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Systematic Review

Modular Engineered-Wood Housing in Low-Technification, Seismic-Prone Settings: A Systematic Review of Structural Performance, Digital Fabrication, and Low-Carbon Performance

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Abstract

This qualitative systematic review evaluates the potential of modular prefabricated OSB/plywood housing systems in low-technification, high-seismicity settings. These systems are promoted as low-carbon options for emerging contexts, and we assess how far the evidence supports that promise and under which conditions they can contribute to net-zero housing pathways. An adapted PRISMA 2020 workflow was applied to Scopus (TITLE-ABS, 2000–2025); 153 studies were synthesized in a table-first, coded matrix into axes for structural, digital fabrication, sustainability/circularity, and extrapolatable systems—supplemented by curated housing cases—with other EWPs used only for contrast. To address fragmentation and heterogeneity across domains, we developed a domain-based QA/QC instrument (STRUCTURAL, LCA, and FABRICATION) to judge whether studies provide minimally comparable evidence. Structural performance is relatively mature for certain patterns (calibrated FEM, cyclic tests, some 1:1 trials), whereas digital fabrication and LCA evidence remain partial: file-to-factory workflows rarely report verifiable QA/QC traceability, and most LCAs stop at A1–A3 with uneven treatment of A4, C/D, and biogenic carbon. Full convergence of adequate STRUCTURAL, LCA, and FABRICATION evidence within the same system type is rare, so both transferability to low-technification, seismic-prone settings and alignment with net-zero objectives must be characterized as conditional rather than established. The review identifies minimum multi-domain thresholds—technical robustness, whole-life LCA coverage, and verifiable QA/QC—as prerequisites for positioning modular OSB/plywood housing as a credible low-carbon pathway. These conclusions are limited by Scopus-only, English-language coverage and methodological heterogeneity, especially in the LCA.

Keywords: modular prefabrication; engineered wood; OSB; plywood; seismic performance; digital fabrication; design for disassembly (DfD); life-cycle assessment (LCA); biogenic carbon; quality assurance and quality control (QA/QC); net-zero emissions

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1. Introduction

Buildings account for roughly one-third of global energy-related CO_2 emissions, and both operational and embodied impacts matter for net-zero 2050 trajectories. Within this agenda, modular timber construction is increasingly proposed to reduce embodied emissions and support circular design-for-disassembly strategies in housing.

Latin America faces a severe housing crisis in which urban informality is the predominant pathway for populations excluded from the formal market [1]. The crisis is compounded by deficits in basic infrastructure and high exposure to seismic, geotechnical, and climatic risks, especially in settlements located on unstable hillsides or riverbanks [1,2]. In Peru, informal and unregulated self-construction dominates housing provision, and the total quantitative and qualitative housing deficit is approximately 1.51 million units [3]. Within the qualitative component, roughly 91% corresponds to self-built housing, and around 75% fails to meet minimum standards of structural safety and habitability [3,4].

Constraints are also production-related. According to the World Bank [5], productivity is approximately 5% of that of global frontier firms. In construction, productivity has grown more slowly than the national economy since 2014, and government studies attribute these lags mainly to the low adoption of digital technologies and limited investment in research and development [6]. At the firm level, the sector exhibits volatile and weak productivity dynamics [7]. Consistent with this, evidence from building projects in the Lima–Callao area shows moderate and late digitalization: ~36% BIM adoption, and ~71% of this usage concentrated in the construction phase [8]. Against this backdrop, demand for affordable, sustainable, and scalable housing solutions [9] has renewed interest in modular prefabricated timber systems [10]. Oriented strand board (OSB) and plywood, therefore, emerge as a pragmatic entry point to dry prefabrication in settings marked by informality and seismic vulnerability, and are increasingly framed as low-carbon options within net-zero housing agendas in emerging economies. However, in low-technification, seismic-prone settings, credibility requires verifiable and transferable evidence—not material-only claims. Accordingly, this systematic review focuses on OSB/plywood-based modular systems at the housing scale.

1.1. Structural, Technological, and Environmental Gaps

The structural inadequacy of self-built housing in Peru poses a heightened risk in a seismically active territory. Although Peru is used as a paradigmatic case, similar combinations of seismic risk, housing informality, and regulatory lag occur in several emerging economies. Vulnerability is linked to limited engineering design; scarce structural verification/validation (calculation or testing); production and quality-control constraints in informal delivery; and building codes not adapted to newer timber typologies and modular systems [3]. In Peru, the RNE E.010 "Madera" (Peruvian National Building Regulations, timber standard) does not explicitly contemplate the structural use of OSB or plywood, nor does it regulate modular prefabricated systems, creating a regulatory gap.

Regional asymmetries illustrate this gap: Chile has advanced timber regulations and enabling policies that support industrialized prefabrication (e.g., the Casablanca project, 394 homes) [11].

On the production side, during 2005–2015, 80% of wood products originated from sawn wood, while plywood accounted for 7.7% and laminated timber for 0.4% [12]. Higher-complexity materials, such as cross-laminated timber (CLT) and glued laminated timber (glulam, GLT), are widely developed elsewhere [13,14], whereas in Peru, production is marginal and dependent on imports [15]. Regionally, Brazil, Chile, Uruguay, and Argentina have consolidated industrial capacities to process EWP at multiple scales, enabling incorporation into more complex housing projects; in Peru, OSB and plywood remain the most prevalent products. Accordingly, this review treats OSB/plywood—rather than CLT/GLT/LVL—as the operational baseline for transferability in low-technification settings; other EWPs are used only as essential contrasts.

From an environmental perspective, conventional solutions often rely on materials with a high greenhouse-gas (GHG) emissions footprint (CO_2-eq) and high energy de-

mand. Portland cement concrete contributes ~5–8% of global CO_2 emissions [16]. For EWP systems, the literature reports high sensitivity to system boundaries and database choices; performance depends on system conditions and the life-cycle scope considered [17]. This sensitivity becomes decisive when claims are framed as net-zero pathways rather than material-only benefits. In sum, regulatory gaps, limited productive capacity, and boundary-sensitive environmental performance constrain the adoption of industrialized wood in housing, underscoring the need for a systematic, multi-domain assessment of OSB/plywood modular solutions and the conditions under which they can credibly support net-zero housing agendas in seismic, low-technification contexts.

1.2. Relevance of OSB/Plywood in Modular Prefabrication

Within the EWP family, OSB and plywood are commercially available, relatively cost-competitive, and compatible with low-complexity CNC machining [18]. Unlike CLT or GLT—which typically require more demanding industrial and logistical infrastructure [19]—OSB/plywood can be processed with accessible computer numerical control (CNC) technologies, supporting distributed manufacturing and open-source code/documentation models in low-infrastructure settings [20,21]. This makes OSB/plywood especially relevant for pathways based on micro-factories, guided self-build, and standardized panel-based assemblies—provided that traceability and QA/QC are operationalized.

From a performance standpoint, plywood cross-lamination and OSB strand orientation provide stable behavior in bending, shear, and compression. In lightweight structures, performance is adequate when geometric optimization and efficient connections are combined. Tests on plywood panels report demountable half-lap joints or integrated mechanical fasteners with controlled stiffness and ductility [20,22].

Operationally, lightweight standardized panel formats and dry, off site construction enable rapid, replicable assembly, with savings relative to masonry or reinforced concrete in specific cases [23]. Recent experiences document housing modules fabricated by CNC from OSB/plywood with controlled logistics and low on site impact [24]. Even so, "accessibility" is decision-relevant only when it is verified through explicit workflows (file-to-factory traceability, dimensional control, and QA/QC checkpoints); otherwise, transfer remains largely inferential.

1.3. Rationale for the Systematic Review and Gaps in the Literature

Despite growing interest in modular prefabricated systems [25] and EWP for sustainable construction [26], gaps persist in the technical, comparative, and context-sensitive syntheses for OSB- and plywood-based modular housing. Existing reviews largely focus on CLT, GLT, or LVL, which are comparatively mature in structural validation, manufacturing reporting, and environmental assessment; by contrast, OSB/plywood evidence remains comparatively scarce for housing-scale modular applications in the emerging contexts defined above.

Ghazanfari et al. [27] highlight the lack of systematic reviews on OSB testing methods and mechanical properties, limiting structural verification in building applications. Kromoser et al. [28] note that plywood remains underutilized in modular systems, partly due to limited empirical evidence under real conditions (e.g., load, moisture, and seismic loading). More broadly, in other material families, reviews have begun to integrate seismic performance with life-cycle assessment (LCA) environmental impacts within unified frameworks [29], but an equivalent domain-integrated synthesis for modular OSB/plywood housing remains missing.

Methodologically, technocentric approaches predominate, with limited evaluation of scalability in low-infrastructure or informal settings. Parracho et al. [30] address digital innovations without discussing viability in lagging contexts, while Premrov and Žegarac Leskovar [31] focus on advanced structural solutions with limited attention to transfer into housing emergencies. In contrast, technosocial perspectives—such as Cohen and Cañizares [32]—emphasize local appropriation, collaboration, and adaptation. Even so, few studies integrate structural, digital, and environmental dimensions in a unified manner. A regional gap compounds this limitation: the Andean setting operates with legacy frameworks, such as the Manual del Grupo Andino [33] (legacy Andean Community design manual), which does not contemplate composite materials or modular systems.

