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Systematic Review

Hybrid Timber-Based and Conventional Building Systems: A Systematic Review

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Abstract

Timber and other bio-based materials are increasingly discussed as ways to reduce the environmental impact of buildings, but their integration into larger building systems involves different material roles rather than simple substitution. This review examines how timber-based and other bio-based components are combined with reinforced concrete, steel and masonry in hybrid building systems. This systematic literature review was conducted in accordance with the PRISMA guidelines using Scopus and Web of Science. The final synthesis included 141 studies. Four main hybrid building configurations were identified: steel structures incorporating timber components; load-bearing timber structures with reinforced concrete cores or shear walls; timber or other bio-based building envelopes combined with conventional frames; and reinforced concrete structures incorporating timber components. The comparison shows how material functions shape the benefits, limitations and design priorities of each configuration. Structural hybrid systems offer opportunities to improve lateral response, reduce structural mass and lower embodied carbon. Their design also requires consideration of connection behaviour, stability and deformation compatibility. For bio-based building envelopes, the focus shifts to thermal performance, moisture behaviour and the environmental impact of the complete wall assembly. Engineered timber dominates load-bearing roles, whereas other bio-based materials mainly serve insulation and envelope functions. Together, these findings provide literature-based guidance for comparing hybrid solutions during early design.

Keywords: bio-based materials; mass timber; cross-laminated timber (CLT); multi-material construction; structural combinations; steel–timber systems; timber–concrete composite systems

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1. Introduction

1.1. Background and Rationale

Embodied carbon and material selection have become important design issues in building engineering. Structural systems, envelope solutions, and material choices influence not only the environmental profile of a building but also its technical feasibility, construction process, and long-term performance. This has increased interest in timber-based and other bio-based construction products as potential routes for reducing embodied impacts and storing biogenic carbon in building components [1].

Timber construction has evolved from traditional timber framing to engineered timber products such as cross-laminated timber (CLT), glulam, laminated veneer lumber (LVL), and other mass timber systems. These products have expanded the structural use of timber

in floors, walls, beams, columns, frames and roof systems, including in multi-storey and larger building applications [2]. However, timber is not a direct universal substitute for reinforced concrete or steel in every structural role. Larger buildings must satisfy structural, fire-safety, serviceability, durability, acoustic, construction and regulatory requirements at the same time.

Other bio-based materials, such as hemp, straw, flax, cork, cellulose, sheep wool and related products, are also increasingly discussed in sustainable construction. These materials are often associated with envelope, insulation, infill, internal partition or moisture-buffering functions rather than primary load-bearing structural systems [3]. This distinction is important because the term "bio-based materials" encompasses products with very different mechanical, physical, and constructional roles. Therefore, their contribution to building systems needs to be assessed based on their actual function, not solely on their renewable origin.

1.2. Hybrid Timber-Based and Conventional Systems

Hybrid timber-based systems are increasingly discussed because they allow timber or other bio-based components to be combined with conventional structural materials in building systems [2]. Throughout this review, the term "conventional materials" is used to distinguish non-bio-based construction materials, primarily steel, concrete and masonry, from timber and other bio-based materials. The relevance of hybrid systems lies not only in the use of lower-carbon or renewable materials but also in the ability to assign different materials to distinct structural and envelope functions.

Hybrid systems are therefore not simply material substitutions. Their potential depends on how timber-based, other bio-based and conventional components are arranged within the structural and envelope configuration.

For larger and public building applications, this configuration perspective is particularly relevant. Such buildings require that structural, fire-safety, serviceability, durability, construction, and regulatory requirements be addressed together. A structured review of hybrid timber-based and conventional systems can therefore help clarify how different material combinations are currently investigated and what design rationale is reported in the literature.

1.3. Research Gap

Previous studies and reviews have provided important knowledge on hybrid timber-based structures, engineered timber products and bio-based construction materials [2,3]. However, the available evidence remains fragmented across different structural scales, material combinations and assessment perspectives. Many studies focus on individual components, such as timber–concrete composite floors, CLT infill panels, hybrid shear walls, façade systems or connections. These studies provide detailed technical evidence, but they do not always show how different hybrid components relate to broader building- or frame-level configurations.

