Eligibility	Reports assessed for eligibility (full text)	[n]
Eligibility	Reports excluded, with reasons	[n]
Inclusion	Studies included in the synthesis	[n]

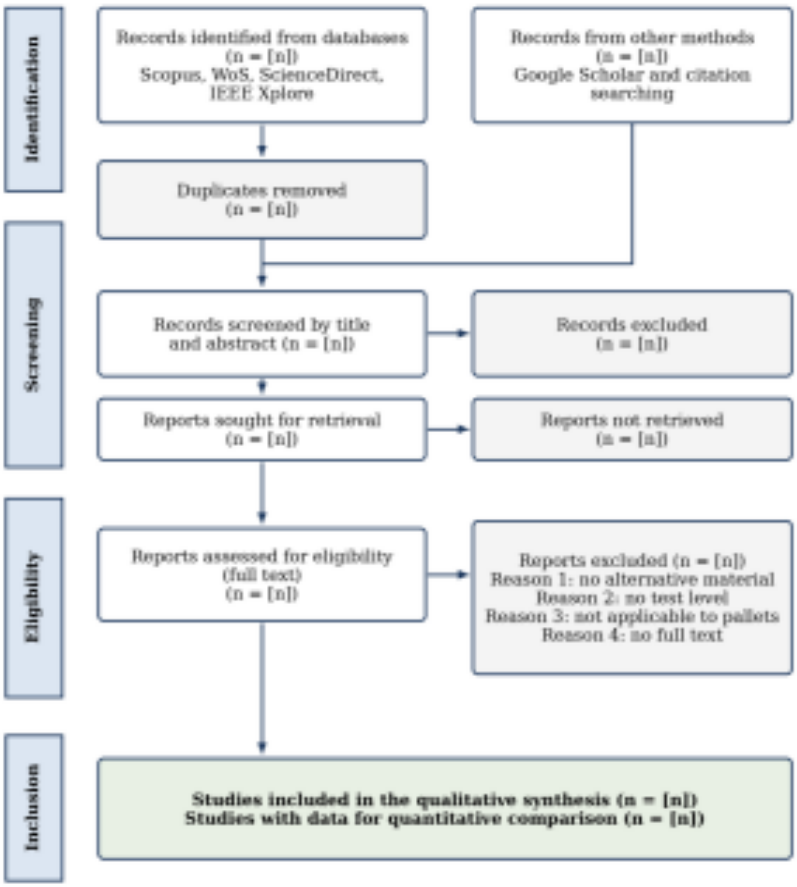

Figure 1: PRISMA 2020 flow diagram of the study selection process

Comparative synthesis of the material families

Table 4 presents the expected comparative profile of the five material families against the main pallet criteria. The ratings are indicative and are derived from the literature analyzed; they should be refined with the quantitative data extracted from the included studies.

Table 4: Indicative comparison of material families for pallets

Material family	Stiffness / load capacity	Moisture and decay resistance	Embodied carbon (relative)	End of life	Indicative TRL
Solid wood (baseline)	Medium to high	Low	Low	Reuse, repair, energy recovery	9
Recycled / virgin plastics	Medium (prone to creep)	High	Medium to high	Mechanical recycling	9
Natural-fiber biocomposites	Medium to high	Medium (depending on treatment)	Low to medium	Recycling or composting depending on matrix	5–7
Wood–plastic composites	Medium	Medium to high	Medium	Difficult to separate	7–9
Engineered bamboo / lignocellulosic panels	Medium to high	Low to medium	Low	Reuse, biodegradable	5–8
Mycelium and paper-based	Low	Low	Very low	Compostable	3–6

DISCUSSION

The synthesis suggests that no material currently dominates all criteria, which explains the persistent prevalence of wood. Plastics solve the problems of moisture and hygiene, but they do not necessarily reduce the environmental burden unless the recycled content is high and closed-loop recovery is guaranteed (Geyer et al., 2017; Hopewell et al., 2009). Thermoplastics reinforced with natural fibers appear as the most balanced route: they improve stiffness and creep resistance relative to unreinforced polymers and reduce the fossil content, provided that fiber–matrix adhesion and moisture absorption are controlled (Faruk et al., 2012; Pickering et al., 2016).