Against this backdrop, the present review contributes a structured and reproducible synthesis that integrates structural performance, digital fabrication, and sustainability/circularity evidence for OSB/plywood modular housing, using a pattern-based organization to assess evidence maturity and conditional transferability—i.e., transferability that depends on meeting minimum multi-domain thresholds rather than on isolated claims.

1.4. Objectives, Scope, and Structure of the Study

This review focuses on housing-scale modular systems that use OSB/plywood as primary structural materials. Because OSB/plywood evidence remains scarce and fragmented, selected studies on other EWPs (e.g., CLT, GLT, and LVL) are considered only when they provide essential methodological contrasts or boundary conditions and help interpret OSB/plywood evidence without substituting for it.

The purpose is to synthesize and critically analyze evidence across three dimensions —(i) structural performance, (ii) digital fabrication (file-to-factory, BIM–CAM), and (iii) sustainability/circularity—to clarify under which conditions OSB/plywood modular systems are viable and transferable in low-technification, seismic-prone settings. Guiding Question: To what extent—and under which conditions—are OSB/plywood modular systems viable and transferable when these three dimensions are jointly considered?

The remainder of the paper is structured as follows: Section 2 describes the methodology; Section 3 presents the results, organized into five axes; Section 4 discusses findings, limitations, and transferable principles; and Section 5 provides the conclusions.

2. Materials and Methods

2.1. The General Methodological Approach

This study followed PRISMA 2020 and conducted a qualitative systematic review to identify patterns, gaps, and conditions for conditional transferability of modular prefabricated engineered-wood (EWP) systems to housing, using OSB/plywood in emerging, low-technification contexts as the default analytical lens. Evidence was organized into three technical axes—structural performance (Axis 1), digital fabrication (Axis 2), and sustainability/circularity (Axis 3)—plus two complementary blocks that support the decision-oriented synthesis: extrapolatable non-housing systems (Axis 4) and relevant housing cases (Axis 5, expert-curated).

The identification–screening–inclusion flow is summarized in Figure 1. Screening and extraction were conducted by two independent reviewers with consensus (no automation), following the PRISMA 2020 guidelines [34]. The completed PRISMA checklist is provided in the Supplementary Materials. Because the corpus is technically heterogeneous and effect measures are not applicable, the synthesis without meta-analysis followed SWiM (Synthesis Without Meta-analysis) good practice to justify grouping and aggregation [35]. Medians and, where informative, interquartile ranges (IQRs) summarize ordinal quality

categories (not effect sizes). No formal assessment of reporting bias (missing-results bias) was performed; this risk is acknowledged in Section 2.6.

To make heterogeneity auditable and comparability explicit, we implemented a single cross-cutting tri-domain QA/QC instrument (STRUCTURAL, LCA, and FABRICATION) with conservative domain-specific critical gates ("caps") that restrict the maximum attainable category when enabling verification information is missing (Table S1; workflow in Figure 2). Pattern- and axis-level confidence was estimated using a framework inspired by CERQual [36], operationalized via stepped critical-gates rules per domain (Section 2.5). The coded synthesis matrix is reported in full in Table S2 (Supplementary Materials) and excerpted in Section 3 (Results).

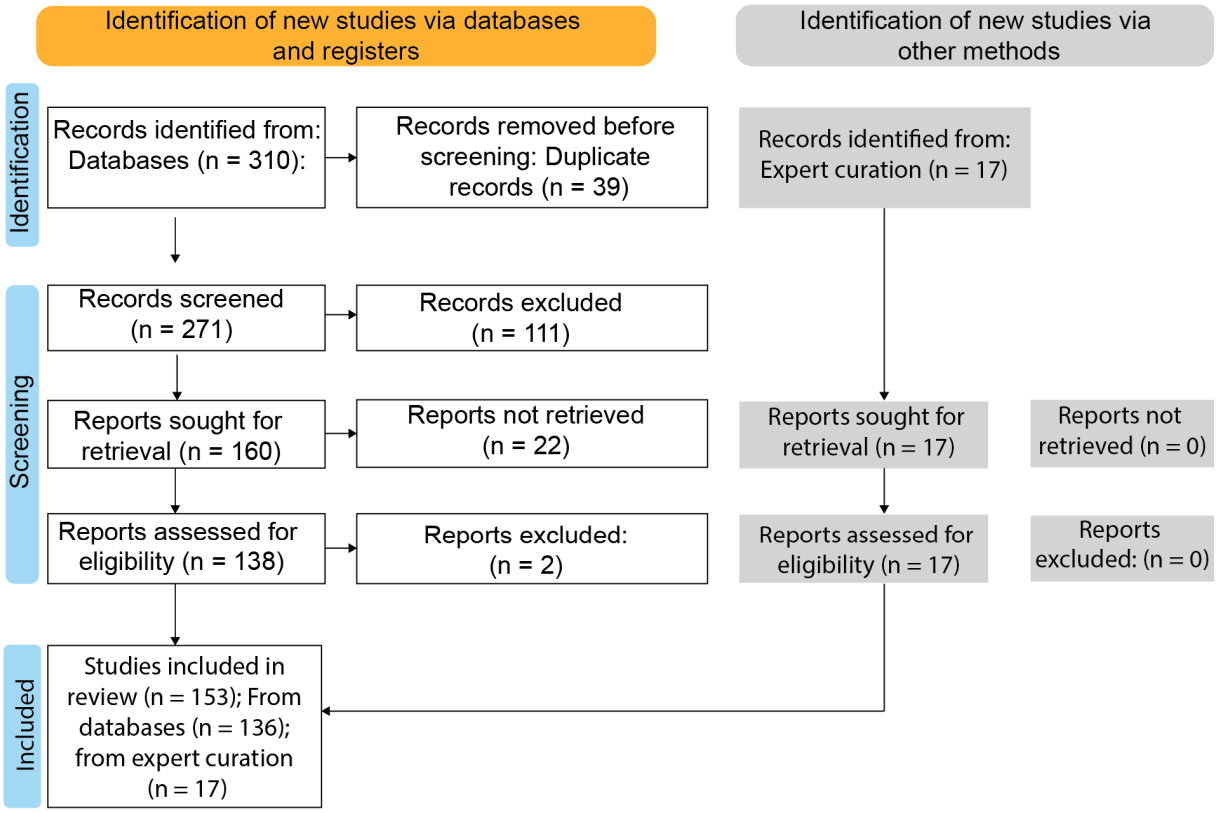


Figure 1. PRISMA 2020 flow diagram for study selection (n = 153 included: databases = 136; expert curation = 17). Reports excluded with reasons: n = 2 (see Table S7 in the Supplementary Materials). Diagram adapted and generated with the official PRISMA 2020 Flow Diagram Generator [37].

During data extraction, data were recorded as reported by the studies (SI units where applicable). Missing or ambiguous items were coded as N/A without imputation; non-reporting did not entail exclusion but limited comparability and/or the attainable QA/QC category through caps.

To restrict cross-pattern inference, we applied predefined axis-specific comparability gates (Supplementary Protocol), with the operational comparability requirements detailed in the Supplementary Materials ("Detailed description of the corpus and patterns (Axes 1–5)"). In brief, Axis 1 required reporting of validation scale, cyclic protocol/drift history (where applicable), and boundary conditions; Axis 2 required end-to-end BIM–CAM traceability, fabrication QA/QC scope (e.g., passports/labeling and acceptance, go/no-go, or dimensional control), physical validation, and key fabrication parameters; Axis 3 required a declared functional unit and system boundaries, explicitly A4, and at least one end-of-life scenario (C/D) with decision-relevant, transparent biogenic-carbon treatment, and a traceable inventory; and Axis 4 required demonstrated demountability logic, rep-

resentative interfaces/boundary conditions, physical validation (or justified scaling), and reproducible documentation. Studies missing one or more enabling fields were retained for traceability (Table S2) but excluded from cross-pattern inference within the affected axis, with reasons documented in the Supplementary Protocol and in the Supplementary Materials ("Detailed description of the corpus and patterns (Axes 1–5)"). Separately, QA/QC caps constrain the maximum attainable domain rating when enabling verification information is missing, and non-evaluable domains are coded as N/A and excluded from aggregation and confidence estimates (Tables S1 and S2).

The review was not registered. The protocol was defined ex ante and is described in Section 2; a dated Supplementary Protocol documents the plan and deviations.