This creates a gap in understanding how timber-based or other bio-based components are combined with conventional materials across building-related systems. For larger and public building applications, this gap is relevant because design decisions are rarely made at the material level alone. They depend on how the load-bearing structure, stability system, floor and roof systems, façade or envelope concept and connections work together. A structured synthesis of recurrent hybrid combinations can therefore help clarify which configurations are most often discussed, what benefits and limitations are reported, and how different material groups are used within these systems.

This review addresses this gap by organising the literature around recurrent hybrid structural combinations rather than around individual materials or isolated performance aspects. The focus is on combinations in which timber-based or other bio-based components are used together with reinforced concrete, steel, masonry or other conventional materials in building-related structural systems.

1.4. Aim and Research Questions

This study aims to identify and synthesise the main hybrid structural combinations in which timber-based or other bio-based components are combined with reinforced concrete, steel or masonry in building systems. It also evaluates the reported design rationale, benefits and limitations of these combinations in relation to larger and public building applications.

The research question was formulated using an adapted PICO framework, in which the population/problem was defined as building-related structural systems, the intervention/interest as timber-based or other bio-based components, the comparison/context as reinforced concrete, steel, masonry and other conventional material counterparts, and the outcomes as recurrent hybrid combinations, reported benefits, limitations and material roles.

The review addresses the following main research question:

What hybrid structural combinations of timber-based or other bio-based components with conventional materials are reported in research and practice, and what are their main benefits and limitations?

To structure the analysis, three supporting research questions were used:

RQ1. What recurrent hybrid structural combinations are identified in the reviewed literature?

RQ2. What benefits and limitations are most frequently reported for these combinations?

RQ3. How are timber-based, other bio-based and conventional materials used within these combinations?

2. Methods

2.1. Review Design

This study was designed as a systematic literature review with a structured categorisation of the included studies. A working review protocol was developed before the database search; however, the review was not prospectively registered, and the protocol was not publicly registered or published. The review process followed the PRISMA guidelines for the search, screening, eligibility assessment and study selection process [4]. The structured categorisation drew on systematic mapping principles to organise the included literature according to recurring hybrid structural combinations, material roles and reported design rationale [5].

The review applied a structured qualitative and frequency-based synthesis. The included studies differed in research design, structural scale, material combinations and reported performance indicators. The analysis therefore focused on identifying recurrent patterns in how timber-based or other bio-based components are combined with reinforced concrete, steel, masonry or other conventional materials in building-related structural systems.

The groups identified through the structured categorisation are used as literature review categories rather than as official or standardised structural typologies. The database search strategy and overall review scope followed the working protocol, while the analytical categorisation was refined during the synthesis to reflect recurrent patterns identified across the included studies. Their purpose is to organise the evidence and clarify how timber-based or other bio-based components are combined with conventional materials in building-related structural systems.

2.2. Search Strategy and Databases

The literature search was conducted in Scopus and Web of Science on 12 May 2026. These two bibliographic databases were selected to cover journal articles and conference/proceeding papers relevant to civil engineering, construction technology, materials science and related fields.

The search strategy was developed around three concept blocks: (i) timber-based or other bio-based construction materials; (ii) conventional materials such as reinforced concrete, steel, concrete and masonry; and (iii) hybrid building systems, structural systems, components or elements. The aim of the search was to capture studies addressing combinations of timber-based or other bio-based components with conventional materials in building-related structural or system-relevant contexts.

The search was focused on hybrid systems and system-relevant building elements. Studies dealing only with pure timber buildings, pure conventional structures or material-level properties without a clear building element or system context were not targeted by the search strategy. The complete database-specific search strings and applied limits are provided in Appendix A.

In Scopus, the final search was limited to the subject areas Engineering and Materials Science, the document types Article and Conference Paper, and the language English. In Web of Science, the final search was limited to English-language records, the document types Article and Proceeding Paper, and the Web of Science categories Engineering Civil and Construction Building Technology.

Targeted snowballing was used as an additional route for identifying studies that were directly relevant to the review question but were not retrieved through the final database search. These records were documented separately in the PRISMA flow diagram and assessed using the same eligibility and coding logic as the database records.