WPCs are the closest to commercial maturity, but their end-of-life limitations contradict the principles of the circular economy (Ellen MacArthur Foundation, 2013). Bamboo and mycelium-based materials offer the lowest embodied carbon, although their mechanical limits and moisture sensitivity confine them, for now, to light-load, hybrid, or single-trip applications (Sharma et al., 2015; Jones et al., 2020).

A key finding for future development is the methodological gap between material characterization and pallet certification. Studies that stop at specimen-scale tests cannot demonstrate compliance with pallet-scale protocols such as those of the ISO 8611 series (ISO, 2011) and therefore overestimate technological maturity. Likewise, environmental comparisons are sensitive to the number of use cycles: a lighter bio-based pallet that fails after a few trips may have a worse life cycle profile than a durable plastic pallet (Gasol et al., 2008).

Toward a new material to replace wood

Based on the evidence analyzed, the design of a new wood-replacement material should be built around four decisions: a cellular or sandwich architecture that maximizes stiffness per unit of mass (Gibson & Ashby, 1997); a hydrophobic, bio-based or recycled matrix; a natural-fiber or lignocellulosic reinforcement with a validated surface treatment; and a design-for-disassembly approach that allows the constituent materials to be recovered. Table 5 summarizes the design requirements derived from this synthesis.

Table 5: Proposed design criteria for a wood-replacement material for pallets

Criterion	Proposed requirement	Material strategy
Load capacity	Meet the static, dynamic, and racking load tests of ISO 8611	Natural-fiber-reinforced skins and cellular core
Durability	Low creep and low water absorption over multiple cycles	Hydrophobic matrix, fiber surface treatment, coupling agents
Hygiene and compliance	No need for fumigation; cleanable surface	Non-wood material or with a hydrophobic barrier
Circularity	Recyclability or biodegradability at end of life	Mono-material or disassemblable design
Environmental impact	Lower LCA impact than wood and plastic for the same number of trips	High recycled and bio-based content
Cost and manufacturing	Competitive with current plastic pallets	Scalable processes (extrusion, compression)

Selected material and rationale for its choice

When the six alternatives in Table 4 are contrasted with the design requirements in Table 5, the material that best balances stiffness, moisture stability, circularity, and technological maturity is a polypropylene thermoplastic composite (preferably recycled, rPP) reinforced with lignocellulosic fibers or flours (hemp, henequen, rubberwood, or others of agricultural or forestry origin), coupled with maleic anhydride-grafted polypropylene (MAPP), processed by extrusion and compression molding and designed with a ribbed or sandwich geometry.

This material lies at the intersection between natural-fiber biocomposites and wood–plastic composites: the polyolefin matrix acts as a hydrophobic barrier and the lignocellulosic reinforcements provide stiffness and bio-based content.

Table 6 summarizes the assessment of each family against the selection criteria. The assessments are qualitative and are derived from the reviewed literature; no family meets all the criteria, so the selection should be understood as the best available combination and not as a material without limitations.

Table 6: Assessment of the material families against the selection criteria

Material family	Stiffness and load capacity	Creep and moisture	Circularity	Decision
Solid wood	Meets	Does not meet (hygroscopic; requires treatment under ISPM 15)	Partial (repairable; energy recovery)	Comparison baseline
Recycled / virgin plastics	Partial (low stiffness without reinforcement)	Partial (water resistant, but prone to creep)	Partial (mechanical recycling with loss of properties)	Used as the matrix, not as the sole material
Natural-fiber biocomposites	Partial to meets	Partial (depends on fiber treatment)	Partial to meets	Selected as the composite's reinforcement system
Wood–plastic composites	Partial	Partial to meets	Does not meet (difficult to separate)	Incorporated as a formulation variant (waste wood flour)
Engineered bamboo / lignocellulosic panels	Partial to meets	Partial (moisture sensitive)	Meets	Complementary alternative, mainly as reinforcing fiber
Mycelium and paper-based	Does not meet	Does not meet	Meets	Discarded as a load bearing material; possible core or single trip use

Evidence from tests supporting the selection

The evidence available for the selected material is concentrated at the specimen and component level and is summarized in Table 7. The values correspond to the results published by the cited studies and not to tests carried out by the authors of this review. In addition, they differ in the matrix, fiber type and content, processing conditions, and the standard used, so they should be read as orders of magnitude and trends, not as design values.