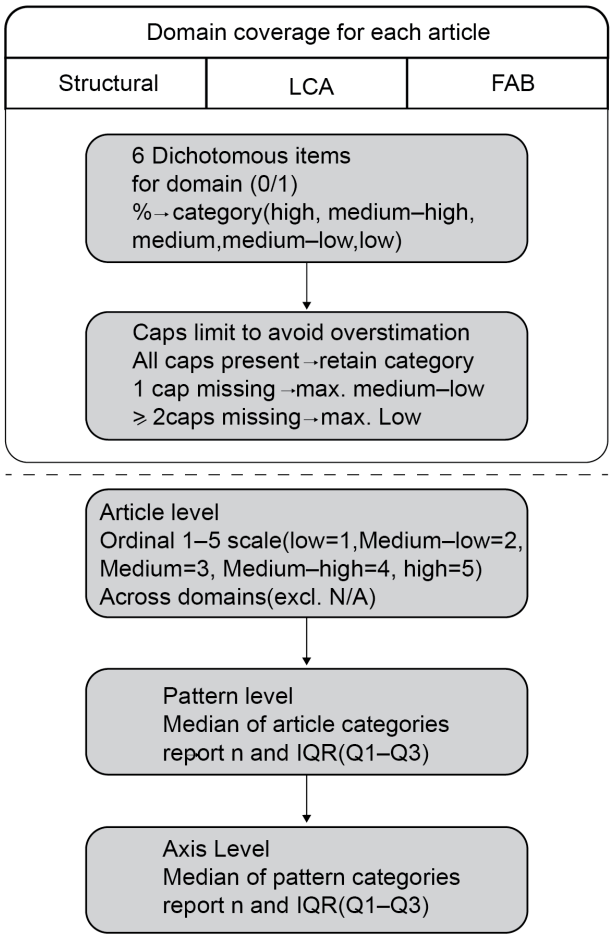


Figure 2. QA/QC instrument and cap workflow. Each domain (STRUCTURAL, LCA, and FABRICATION) is scored with six dichotomous items (0/1). Domain percentages map to five performance categories (low to high) under caps that constrain the maximum attainable category. Domain coverage (evaluated vs. N/A) is shown in Table S1 and summarized by pattern/axis in Table S2.

2.2. Information Sources and Search Strategy

The primary search was conducted in Scopus (Elsevier, web interface), forming the systematic base corpus for Axes 1–4. We queried the TITLE-ABS field to prioritize terminological precision and applied limits of 2000–2025, Englishlanguage, and peer-reviewed document types (journal articles and conference proceedings). The search was last updated on 5 June 2025 (UTC–5). Search strings were constructed and iterated by axis (pilot runs and refinement) to balance precision and coverage. The complete search log and the exact strings by axis are documented in the Supplementary Materials (Tables S3–S6).

Although OSB/plywood is the focus, CLT/GLT/LVL terms were included as semantic anchors to avoid missing studies that provide essential methodological contrasts or boundary conditions (e.g., validation logic, DfMA/DfD documentation, or QA/QC traceability). Non–OSB/plywood evidence is used for contrast only and does not expand the scope of inference; OSB/plywood was applied at screening and eligibility. Duplicates were managed using Scopus's native function (no additional manual deduplication). No external registries were searched, nor was citation chasing undertaken.

2.3. Inclusion and Exclusion Criteria

To ensure relevance, quality, and traceability, inclusion/exclusion criteria were organized into topical, evidence-scope, contextual/applicative, and technical/formal dimensions aligned with the review objectives and PRISMA 2020. We included peer-reviewed full-text journal articles and conference proceedings (in English; 2000–2025) reporting technical/analytical/design evidence relevant to at least one axis (STRUCTURAL, LCA, or FABRICATION) for modular EWP systems, with OSB/plywood as the default lens and selective inclusion of other EWP only when offering transferable comparative value. We excluded non-modular or non-structural work; purely descriptive/opinion items without relevant methods/results; the gray literature without peer review or without full-text access; and non-housing applications lacking a methodological justification for transfer. Table 1 summarizes these criteria.

Table 1. Inclusion and exclusion criteria, organized by topical, technical/formal, and contextual/applicative types.

Criterion Type	Inclusion Criteria	Exclusion Criteria
Topical	Modular construction systems using EWP, with particular attention to OSB/plywood; selective inclusion of CLT/GLT/LVL when offering comparative/transferable value (applied at screening/eligibility, not at search).	Projects that are purely decorative/non-structural or lack modularity.
Evidence scope	Technical/analytical/design evidence in at least one axis: structural performance, digital fabrication, or sustainability/circularity.	Descriptive or opinion pieces without relevant data, methods, or technical results.
Contextual/Applicative	Direct housing application or justified extrapolation from other domains (clear transferability criteria).	Non-housing applications without a methodological justification for transfer.
Technical/Formal	Peer-reviewed journal articles and conference proceedings, full-text available, in English, years 2000–2025.	The gray literature (reports/theses/patents), documents without peer review or full-text access.

2.4. Screening and Selection Process

Screening followed PRISMA 2020: (1) duplicate removal (Scopus's native filter); (2) title/abstract screening; and (3) full-text screening. Two reviewers screened independently in stages (2) and (3) and resolved disagreements by consensus; in doubtful cases, inclusion was prioritized.

From 310 records identified in Scopus, 39 duplicates were removed (271 were unique). Title/abstract screening excluded 111, and 160 proceeded to full-text retrieval. Of these, 138 were retrieved (not retrieved: n = 22). After full-text screening, 2 were excluded for failing eligibility criteria (Table S7). The systematic corpus, therefore, comprised 136 Type A items contributing to Axes 1–4 (Figure 1).

The final corpus (n = 153) was tagged by provenance: Type A (n = 136; Scopus search; Axes 1–4) and Type B (n = 17; expert-curated; Axis 5 only). Type B items did not originate from the systematic search and were used solely for qualitative operational contrast; however, both sets underwent the same coding and tri-domain QA/QC appraisal for traceability (Section 2.5). Type B items were excluded from medians, IQR, and confidence estimates in Axes 1–4 (no weighting; see Sections 2.5 and 4.4). The end-to-end pipeline (database → screening → extraction → scoring → aggregation) is summarized in Figure 3.

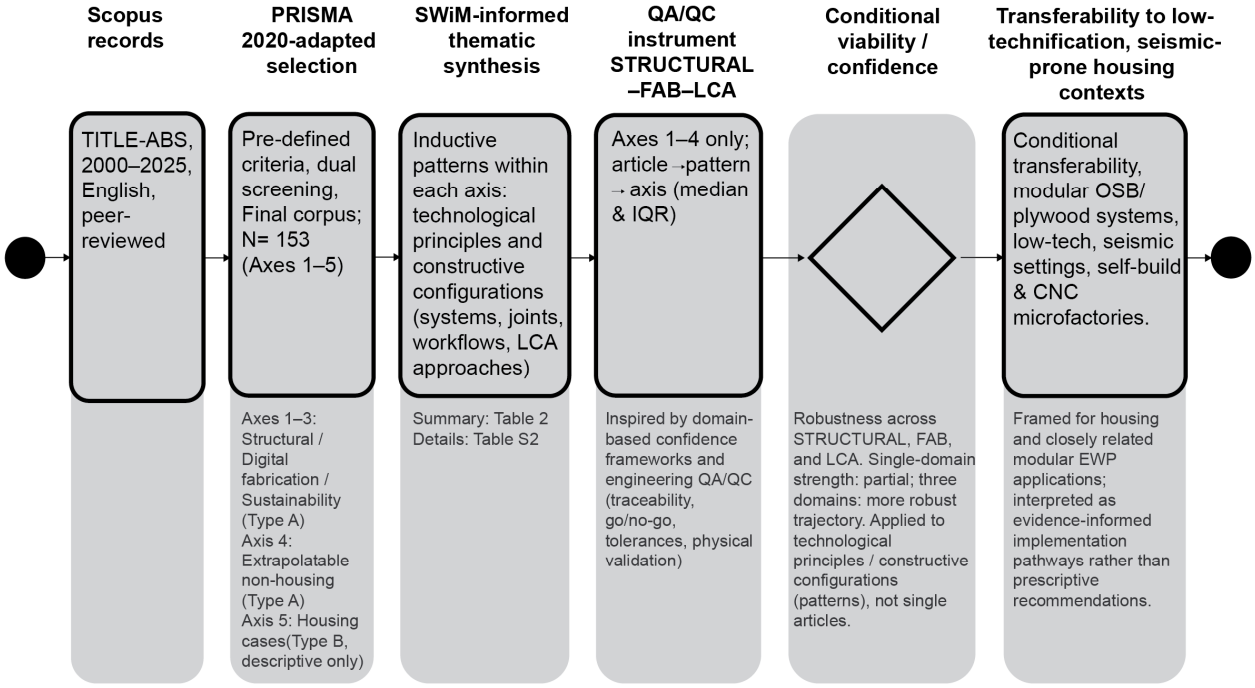


Figure 3. End-to-end methodological pipeline from database records (Scopus) through screening, extraction, domain scoring, and aggregation (article → pattern → axis). Type B (expert-curated) items are confined to Axis 5 and excluded from medians, IQR, and confidence estimates in Axes 1–4 (no weighting applied).

2.5. Coding, Extraction, and Quality Criteria

Two reviewers extracted axis-specific outcomes (Axes 1–5) and common metadata (year, country, publication type, experimental scale, system typology, EWP material/base, joint type, analytical technique, and architectural application). Missing or ambiguous items were recorded as N/A without imputation; non-reporting did not entail exclusion. Domain coverage is explicit: STRUCTURAL, LCA, and FABRICATION domains that were not evaluable are marked N/A.