2.3. Eligibility Criteria

The eligibility criteria were defined to identify studies on hybrid building-related structural solutions in which timber-based or other bio-based components are combined with conventional construction materials. Eligible studies had to address combinations involving timber-based or other bio-based materials with reinforced concrete, steel, masonry, or other conventional materials. The reviewed combination also had to be related to a building structural system, a building element or a component with clear relevance to the structural behaviour or configuration of a building.

Studies were included when they provided information on at least one of the following aspects: structural configuration, material roles, design rationale, reported benefits, reported limitations or performance assessment of a hybrid solution. Eligible publication types included journal articles and full conference/proceeding papers.

The review was not limited to a single building type. Studies dealing with public, commercial, institutional, residential, multi-storey or larger-scale building contexts were considered when the structural system or hybrid combination was relevant to the review question.

Studies were excluded when they addressed only material-level properties without a clear link to a building element or structural system. Pure timber systems, pure conventional systems and non-building applications such as bridges, roads, furniture or product design were also excluded. Studies focused only on connections were excluded when the connection was not discussed as part of a hybrid building element or structural system. Review articles, non-English publications and records for which the full text could not be obtained were not included in the final synthesis.

2.4. Study Selection

After duplicate records were removed, 1275 database records were screened for relevance. The screening process was conducted in two stages by J.P. according to the predefined eligibility criteria. First, titles, abstracts and keywords were reviewed against the eligibility criteria. Records outside the scope of the review were excluded at this stage.

Following title, abstract and keyword screening, 189 full-text articles were considered for eligibility. Of these, 47 full-text articles could not be accessed, and 8 were excluded with reasons. The excluded articles comprised duplicate, overlapping or conference-version publications (n = 6), a study that was not eligible after full-text screening (n = 1), and a non-English full text (n = 1).

Following the full-text stage, 134 studies from the database search were included. In addition, targeted snowballing identified seven further studies that were directly relevant to the review question. These studies were assessed using the same eligibility and coding logic as the database records and were included in the final synthesis. The final review therefore included 141 studies. The full-text records excluded with reasons and the corresponding reasons for exclusion are provided in Supplementary Table S2.

The study selection process, including database searching and targeted snowballing, is presented in the PRISMA flow diagram in Figure 1.