Table 7: Tests reported in the literature that support the material selection

Test	Material tested	Reported result	Source	Implication for the pallet
Flexure (ISO 178 / ASTM D790)	PP with 20–50 wt% henequen and 4% MAPP	Flexural modulus of 1.15 GPa for unreinforced PP and 3.75 GPa with 50% fiber, increasing linearly with fiber fraction	Seculi et al. (2026)	Stiffness approximately 3.3 times that of unreinforced PP
Flexure (strength) and coupling agent dosage	PP with 20–50 wt% hemp strands and MAPP	Most favorable MAPP dosage of 0.06 g per gram of fiber; maximum improvement in flexural strength of 148% at the highest fiber loading; intrinsic strand strength of 953 ± 116 MPa	Vallejos et al. (2023)	The coupling agent is decisive for load transfer
Tension and comparison with glass reinforcement	PP with henequen, with and without coupling agent (injection)	Strong interface with coupling agent; 50 wt% henequen can replace 20% glass fiber in PP; 50% limit due to loss of co continuity	Espinach et al. (2022)	Partial replacement of synthetic reinforcements; fiber loading ceiling
Flexural creep, 1000 h, at 20, 30, and 40% of ultimate strength	Unreinforced rPP versus rPP and rubberwood flour composite	Deflection of rPP: 2.45, 4.65, and 6.68 mm. Deflection of the composite: 1.53, 2.41, and 3.37 mm (38–50% reduction, calculated from these values)	Ratanawilai et al. (2023)	Lower delayed deformation under sustained load
Creep and blend design	rPP, rubberwood flour, MAPP, UV stabilizer, and lubricant	More flour reduces creep; MAPP and UV stabilizer increase it; validated formulation: 50.5% rPP, 44.9% flour, 3.5% MAPP, 0.1% UV, and 1.0% lubricant	Homkhiew et al. (2013)	The formulation requires a trade-off between additives

Test	Material tested	Reported result	Source	Implication for the pallet
Water absorption and swelling	rPP and virgin PP with rubberwood flour	Absorption and swelling increase with flour content and time; rPP absorbs more than virgin PP at 45% flour; absorption below 3% does not significantly affect flexural strength	Homkhiew et al. (2014)	Absorption threshold as an acceptance criterion
Long-term creep with water immersion	Composite of rPP, rubberwood flour, calcium carbonate, and MAPP	Creep increases with stress, temperature, and immersion time; estimated service life above 10 years at 3 MPa and 25 °C in the control sample	Ratanawilai & Srivabut (2022)	Need for a hydrophobic barrier and fiber treatment
Flexure and accelerated creep (TTSP)	Bamboo and recycled PLA	The modulus of rupture and the modulus of elasticity increase up to 60% fiber and then decrease sharply	Yang et al. (2015)	There is a maximum fiber loading
Accelerated creep by stepped isostress method	Bamboo and PP composites with layered structure	Long-term creep of layered structures was evaluated through accelerated tests	Hsu et al. (2018)	Method transferable to sandwich skins and cores
LCA (ISO 14040 / 14044), 1000 trips, 1200 × 800 mm pallet	Pallets of wood, virgin plastic, and wood–polymer composite with waste	Attributional: the composite has lower impact in several categories and wood has lower global warming without biogenic carbon. Consequential: the composite is better in all categories. Plastic has the highest impact in both approaches	Khan et al. (2021)	Environmental support conditional on LCA assumptions