Given the predominantly technical–experimental nature of the corpus, conventional clinical risk-of-bias tools (e.g., RoB 2, ROBINS-I) were not applicable. Instead, we applied a cross-cutting QA/QC instrument with three domains—STRUCTURAL, LCA, and FABRICATION—to assess evidence usability and reporting completeness, and to support horizontal comparability across axes. The instrument (items, scoring thresholds, and cap rules) is provided in Table S1; study-level fields and QA/QC outputs are reported in Table S2 (excerpted in Section 3).

Each domain is scored using six dichotomous items (1 = reported and usable; 0 = absent or ambiguous). Domain scores are converted to percentages and mapped to five ordinal categories (low to high). To avoid overestimation when enabling verification information is missing, domain-specific caps restrict the maximum attainable category (e.g., cyclic protocol and boundary conditions in STRUCTURAL; A4 and C/D in LCA; BIM–CAM traceability and go/no-go or dimensional control in FABRICATION). Caps constrain the ceiling only, they do not inflate scores.

Aggregation proceeds in three levels. At the study level, ordinal domain categories (excluding N/A) are averaged to produce a study-level category. At the pattern level (within each axis), we report the median study-level category with *n* and IQR (Q1–Q3), excluding N/A. At the axis level, we report the median of pattern categories with *n* and IQR; here, *n* denotes the number of contributing patterns (not unique studies), because some studies inform multiple patterns/axes. Type B items (Axis 5) are coded with the same fields for traceability in Table S2 but are excluded from confidence aggregation in Axes 1–4.

2.6. Methodological Limitations

Coverage and selection are limited by the Scopus-only, English-language, peer-reviewed corpus (cutoff 5 June 2025) and by the absence of citation chasing, registries, and a structured gray-literature search, which may introduce indexation and language bias (Table S7). Availability bias was observed (22/160 full texts not retrieved). Technical heterogeneity across structural protocols and LCA setups limits direct comparability; we addressed this through a priori comparability gates, restricted-comparability decisions documented in the Supplementary Protocol and, more broadly, in the Supplementary Materials ("Detailed description of the corpus and patterns (Axes 1–5)"), and conservative caps (Table S1). Study-level traceability and QA/QC remarks are reported in Table S2; these choices limit generalizability. Dichotomizing QA/QC criteria (0/1) simplifies reporting and relies on expert judgment despite consensus review. Use of N/A avoids penalizing non-evaluable domains but can raise article-level categories when only one domain is evaluable; domain coverage is therefore made explicit in Table S1 and summarized by pattern/axis in Table S2. Inter-rater agreement was not quantified with a formal index (e.g., Cohen's kappa). No formal assessment of missing results bias was performed; this risk is acknowledged here and in the Discussion Section.

Within these limitations, dual screening, explicit comparability gates, and the capped tri-domain QA/QC instrument provide a transparent, pattern-oriented basis for the axis-level synthesis reported in Section 3.

3. Results

Findings are reported through a table-first synthesis. Table 2 is an excerpt of the coded matrix; Table S2 reports the full matrix, and Table S1 details the QA/QC instrument. OSB/plywood is the default interpretive lens; non–OSB/plywood evidence is cited only when it materially affects interpretation.

Table 2. Synthesis matrix of the corpus (excerpt).

No.	Author(s)	Year	Country	Type of Wood	Type of Evidence	Analytical Technique	Architectural Application	Key Observations	Quality Remarks
Axis 1: Structural performance									Medium–high (n = 7; IQR = 3–4)
Pattern 1: Timber–Concrete Composite (TCC) connection tests in hybrid systems for prefabricated floors.									Medium–high (n = 3; IQR = 4–4)
[38]	Lukaszewska et al.	2006	Sweden/ Italy	GLT	Experimental	Push-out and shear testing	Non-residential (prefabricated floor)	It assesses seven dry GLT–concrete connectors, optimizing composite action without in-situ concrete casting.	Structural 6/6 (100%, high; cap 4/4) · LCA N/A · Fab 2/6 (33%, medium–low; cap 2/3)
[39]	Lukaszewska et al.	2008	Sweden/ Italy	GLT	Experimental	Push-out and shear testing	Non-residential (prefabricated floor)	It compares stiffness, strength, and ductility in dry connectors for composite systems.	Structural 6/6 (100%, high; cap 4/4) · LCA N/A · Fab 2/6 (33%, medium–low; cap 2/3)
[40]	Parida et al.	2013	Sweden/ Italy	CLT	Experimental + numerical	Experimental testing + analytical modeling	Residential (mid-rise)	High stiffness and strength; ductility limitations due to brittle failure in bonded regions.	Structural 6/6 (100%, high; cap 4/4) · LCA N/A · Fab 2/6 (33%, medium–low; cap 2/3)

Table 2 is organized by axis (1–5). Within each axis, studies are ordered by year and, where applicable, by pattern. Because some studies contribute to multiple patterns and/or axes, pattern/axis counts do not equal the number of unique Type A studies. Type B items (Axis 5) are listed separately and excluded from pooled confidence aggregation. "Quality Remarks" summarize the domain-wise QA/QC appraisal (STRUCTURAL, LCA, and FABRICATION) derived from the instrument in Section 2.5 (Table S1); the full coded corpus is in Table S2.

Section 3.1 summarizes cross-cutting messages; the remainder of Section 3 synthesizes results by axis (Axes 1–5) and states the minimum criteria enabling comparability and cross-axis inference. Pattern-by-pattern descriptions and study-level detail are provided in the Supplementary Materials ("Detailed description of the corpus and patterns (Axes 1–5)").

3.1. Summary of Findings

We synthesized 153 items (Type A = 136; Type B = 17). Pattern/axis counts do not correspond to unique studies because some items contribute to multiple patterns and/or axes.

In terms of pattern-level QA/QC maturity (Axes 1–4), only 9/35 patterns reach ≥medium (six medium–high, three medium); the remainder are medium–low (19/35) or low (7/35). Tri-domain convergence was not observed in the pooled patterns; maturity is predominantly partial (one- or two-domain strength).

Across Axes 1–4, four recurring bottlenecks limit interpretability and transferability: (i) limited full-scale (1:1) validation (or reduced-scale testing without a robust justification) at the module/system level; (ii) incomplete whole-life LCA reporting, with insufficient coverage of A4 and C/D and assumptions/inventories not consistently made explicit; (iii) uneven file-to-factory traceability and FABRICATION QA/QC (BIM–CAM traceability, component identification, and go/no-go dimensional control); and (iv) incomplete or non-replicable reporting of STRUCTURAL enabling information (declared cyclic protocol and boundary conditions).

Patterns are interpreted based on cross-domain convergence (STRUCTURAL, LCA, and FABRICATION) and fulfillment of comparability gates and domain critical gates ("caps"). Operationally, patterns are classified as near (three domains evaluable and an aggregated rating of high), partial (exactly two domains evaluable and an aggregated rating of medium–high/medium), or fragmentary (≤1 domain evaluable and/or an aggregated rating of medium–low/low).

3.2. Thematic Analysis Across the Five Axes

Corpus traceability and pattern-level coding are reported in Table S2. Table 3 provides the pattern-to-evidence map (traceability index) across Axes 1–5, reporting pattern labels, study counts (n), provenance type (A/B), and reference mapping. We report cross-pattern signals and the minimum comparability and verification gates. Axis-level comparative inference follows the axis-specific comparability gates defined in Section 2.1; studies failing any gate are tagged as restricted comparability (Table S2) and excluded from cross-pattern inference.

Table 3. Pattern-to-evidence map (traceability index).

Axis	Pattern ID	Pattern Label	n	Type	References
1	1.1	Timber–Concrete Composite (TCC) connection tests in hybrid systems for prefabricated floors	3	A	[38–42]
1	1.2	Embedded timber connections for lateral and axial force transfer	1	A	[40–43]
1	1.3	Seismic testing of prefabricated timber panels with validated lateral response	5	A	[20,44–47]
1	1.4	Structurally validated timber–steel and timber–glass hybrid systems	3	A	[41–44,48,49]
1	1.5	Modular three-dimensional systems with experimentally evaluated innovative connections	3	A	[41–43,46,47,50]