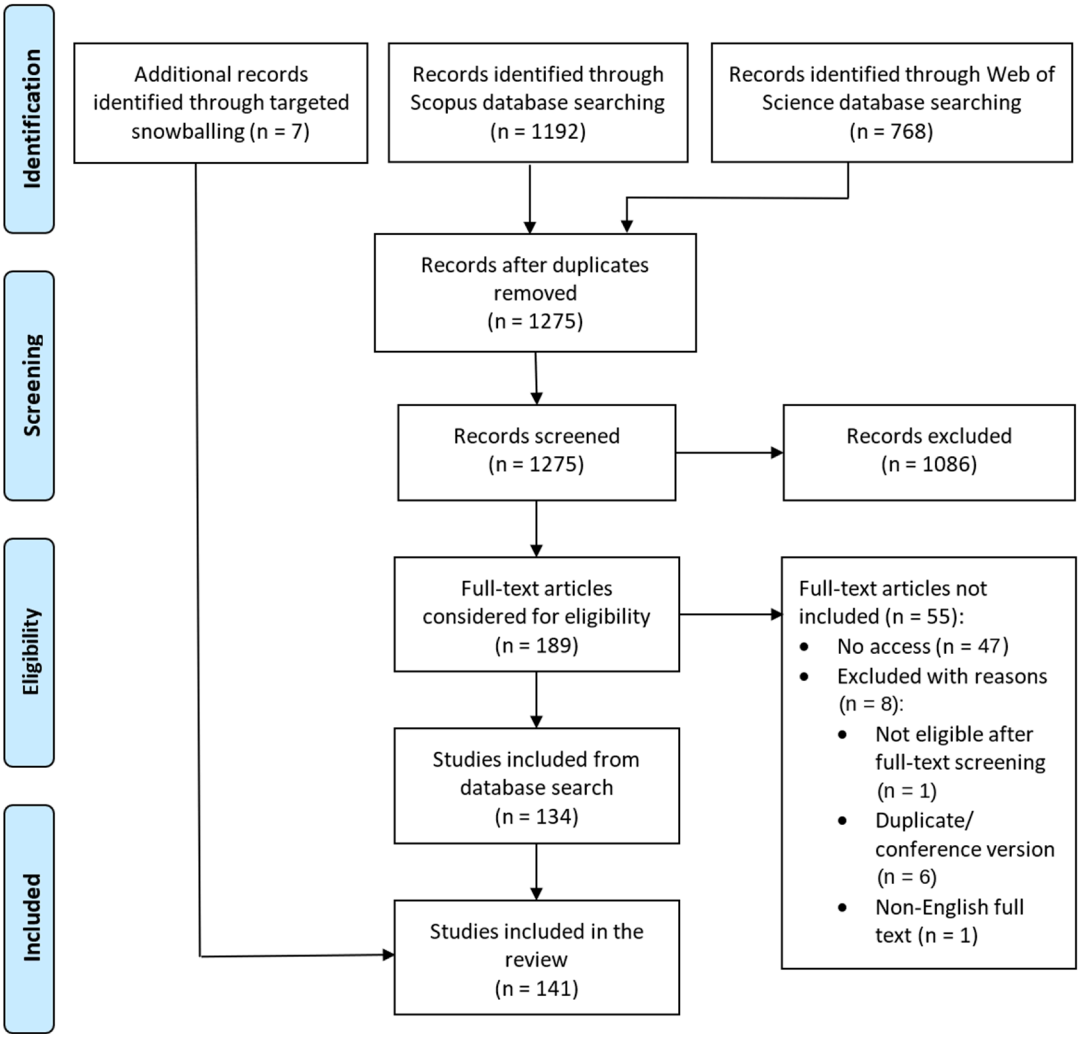


Figure 1. PRISMA flow diagram of the study selection process.

2.5. Data Extraction and Coding

Data extraction and coding were performed by J.P. using a structured coding table developed for this review. For each included study, bibliographic information and analytical coding fields were recorded. The main coding fields covered the hybrid structural combination, timber-based or other bio-based components, conventional components, study type, evidence type, building context, reported benefits, reported limitations, material roles and coding notes.

The coding process focused on how materials were combined within building-related structural systems or elements. Timber-based components included engineered timber products, such as cross-laminated timber, glulam and laminated veneer lumber, as well as timber-frame and wood-based panel systems when they had a structural or system-relevant role. Other bio-based materials were coded separately when they appeared as insulation, infill, envelope or non-load-bearing components. Conventional components included reinforced concrete, concrete layers, steel, masonry, mechanical fasteners and steel connectors, depending on the role reported in each study.

Reported benefits and limitations were coded as non-exclusive categories. A single study could therefore be assigned more than one benefit or limitation code when multiple aspects were reported. The coding captured both technical and non-technical aspects, including structural efficiency, stiffness, seismic behaviour, prefabrication, reduced weight, lower embodied carbon or global warming potential, fire safety, vibration and serviceability, connection complexity, cost, design-code/regulatory uncertainty, data uncertainty and modelling uncertainty. The coding categories and their definitions are provided in Appendix B.

Coding notes were used to record interpretative details that could not be captured by categorical fields alone. These notes supported later grouping and interpretation, particularly where a study addressed a specific component, connection, floor system, wall system, façade system or building configuration rather than a complete building-level structural system.

The final coding table served as the basis for the qualitative synthesis and the frequency counts reported in Section 3.

2.6. Synthesis Approach

The synthesis was organised in three steps. First, the included studies were reviewed to identify recurring hybrid structural combinations. The grouping was based on how timber-based or other bio-based components were combined with reinforced concrete, steel, masonry, or other conventional materials in building-related structural systems and elements.

Second, the identified combinations were consolidated into broader review categories. These categories were used to organise the literature and to support comparison across studies. They should not be interpreted as official or standardised structural typologies. More specific solution types, such as timber–concrete composite floors, steel–timber wall or floor systems, timber infill panels, hybrid shear walls and façade or envelope systems, were retained in the coding table and used to inform the interpretation of the broader groups.