Rationale for the choice based on the tests

Stiffness and strength. Reinforcement with lignocellulosic fibers coupled with MAPP consistently increases the stiffness of polypropylene. In the PP–henequen system, the flexural modulus went from 1.15 GPa in the unreinforced polymer to 3.75 GPa with 50 wt% fiber, an increase of about 3.3 times (Seculi et al., 2026), and 50% henequen made it possible to replace a PP with 20% glass fiber in the tensile properties study (Espinach et al., 2022). In hemp composites, the coupling agent dosage was decisive and the maximum improvement in flexural strength reached 148% at the highest fiber loading (Vallejos et al., 2023). These results explain the choice of a PP matrix with lignocellulosic reinforcement and MAPP, because they directly address the low stiffness that, according to Table 4, limits unreinforced plastics.

Creep. Creep under sustained load is the critical criterion in racking. In 1000 h flexural tests with loads of 20, 30, and 40% of ultimate strength, the deflection of unreinforced rPP was 2.45, 4.65, and 6.68 mm, compared with 1.53, 2.41, and 3.37 mm for the composite with wood flour, equivalent to reductions of 38 to 50% calculated from those values (Ratanawilai et al., 2023). Formulation optimization also showed that increasing the flour fraction reduces creep, whereas MAPP and the UV stabilizer increase it, so the validated formulation represents a compromise between these effects (Homkhiew et al., 2013). This result supports the use of rPP with a high reinforcement loading and warns that the coupling agent and additives must be dosed with creep tests of their own.

Moisture. The main weakness of lignocellulosic reinforcements is their hydrophilic character. In composites of rPP and rubberwood flour, water absorption and swelling increased with flour content and immersion time, rPP absorbed more water than virgin PP at 45% flour, and absorption below 3% did not significantly affect flexural strength (Homkhiew et al., 2014). Creep also increased with stress, temperature, and immersion time, although the estimated service life exceeded 10 years at 3 MPa and 25 °C in the control sample (Ratanawilai & Srivabut, 2022). These findings justify keeping the polyolefin matrix as a barrier, setting a water absorption threshold as an acceptance criterion, and treating the fiber surface, as proposed in Table 5.

Reinforcement fraction and architecture. Studies with PP converge on a working window of about 45–50 wt% fiber: Espinach et al. (2022) limited henequen composites to 50% because PP cannot accommodate a higher amount without losing its co-continuity, and the formulation validated by Homkhiew et al. (2013) contains 44.9% flour. In a different bio-based system, bamboo and recycled PLA, the modulus of rupture and the modulus of elasticity grew up to 60% fiber and then decreased sharply (Yang et al., 2015), which confirms that there is a maximum fiber loading beyond which the material degrades. In turn, bamboo and PP composites with a layered structure have been evaluated with accelerated creep tests using the stepped isostress method (Hsu et al., 2018), a transferable route for validating skins and cores in a sandwich architecture.

Environmental performance. The available LCAs support the use of composites made with waste, but with nuances. With 1000 trips as the functional unit, the wood–polymer composite pallet made from construction and demolition waste had the lowest impact in abiotic fossil depletion, acidification, eutrophication, global warming (with biogenic carbon), and ozone depletion in the attributional approach, and the best performance in all categories in the consequential approach. The virgin plastic pallet had the highest impact in both approaches, and the wood pallet had the lowest global warming without biogenic carbon (Khan et al., 2021). However, the review by Deviatkin et al. (2019), which analyzed 16 studies and 43 pallets, notes that inventory data for wood–polymer composite pallets are scarce, and Bengtsson and Logie (2015) found that pooled softwood pallets had the lowest impact and that a 100% recycled HDPE pallet manufactured in Australia could have a higher impact than one made of virgin plastic manufactured in China. The environmental advantage of the selected material is therefore conditional on the number of trips, the source of energy, and the end of life, and must be verified with an LCA of its own in accordance with ISO 14040 and ISO 14044.