Table 3. *Cont.*

Axis	Pattern ID	Pattern Label	n	Type	References
1	1.6	Seismic validation of hybrid timber substructures via quasi-static testing	3	A	[41–45,47]
1	1.7	Modular structural systems using alternative and recycled materials: experimental evaluation and sustainability	2	A	[51,52]
2	2.1	Grammar and scripting as a driver of design and production	12	A	[53–64]
2	2.2	Articulation between geometry and assembly logic	18	A	[56,57,60–75]
2	2.3	Moldless fabrication and composite surfaces	19	A	[53,55,56,60,61,65,66,68–79]
2	2.4	Accessible/open file-to-factory strategies	17	A	[53–57,60–64,66,68,73–75,77,79]
2	2.5	Modular prefabrication with flat geometry	12	A	[53–55,59,60,65–67,71,74,77,80]
2	2.6	Fastener-free all-wood systems	11	A	[54,55,57,60,65–67,71,74,80,81]
2	2.7	Digitally mediated self-build	6	A	[54–56,74,77,80]
2	2.8	Empirical validation through full-scale (1:1) prototyping	24	A	[53–57,60,61,64–68,70–81]
2	2.9	BIM and digital traceability in fabrication	3	A	[59,63,68]
3	3.1	Comparative LCAs: engineered timber vs. conventional systems	14	A	[23,82–94]
3	3.2	LCA of industrial processes for OSB, plywood, and CLT	13	A	[95–107]
3	3.3	End-of-life, disassembly, and circularity	9	A	[90,91,94,108–113]
3	3.4	Design-for-circularity strategies (DfMA, DfD, and flexibility)	12	A	[52,90,91,114–122]
3	3.5	Regional contextualization and emerging-context studies	20	A	[17,88,89,92,104,110,112,122–134]
3	3.6	Transport, logistics, and supply chains	7	A	[17,100,126,135–138]
3	3.7	Climate-mitigation scenarios, energy, and biogenic carbon	14	A	[17,89–91,96,101,108,109,111,130,134,139–141]
3	3.8	Digital integration, BIM–LCA, and traceability	8	A	[23,82,91,118,136,138,142,143]
3	3.9	Methodological reviews and reference frameworks	12	A	[82,90,91,108,109,139,140,143–147]
3	3.10	Emergent methodological innovation in sustainability and circularity	7	A	[91,108,111,123,125,148,149]
3	3.11	Developing evidence ($\leq$2 papers per topic and/or limited validation)	4	A	[46,50,150,151]
4	4.1	Fastener-free structural assemblies: interlocking, geometric precision, and sustainability	6	A	[60,81,152–155]

Table 3. *Cont.*

Axis	Pattern ID	Pattern Label	n	Type	References
4	4.2	Segmented shells and roof systems in laminated timber: formwork-free structural precision	6	A	[60,154–158]
4	4.3	Robotic fabrication of complex geometries in curved timber without conventional lamination	2	A	[158,159]
4	4.4	Automation and parameterization in structural prefabrication	5	A	[57,157,160–162]
4	4.5	Integrated experimental flows: generative AI, structural simulation, and assisted assembly	1	A	[163]
4	4.6	Technosocial approaches in digital architecture: participation, transfer, and training	3	A	[60,74,163]
4	4.7	Computational environmental assessment: LCA applied to digital timber systems	1	A	[164]
4	4.8	Structural segmentation for prefabricated temporary timber systems	4	A	[71,154,156,165]
5	5.1	Emergent systems with extrapolatable value	1	B	[166]
5	5.2	Instant House (MIT): cultural integration, digital tectonics, and foundational lessons	3	B	[167–169]
5	5.3	Sim[PLY]: structural simplicity, demountability, and direct usability	1	B	[170]
5	5.4	ECL System (SECU, SICU, and MACU): pedagogical prototyping and cultural appropriation in African contexts	1	B	[171]
5	5.5	Veneer House system: post-disaster architecture as a cultural and pedagogical device	1	B	[172]
5	5.6	DfMA system with low-grade CLT: structural modularity and efficient deployment	1	B	[173]
5	5.7	Standard modular system with universal assembly: demountability, flexible automation, and circularity	1	B	[166]
5	5.8	AUAR (Automated Architecture Ltd., London, UK): discrete automation and openness tensions in robotized modular systems	3	B	[174–176]
5	5.9	WikiHouse: open system, decentralized validation, and conditional appropriability	6	B	[20,23,24,177–179]

3.2.1. Axis 1: Structural Performance

Axis 1 comprises 12 studies (Type A). Traceability and pattern coding are reported in Table S2; axis-level comparative inference follows the axis-specific comparability gates defined in Section 2.1.

In Axis 1, four main points emerge:

1. Evidence concentrates on connection/interface behavior and is often interpreted through combined physical testing and calibrated FEM.
2. However, transfer to OSB/plywood modular assemblies remains constrained by limited system-level full-scale (1:1) validation, non-uniform cyclic protocols, and incomplete/heterogeneous boundary-condition reporting, weakening cross-study comparability.

3. Reporting of hysteresis-derived outputs and stiffness/ductility definitions is uneven, further limiting cross-study synthesis.
4. OSB/plywood thickness constraints (18–24 mm) imply diaphragm/joint redesign requirements that are not consistently validated; demountability/durability are rarely verified under service-like exposure. Cross-domain coupling to FAB and LCA remains scarce; therefore, Axis 1 is a necessary precondition for transferability rather than a standalone transfer argument.

Confidence is medium–high (n = 7 patterns; median = 4; IQR = 3–4; n denotes contributing patterns), and is strongest when cyclic protocols/drift histories and boundary conditions are explicit and when experimental findings align with FEM interpretations. Direct OSB/plywood evidence remains comparatively limited (Table S2).

3.2.2. Axis 2: Digital Fabrication

Axis 2 comprises 29 studies (Type A). Traceability and pattern coding are reported in Table S2; axis-level comparative inference follows the axis-specific comparability gates defined in Section 2.1.

In Axis 2, four main points emerge:

1. Parametric-to-CNC, flat-panel workflows and integral joints dominate, offering a plausible low-threshold file-to-factory basis for OSB/plywood systems;
2. However, end-to-end BIM–CAM closure and batch-level QA/QC are inconsistently reported and rarely closed end-to-end; together with irregular tolerance/parameter reporting, this limits reproducibility and weakens scalability claims;
3. Physical prototyping is common, but operational metrics (achieved tolerances/deviation, cycle time, yield, and error/rework rates) are inconsistently reported, constraining cross-study synthesis;
4. Fully reproducible packages (drawings plus CAM/DXF/scripts/G-code and manuals) remain rare, restricting independent verification and transfer to low-infrastructure settings; consequently, Axis 2 functions as the verification substrate for Axes 1 and 3 rather than a standalone transfer argument.

Confidence is medium–low (n = 9 patterns; median = 2; IQR = 2–2; n denotes contributing patterns) and is strongest when BIM–CAM traceability, QA/QC checkpoints, reproducible files, and physical validation are explicit. It is limited by sparse operational metrics, partial openness, and irregular tolerance/parameter reporting (Table S2).

3.2.3. Axis 3: Sustainability and Circularity

Axis 3 comprises 75 studies (Type A). Traceability and pattern coding are reported in Table S2; axis-level comparative inference follows the axis-specific comparability gates defined in Section 2.1. In Axis 3, four main points emerge:

1. Engineered timber often shows an environmental advantage over conventional systems, but reported advantages are highly sensitive to boundaries, A4/C/D coverage, and biogenic-carbon handling; for OSB/plywood, the limited and fragmented evidence amplifies this sensitivity.
2. (A1–A3 (“cradle-to-gate”) dominates the corpus; whole-life coverage (A4 and C/D) is inconsistent, limiting net-zero-relevant inference and transfer to emerging contexts.
3. Recurrent hotspots—adhesives/resins, process energy (drying/pressing), and the electricity mix—repeatedly condition results, while territorial variables (transport distances/modes, supply chain structure, regional databases) can materially change conclusions.
4. Circularity is more often modeled than verified: DfD/DfMA and reuse/recycling scenarios can improve results, but recovery assumptions are heterogeneous and

rarely supported by traceability or credible recovery chains. Scale-bridging between material/component studies and WBLCA remains uneven; therefore, Axis 3 sets the minimum evidence floor for conditional transferability rather than a standalone net-zero argument.

Confidence is medium–low (n = 11 patterns; median = 2; IQR = 2–2; n refers to patterns) and is strongest when FU/boundaries, inventories/EPDs and energy assumptions, A4 and C/D (when decision-relevant), sensitivity disclosure, and biogenic-carbon accounting are explicit. It is limited by A1–A3 predominance, contested biogenic-carbon accounting and substitution-credit practices, circularity modeled with non-verifiable assumptions, scarce regional/primary data for emerging contexts, and mixed scales without robust bridging protocols. For OSB/plywood, these limitations are amplified by lower availability of comparable WBLCA and reliance on non-regionalized logistics/energy assumptions (Table S2).

3.2.4. Axis 4: Extrapolatable Non-Residential Studies

Axis 4 comprises 20 studies (Type A). Traceability and pattern coding are reported in Table S2; axis-level comparative inference follows the axis-specific comparability gates defined in Section 2.1. In Axis 4, four main points emerge:

1. Transferable value lies in assembly logic (segmentation, geometric control, and demountable joining) more than typology; however, several principles presuppose dimensional control and fabrication domain QA/QC and supply chain stability that may exceed low-technification thresholds, so transfer toward OSB/plywood remains conditional (Table S2).
2. Evidence is dominated by non-residential demonstrators; despite some 1:1 builds, code-relevant verification and reporting of interfaces/boundary conditions at a replicable level are uneven, limiting housing-grade inference (Table S2).
3. Digital workflows are frequent (parametric/CNC/robotic, co-simulation), but operational closure is rare: tolerances, dimensional control, acceptance/rejection points, rework logic, and reproducible packages are inconsistently reported—critical for three-axis CNC micro-factories where reproducibility depends more on QA/QC than on geometric sophistication (Table S2).
4. Sustainability is largely implicit: LCA coverage is limited/uneven (often coded as N/A), and OSB/plywood-attributable evidence is fragmented. Cross-domain coupling across STRUCTURAL, LCA, and FABRICATION remains weak; therefore, Axis 4 is best read as an innovation testbed that becomes decision-relevant only when bounded by Axes 1–3 (Table S2).

Confidence is medium–low (n = 8 patterns; median = 2; IQR = 2–3; n refers to patterns) and is strongest when experiment–FEM coherence is demonstrated and when demountable timber-to-timber (DfD) logic and interfaces/assembly hierarchies are reported with replicable boundary conditions. It is limited by the predominance of academic prototypes, scarce housing-relevant 1:1 validation, partial file openness, thin operational metrics, and minimal/fragmentary LCA. For OSB/plywood, direct evidence remains fragmented, and extrapolation is conditioned by the criteria above (Table S2).

3.2.5. Axis 5: Relevant Housing Cases—Diverse Pathways to Accessible Digital Prefabrication

Axis 5 comprises 17 expert-curated housing cases (Type B): 14 from the peer-reviewed, Scopus-indexed literature not captured by the systematic search, and three from other sources (patents and technical/academic reports). Cases are coded using the same fields and QA/QC scheme (STRUCTURAL, LCA, and FABRICATION; Section 2.5) to ensure traceability in Table S2. Because items are curated (Type B), they are excluded from the pooled

confidence aggregation (Axes 1–4) and used solely for qualitative operational contrast. Key implementation pathways and enabling artifacts (e.g., manuals/BOM/BOP, tolerance policies, QA/QC acceptance–rejection checkpoints, file availability, 1:1 prototyping, and regulatory alignment) are documented in Table S2.

Axis 5 is structured into two blocks: (i) emergent systems with extrapolatable value, and (ii) digital architectures at scale (open logic vs. corporate automation). The main text reports only cross-cutting routes and constraints.

Across both blocks, four cross-cutting points emerge:

1. Accessibility is primarily operational: the most transferable routes reduce skill/tooling thresholds through legible assembly sequences, guided manuals, repeated parts, and error-tolerant joint logics;
2. Transfer is constrained by pilot-only validation and missing enabling artifacts—incomplete manuals/BOM/BOP, absent tolerance policies and QA/QC checkpoints, and limited benchmarking across cost/time/logistics—which reduces external replicability in low-infrastructure settings;
3. Scale creates a tension between closure and independent transfer: end-to-end file-to-factory closure improves delivery control, while openness is not equivalent to usability when workflows require high computational mediation and tolerance tuning;
4. Net-zero-relevant claims remain context-sensitive and are rarely validated across STRUCTURAL, LCA, and FABRICATION: environmental performance varies with territorial assumptions (grid mix, logistics, and supply chains), and integrated STRUCTURAL, LCA, and FABRICATION verification is uneven; therefore, Axis 5 clarifies implementation routes and barriers but does not constitute pooled evidence for comparative inference.

As curated Type B cases, no pooled confidence is reported. Interpretability is higher when cases report 1:1 builds/pilots alongside operational artifacts (manuals/drawings/BOM/CAM files) and demonstrated reversibility; otherwise, they are treated as illustrative only. Limitations include curated selection, heterogeneous evidence types, partial standardization of STRUCTURAL, LCA, and FABRICATION reporting, and still-limited lot-level QA/QC traceability. By design, these cases do not alter confidence profiles for Axes 1–4; their function is operational (routes/barriers), not probative (Table S2).

4. Discussion

4.1. Primary Contribution and Scope Guardrails

This qualitative systematic review (n = 153; Type A = 136; Type B = 17) synthesizes evidence on modular OSB/plywood housing and operationalizes conditional transferability through three cross-cutting requirements: (i) comparable maturity of technical evidence, (ii) full life-cycle environmental robustness, and (iii) verifiable reporting quality (QA/QC). Digital fabrication (scripting, file-to-factory, and flat-panel CNC workflows) functions as enabling infrastructure, translating design into production and supporting replicable QA/QC and auditable DfMA/DfD assembly/disassembly. OSB/plywood is the default lens; non–OSB/plywood evidence is used only for boundary conditions or essential contrasts and does not expand the scope of inference. Together, these requirements define the minimum evidential thresholds for discussing modular OSB/plywood as low-carbon, net-zero-aligned housing—rather than as generic "green" alternatives.

4.2. What Counts as Transferable Evidence: Comparability, QA/QC, and Whole-Life Robustness

Positive results are insufficient for conditional transferability: cross-study inference requires comparable protocols (e.g., standardized cyclic tests with prescribed drift histories, where applicable) and reporting of key metrics (stiffness, ductility, and failure modes).

When code-facing transfer is claimed, studies should also report full-scale (1:1) validation and minimum operational metrics (assembly/disassembly time and cost), with explicit boundary conditions (support/anchorage, diaphragm action, out-of-plane restraint, and load application) because these govern system response. In this corpus, structural validations are often supported by calibrated FEM; however, protocol heterogeneity and limited evidence on durability and repeated demountability constrain direct transfer to demanding codes.

Net-zero-aligned or transfer claims additionally require an LCA floor: modeling beyond A1–A3 with explicit A4 and at least one end-of-life scenario (C/D) (modeled or justified), plus transparent biogenic-carbon accounting (scope and rules) and a traceable inventory (database/EPD source and version; key energy assumptions) with at least basic scenario/sensitivity disclosure. These minimum requirements are operationalized through the QA/QC instrument (STRUCTURAL, LCA, and FABRICATION; Section 2.5; Table S1) and documented in Table S2 (Table 2 provides an excerpt).

Finally, fabrication evidence becomes decision-relevant only when it is auditable and reproducible: end-to-end BIM–CAM traceability, explicit dimensional control/tolerance logic, and verification checkpoints (passports/labeling and go/no-go templates), ideally supported by reproducible file sets (drawings plus CAM/DXF/scripts/G-code and manuals) (Tables S1 and S2). Because OSB/plywood is the default lens, non–OSB/plywood studies are used only as boundary conditions to clarify transfer requirements; they do not expand the scope of inference.

4.3. Synthesis by Axes and Operational Gaps

Pattern-level confidence profiles are derived using the procedure in Section 2.5 and documented in Table S2 (full matrix). Here, we focus only on the decision-relevant operational gaps that condition transferability across Axes 1–4.

Axis 1—Structural performance

Evidence is most mature at the connection/interface level—often supported by calibrated FEM—and extends to diaphragms and substructures. Transfer to demanding codes remains constrained by non-comparable seismic protocols, limited system-level 1:1 validation, and scarce evidence on durability and repeated demountability under service-like exposure. Real-world deployability is further limited by underreporting of complex topographies (non-coplanar supports and slopes) and by incomplete specification of boundary conditions.

Axis 2—Digital fabrication

Parametric-to-CNC workflows, flat panelization, and fastener-free joints provide a plausible low-threshold file-to-factory basis for OSB/plywood systems. The key bottleneck is operational closure: end-to-end BIM–CAM traceability, explicit tolerance/kerf/offset rules, and auditable QA/QC checkpoints (passports/labeling; go/no-go templates) are unevenly reported, and operational metrics (time, deviation/yield, and error/rework) remain thin—limiting reproducibility in low-infrastructure settings.

Axis 3—Sustainability and circularity (LCA)

Timber can outperform conventional systems when long-life uses and DfD are credible, but conclusions remain highly sensitive to system boundaries (A1–A3 vs. A4/C/D), biogenic-carbon accounting choices, and logistics. Transfer to emerging contexts is limited by incomplete disclosure of regional drivers (grid mix, A4 distances/modes, recovery pathways, and database choices), the predominance of A1–A3, and limited sensitivity/uncertainty treatment—weakening net-zero-relevant decision robustness.

Axis 4—Extrapolatable non-residential systems

Segmented and interlocking fastener-free systems function primarily as an innovation testbed with conditional relevance to lightweight housing, but the evidence is largely prototypical and often under-documented. Transfer is chiefly limited by incomplete reporting of replicable interfaces/boundary conditions, assembly/disassembly sequences, and dimensional-control policies, alongside scarce housing-relevant 1:1 validation and partial or absent LCA coverage.

Across Axes 1–4, the corpus rarely provides a single housing-grade evidence package that closes STRUCTURAL, LCA, and FABRICATION simultaneously; maturity concentrates in one- or two-domain bundles. Near-term demonstrators are, therefore, most defensible as integration exercises: pair structurally mature backbones with whole-life LCA completeness (A4 plus at least one C/D scenario, with explicit biogenic-carbon rules) and auditable FABRICATION QA/QC (traceability, tolerance logic, and checkpoints), rather than selecting "best overall" cases (Table S2).

Axis 5—Housing cases and interpretive guardrails

Curated housing cases (Type B) are used solely as operational contrast—appropriability, manuals, guided self-build, and adoption pathways—and are excluded from pooled inference; these are discussed in Section 4.5. Illustrative examples (e.g., WikiHouse: open yet high mediation/part count; AUAR: integrated yet proprietary; "universal components": promising yet thin on housing-grade 1:1 verification) frame the recurring tension between accessibility and operational closure. Non–OSB/plywood evidence is used only as a guardrail for evidential discipline (comparability and auditability), not to expand the scope of inference (see Sections 4.1 and 4.2).