Discarded alternatives. Solid wood is retained as the baseline, but its hygroscopicity and the phytosanitary treatment requirement (FAO, 2009) are not resolved by a design change. Virgin plastics showed the highest impact in the LCA by Khan et al. (2021) and depend on fossil feedstocks (Geyer et al., 2017). Mycelium and paper-based panels show low strength and moisture sensitivity (Appels et al., 2019; Jones et al., 2020), so

they are reserved for cores or single-trip packaging. Engineered bamboo offers suitable structural properties (Sharma et al., 2015), but it faces processing costs, adhesive content, and moisture sensitivity, so it is considered more as a source of reinforcing fiber than as a monolithic substitute.

Validation test plan for the selected material

Since the reported evidence does not include complete pallets made with the selected material, the validation program in Table 8 is proposed, organized in three levels: specimen, component, and pallet, plus the life cycle assessment. This program is a methodological proposal and does not correspond to tests already carried out.

Table 8: Proposed validation test program

Level	Test	Reference standard	Variable and acceptance criterion
Specimen	Tension	ISO 527 / ASTM D638	Strength and modulus relative to unreinforced rPP
Specimen	Flexure	ISO 178 / ASTM D790	Flexural strength and modulus relative to reference wood
Specimen	Impact	ISO 179 / ASTM D256	Impact energy at room temperature and at low temperature (brittleness)
Specimen	Water absorption and swelling	ISO 62 / ASTM D570	Absorption below 3% as a reference threshold (Homkhiew et al., 2014) and retention of properties after immersion
Specimen	Creep and accelerated aging	ISO 899 / ASTM D2990; TTSP	Deformation at 1000 h at 20–40% of ultimate strength and extrapolated service life
Component	Deck flexure and block compression with ribbed or sandwich geometry	ISO 178 / ASTM D790 adapted	Flexural stiffness per unit of mass and failure mode
Pallet	Racking flexure, stacking, fork impact, and drop	ISO 8611-1 (ISO, 2011); ASTM D1185	Allowable deflection and working load according to the applicable standard
Pallet	Long-duration racking creep	ISO 8611 / ASTM D1185 with sustained load	Deflection over time under nominal load
System	Cradle-to-grave LCA	ISO 14040 / ISO 14044	Functional unit of 1000 trips; reuse and end-of-life scenarios

Limitations of the review

The review is limited by the heterogeneity of test methods, the predominance of English indexed sources, and the probable existence of gray literature and industrial data (patents, technical data sheets) that are not peer reviewed. Publication bias toward favorable results for the materials cannot be ruled out.

Regarding the selected material, the evidence comes from heterogeneous specimen-scale studies, carried out with different matrices, fibers, and standards, and none of the cited studies evaluates a complete pallet with the proposed formulation under ISO 8611. The selection is therefore a design hypothesis supported by the literature and not an experimental verification, and it requires the test program in Table 8.

CONCLUSION

This study applied the PRISMA 2020 methodology to synthesize the evidence on materials that can replace wood in pallets. The literature places recycled plastics and natural-fiber or wood– plastic composites as the most technologically mature alternatives, whereas engineered bamboo and mycelium-based materials offer the greatest sustainability potential but require further development for load-bearing use. The main gaps are the lack of full-scale pallet tests, the limited long-term durability data, and the inconsistency of life cycle analyses.

Based on the tests reported in the literature, the candidate selected is the polypropylene composite (preferably recycled) reinforced with lignocellulosic fibers coupled with MAPP and with a ribbed or sandwich geometry, because of its higher stiffness and lower creep compared with the unreinforced polymer and because of a favorable environmental profile in the available LCAs, although conditional on reuse assumptions. Its validation at the pallet scale under ISO 8611 and with an LCA of its own is the pending step.

From a practical standpoint, the findings offer manufacturers and logistics operators a framework for comparing alternatives by performance, circularity, and cost. From a research standpoint, the review supports the development of hybrid bio-based composites with sandwich architectures, validated through standardized pallet tests and harmonized LCAs. Future work should run the search protocol with updated databases, include a techno-economic analysis, and develop prototypes tested under the ISO 8611 protocols and in real supply chain conditions.

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