4.4. Regionalized Net-Zero Criteria: A4 Logistics, C/D Plausibility, and Upstream Sensitivity

Climate benefits of timber are not automatic: they are contingent on regional parameters—grid mix, plant siting, A4 distances and modes, and plausible end-of-life scenarios (C/D)—under EN 15804/EN 15978 [180,181]. For decision-relevant OSB/plywood housing claims, whole-life LCAs should be localized (primary data where possible) and screened against the QA/QC criteria in Section 2.5; corporate benefit estimates should be independently validated in the receiving context. This is especially critical in low-technification, seismic-prone settings, where near site production, constrained logistics, and feasible recovery routes can dominate A4 and C/D outcomes and, therefore, the net-zero interpretation.

Upstream forest-policy dynamics can further shift the climate contribution of wood products, reinforcing why net-zero narratives should not be treated as automatic [182,183]. Accordingly, OSB/plywood housing claims remain conditional on transparent whole-life modeling (A4; C/D; biogenic carbon) and on prioritizing long-life uses with operational circularity (DfD and verifiable reuse pathways) [184]. Credible net-zero alignment, therefore, requires coupling design choices with explicit local assumptions and realistic sourcing/recovery constraints, rather than generalized averages that may not hold in the target setting.

4.5. Transfer Pathways in Low-Technification Contexts: Guided Self-Build, Training, and Distributed Micro-Factories

Axis 5 (Type B) cases are used as an operational contrast to clarify transfer pathways: open systems can enable non-expert assembly but require higher digital mediation and part management (Granelo et al. [20]); corporate proposals reduce part count and improve integration at the cost of proprietary dependencies (e.g., AUAR); and "universal components" proposals streamline the design–fabrication–assembly chain but remain thin on housing-

grade verification [166]. Taken together, these cases suggest that guided self-build becomes scalable only when DfMA/DfD, reproducible documentation, and auditable QA/QC are coupled to low-threshold production capacity.

In high-informality Latin American contexts, self-build can shift from a precarious solution to a reliable access pathway if the system is designed for non-experts: few part typologies, step-by-step visual manuals, clear tolerances, component passports, and simple verification (go/no-go) that ensure reproducible quality with three-axis CNC in OSB/plywood. Evidence from assisted-housing programs shows these schemes work when user tasks are bounded and a public/managerial actor provides technical support, organization, and material provisioning—lessons transferable to DfMA/DfD pipelines and distributed micro-factories [185].

Feasibility requires explicit enabling conditions:

1. A regulatory framework and technical responsibility (permits, professional supervision, insurance) to meet seismic safety, fire protection, and habitability;
2. Capability and access gaps closed via school micro-factories and technical support, avoiding exclusion due to limited digital infrastructure;
3. Mandatory QA/QC (dimensional control, component passports, and technical acceptance on site) to maintain safety and traceability;
4. Supply and logistics within defined sourcing radii for OSB/plywood and framework agreements that stabilize cost and quality;
5. Attention to social and land context (tenure, financing, and cultural perceptions of timber) with community accompaniment and targeted financial support.

In sum, guided self-build can strengthen housing responses under low-technification if embedded in minimal quality infrastructure and policies that secure technical, social, and economic viability—and if tied to verifiable safety, QA/QC, and whole-life carbon performance. Under these conditions, self-build can operate as a credible, net-zero-aligned pathway rather than as a merely informal solution.

These transfer conditions are difficult to sustain without capability-building; in practice, academia and distributed micro-factories function as minimum infrastructure that turns documentation and QA/QC into installed capacity. Academia is a key vector for translating technical innovation into installed capabilities: design–build settings and 1:1 prototypes let students and communities rehearse DfMA/DfD, QA/QC, and BIM–CAM traceability under real constraints. Reported experiences—segmented pavilions and formwork-free shells ([157]), segmented plywood roofs [60], "universal components" with full demountability [166], and slot-fit plywood systems for post-disaster contexts [172]—illustrate how teaching can operate as a micro-infrastructure for transfer. Curriculum-wise, this implies studios with verifiable outcomes (drift histories, tolerance bands, assembly time/cost logs), LCA literacy with local data, and school micro-factories equipped with passports and go/no-go templates for lot-level traceability.

This formative role calls for a technosocial reorientation: linking digital competence to access, governance, and sustainability, and evaluating success through documentation and reproducibility rather than singular demonstrators [32]. Key risks (event prototypes, dependence on key individuals, "showability" bias, regulatory misalignment, and hidden costs) can be mitigated through: (i) multi-year agreements with governments/professional bodies to ensure technical reception; (ii) verifiable curricular targets (QA/QC, seismic safety, and time/cost) with external audits; (iii) school micro-factories with explicit budgeting and maintenance plans; (iv) catalogs of minimum-complexity solutions adapted to local contexts; and (v) co-financing of critical inputs within defined supply radii.

In emerging contexts, distributed production in three-axis CNC micro-factories—supported by nesting and open toolchains—offers a coherent scaling pathway compared to highly

robotized macro plants. Near site production shortens the transport stage (Module A4), reduces lead times, and can lower transport-related embodied emissions—directly relevant for net-zero housing strategies. It also builds local capabilities (training, jobs, maintenance, and part refabrication) and enables frugal scalability through nodes that can grow gradually without massive upfront investment [186]. This approach is reinforced by QA/QC kits—verification templates, per-part tolerances, labeling, and component passports—that standardize assembly/disassembly (DfMA/DfD) and improve traceability. A node-based approach can also mitigate concentration risks that centralized high-automation deployments may exacerbate—particularly regional inequalities—while bringing capacity to deliver low-carbon, demountable housing closer to demand centers. Where housing cases are referenced, they serve as scenario-level contrast and do not alter the pooled confidence profiles from the systematic corpus (Axes 1–4).

Viability, however, depends on three conditions: (i) a nearby, stable supply of OSB/plywood with consistent dimensional quality; long travel distances, high cost, or variability erode logistics and tolerance advantages; (ii) regulatory compliance and QA/QC (dimensional control, safety, and traceability via component passports), without which standardization and cross-lot comparability degrade; and (iii) a flow-based operating model that buffers irregular demand, ensures reliable energy, and avoids tooling/spare-part bottlenecks that inflate costs and timelines. In operational terms, these conditions translate into a minimum QA/QC package for each node (dimensional control, component passports, and simple go/no-go inspections) and explicit sourcing and support thresholds (maximum board-sourcing radius, maintenance, and training schemes).

In sum, micro-factories can enable accessible, circular digital prefabrication when paired with explicit operational thresholds (board sourcing radius, minimum QA/QC, support networks, and demand aggregation). These conditions secure performance, repeatability, and cost efficiency, positioning distributed CNC capacity as a concrete pathway to scale net-zero-aligned modular housing in low-technification settings.

4.6. Strengths and Limitations of the Study

This review followed an adapted PRISMA 2020 protocol with dual screening and consensus resolution. A structured QA/QC instrument ensured transparent QA/QC judgments and per-record traceability (Table 2, excerpt; Table S2, full matrix). Findings were integrated across five thematic axes, enabling consistent comparison of advances and gaps.

The search was restricted to Scopus-indexed, English-language, peer-reviewed publications and included PRISMA "unretrieved records", which reinforces the risk of language and indexation bias. This may underrepresent Spanish- and Portuguese-language evidence and the regional gray literature (e.g., local technical reports, institutional guidelines, and program documentation), particularly in Latin American and other emerging contexts where implementation parameters (e.g., A4 logistics and locally parameterized LCA assumptions) are often documented outside Scopus-indexed outlets. Methodological heterogeneity in LCA constrains cross-study comparability, especially for whole-life and regionalized claims. Axis 5 (Type B) was curated for operational contrast; it was not pooled and was excluded from confidence aggregation. We did not conduct backward/forward citation chasing or a formal assessment of reporting bias (optional PRISMA 2020 items), which further limits completeness.

4.7. Immediate Research Agenda

Building on the complementary maturity profiles across Axes 1–4, the agenda below targets the remaining domain gaps needed to deliver auditable, multi-domain demonstrators.

Despite OSB/plywood's low machining threshold (widely available three-axis CNC) and broad regional availability, housing-grade evidence remains less mature than for mass-timber systems (e.g., CLT) in three decision-critical areas: (i) standardized seismic validation with full-scale (1:1) testing and complete reporting of cyclic protocols/drift histories (Axis 1); (ii) operational traceability and QA/QC closure (manuals, component passports, go/no-go templates, dimensional control, and formal site acceptance) (Axis 2); and (iii) whole-life LCA that includes A4 and at least one end-of-life scenario (C/D), with explicit biogenic-carbon accounting (Axis 3). From a net-zero standpoint, this implies that "low-carbon" claims for OSB/plywood housing often outpace the integrated multi-domain evidence required in policy- or code-facing contexts. Targeted evidence strands reinforce feasibility while underlining standardization needs, including efficient all-timber truss solutions with accessible CAD-to-CAM flows [28] and evidence on gaps in comparable OSB/plywood property/test reporting [27]. These gaps define the agenda.

Full-scale Validation and Code Alignment: Standardize cyclic protocols (prescribed drift histories), extend verification to out-of-plane effects where relevant, and include repeated disassembly/durability trials under service-like exposure. Report comparable operational metrics (time, tolerances, costs, and rework) alongside boundary-condition specificity to support code-facing inference; prioritize OSB/plywood-specific protocols to reduce dependence on CLT/GLT analogs.

LCA with Primary Regional Data: Model beyond A1–A3 by including A4 and at least one credible C/D scenario; state biogenic-carbon assumptions explicitly; and report inventories, databases, and method versions transparently. Add basic sensitivity/uncertainty disclosure and prioritize primary local data for regionalized, decision-relevant claims.

Digital Pipelines and QA/QC Closure: Integrate BIM–LCA and BIM–CAM traceability with reproducible QA/QC procedures (labeling/passports, go/no-go templates, and dimensional control) and publish minimum auditable documentation sets (manuals plus drawings/CAM/DXF/scripts/G-code where applicable) to enable cross-lot comparability.

Housing Demonstrators: Deliver 1:1 prototypes fabricated in three-axis CNC microfactories with open documentation and multicriteria evaluation (structural performance, cost, environmental impact, and maintainability), including verification of repeatable assembly/disassembly as a performance criterion.

Health and Manufacturing Processes: Quantify adhesive-related emissions/toxicity and assess feasible lower-impact alternatives; compare router vs. laser cutting in dimensional accuracy, cut quality, heat-affected zone, productivity, and energy use, incorporating occupational and indoor-air-quality considerations where relevant.

Technosocial Pilots and Cultural Acceptance: Implement pilots with measured outcomes on acceptance, perceived safety, maintainability, and willingness to pay; develop manuals and "cultural translation" guides; and evaluate guided self-build under regulatory constraints.

Academia and Training in Low-technification Contexts: Embed DfMA/DfD casework, school micro-factories (three-axis CNC with basic QA/QC) into studios that measure reproducibility and competency gains, using integrated structure–cost–LCA evaluation across cohorts.

Future Evidence Synthesis: Future reviews should complement Scopus with targeted regional databases and a structured gray-literature strategy to better capture Spanish/Portuguese evidence and context-specific implementation parameters.

5. Conclusions

This qualitative systematic review (n = 153; Type A = 136; Type B = 17) shows that modular OSB/plywood systems—typically based on flat-panel CNC workflows—can be

credibly transferred to housing in low-technification contexts only when three minimum evidential conditions are met:

First, mature, comparable technical validation (standardized cyclic tests with drift histories; stiffness/ductility and failure-mode metrics; full-scale (1:1) trials where needed; and explicit, representative boundary conditions).

Second, full life-cycle robustness (LCA extending beyond A1–A3 to include A4 and C/D, with transparent biogenic-carbon treatment and basic sensitivity/uncertainty disclosure).

Third, verifiable reporting quality (QA/QC with end-to-end BIM–CAM traceability, component passports, dimensional control, and reproducible manuals, including operational metrics such as time, tolerances, and rework), operationalized through the tri-domain QA/QC instrument (Table S1) and documented in Table S2 (full matrix; Table 2 provides an excerpt).

These three minimum conditions map onto the four cross-axis bottlenecks identified in Section 3.1: system-level (1:1) validation, whole-life LCA completeness (A4 and C/D), FABRICATION QA/QC closure (traceability and dimensional control), and replicable structural enabling fields (protocols and boundary conditions).

Only when these dimensions converge can modular OSB/plywood systems be positioned as credible low-carbon, net-zero-aligned housing pathways rather than as generic "green" alternatives.

In the current corpus, these thresholds are met only partially and unevenly across STRUCTURAL, LCA, and FABRICATION; thus, OSB/plywood transferability—and any net-zero positioning—remains conditional rather than fully established.

Extrapolatable non-residential patterns (e.g., segmented shells and fastener-free interlocking) show transfer potential toward lightweight housing, but they still require full-scale (1:1) validation and more complete operational documentation. Housing cases (Type B) add technosocial and accessibility value, yet remain discontinuous and under-standardized. Climate performance is context-dependent, driven by energy and logistics (A4) and end-of-life scenarios (C/D). Consequently, even promising systems can support net-zero pathways only where supply chains, logistics, and end-of-life practices enable long-life use and circular, DfD-oriented strategies.

Practically, the review supports a minimum QA/QC package for modular OSB/plywood systems: batch-level dimensional control, component passports, and simple go/no-go inspections at critical interfaces. This package is actionable for housing agencies, technical bodies, and practitioners. In parallel, appropriately scaled three-axis microfactories—operating within defined sourcing radii and basic QA/QC thresholds—offer a plausible pathway for locally manufactured OSB/plywood housing with auditable carbon assumptions in emerging contexts (Axes 2; illustrative contrast in Axis 5). Together, these elements bridge experimental systems and scalable, net-zero-oriented housing programs.

For Latin America and the Caribbean, two levers stand out: (i) guided self-build "designed for non-experts" (few part typologies, step-by-step visual manuals, clear tolerances, and simple go/no-go verification) under a regulatory framework, technical support, and a minimum QA/QC infrastructure; and (ii) distributed, near site three-axis CNC microfactories that shorten A4, build local capacity, and enable DfMA/DfD with traceability. These levers provide a concrete pathway for regulators, housing agencies, and practitioners seeking net-zero-compatible deployment under low-technification constraints.

In sum, digitally fabricated OSB/plywood systems can support affordable, demountable, low-footprint housing if two conditions are met: source-side sustainability thresholds are respected (i.e., forest-sink integrity is maintained), and reproducible quality is ensured through verifiable QA/QC. The transition toward buildings as carbon sinks depends as much on design and circularity as on supply chains and governance aligned with climate

goals. Under this framing, OSB/plywood systems are best understood as conditionally net-zero-aligned: their decarbonization potential depends on convergent evidence across STRUCTURAL, LCA, and FABRICATION domains, and on supply/logistics regimes consistent with long-life use and circular recovery.

Confidence aggregation follows the procedure in Section 2.5; Axis 5 (Type B) cases are illustrative and excluded from pooled confidence estimates. Given the Scopus-only corpus and LCA heterogeneity, additional locally grounded validations remain a priority.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18084096/s1, Supplementary Protocol (v1.0; includes Tables S3–S7); Detailed description of the corpus and patterns (Axes 1–5; include Table S8); Table S1: QA/QC instrument and scoring rules (items, caps, and study-level application); Table S2: Full coded synthesis matrix of the corpus (extended Table 2); PRISMA 2020 Checklist. Table S3. Search combinations used in Scopus for the Structural Performance axis. Table S4. Search combinations used in Scopus for the Digital Fabrication axis. Table S5. Search combinations used in Scopus for the Sustainability and Circularity axis. Table S6. Search combinations used in Scopus for the Extrapolable Non-Residential Systems axis. Table S7. Reports excluded with reasons and records not retrieved. Table S8. Synthesis matrix of the corpus (excerpt). This table reproduces Table 2 in the main text for completeness.

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Abbreviations

The following abbreviations are used in this manuscript:

OSB	Oriented strand board
BIM	Building Information Modeling
EWP	Engineered Wood Products
CLT	Cross-laminated timber
GLT	Glued-laminated Timber
LVL	Laminated Veneer Lumber
GHG	Greenhouse gases
RNE	Peruvian National Building Regulations
CNC	Computer numerical control
QA/QC	Quality assurance/quality control
DfMA	Design for Manufacturing and Assembly
DfD	Design for disassembly

FEM	Finite Element Method/Model
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SWiM	Synthesis Without Meta-analysis
IQR	Interquartile range
CERQual	Confidence in the Evidence from Reviews of Qualitative Research
BIM–CAM	Building Information Modeling–Computer-Aided Manufacturing
N/A	Not available/not reported
EN 15804	European standard for environmental product declarations of construction products
GWP	Global Warming Potential
RoB	Risk of Bias
EST (domain)	Structural domain (QA/QC)
LCA (domain)	Environmental/LCA domain (QA/QC)
FABRICATION (domain)	Digital fabrication domain (QA/QC)
E.010	RNE "Madera": criterios de diseño en estructuras de madera
E.020	RNE "Cargas": acciones y combinaciones
E.030	RNE "Diseño Sísmico": criterios sísmicos
A4	EN 15804: Transport to the construction site (transport to site)
C/D	EN 15804: End-of-life (C) and benefits/loads beyond the system boundary (D)
A1–A3	EN 15804: Product stage (raw material supply–manufacturing)
CAM	Computer-Aided Manufacturing
EN 16449 [187]	Wood and wood-based products—calculation/reporting of biogenic carbon
EN 15978	Building-level LCA framework
ISO 14040 [188]	Environmental management—LCA—principles and framework
ISO 14044 [189]	Environmental management—LCA—Requirements and guidelines.
LCA	Life-Cycle Assessment
EPD	Environmental Product Declaration
BOM	Bill of Materials
RED III	Renewable Energy Directive III
LULUCF	Land Use, Land-Use Change and Forestry

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