Third, frequency counts were prepared for the main hybrid combinations, material groups, reported benefits and reported limitations. These counts were used to describe how often specific combinations, benefits and limitations appeared in the reviewed literature. They were not used to rank the solutions because the reviewed studies differed in scope, scale, methods, and performance indicators.

The synthesis combined qualitative interpretation with descriptive frequency analysis. The qualitative interpretation focused on material roles, structural logic and design rationale, while the frequency analysis was used to identify which combinations, benefits, limitations

and material groups were most frequently reported in the included studies. The results are presented through three main tables: recurrent hybrid structural combinations, reported benefits and limitations, and material roles in the identified hybrid combinations.

Given the methodological heterogeneity of the included studies and the descriptive, qualitative and frequency-based nature of the synthesis, no single formal study-level risk-of-bias tool was applied. Formal assessments of reporting bias and certainty of evidence were also not performed, as the review did not estimate or pool intervention effects.

3. Results

3.1. Overview of Included Studies

The final synthesis included 141 studies [6–146] (Figure 1). The characteristics of all included studies are summarised in Supplementary Table S1. Figure 2 presents the distribution of included studies by publication year. The corpus includes numerical, experimental, case-study, design-oriented, comparative and life-cycle assessment studies, showing that the topic is addressed from several methodological perspectives.

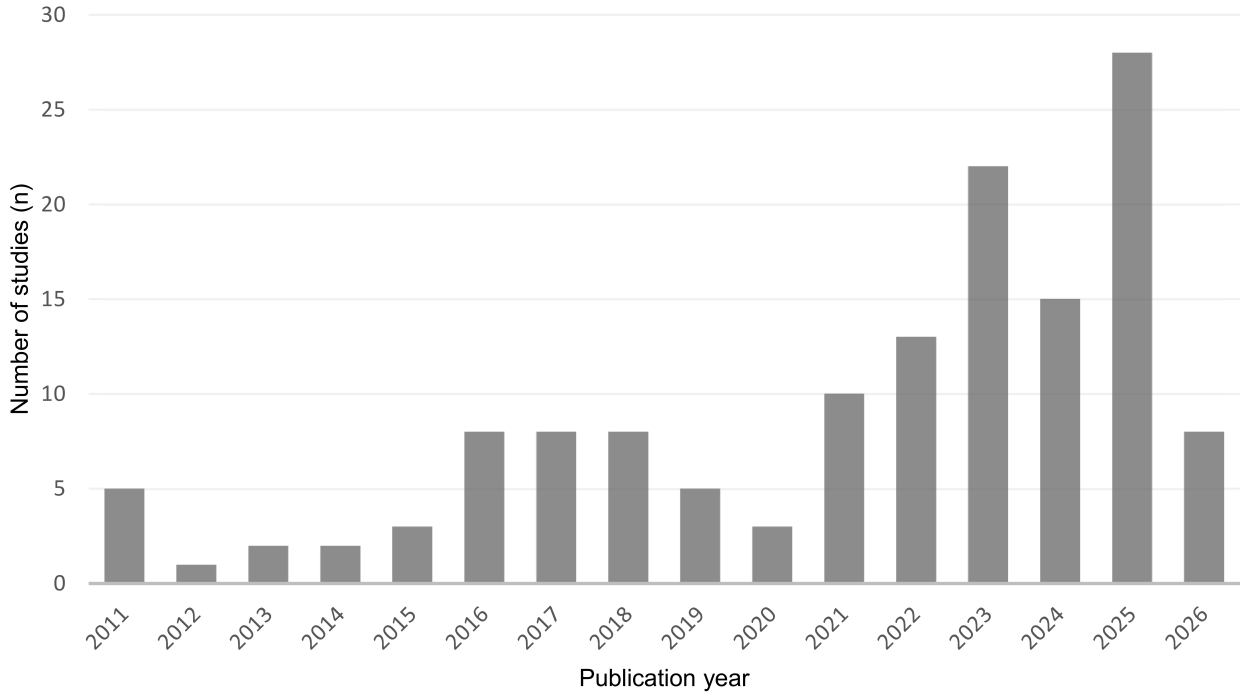


Figure 2. Distribution of included studies by publication year. Note: The 2026 count reflects publications identified up to the database search date, 12 May 2026.

The reviewed studies cover a broad range of building applications, including residential (69 studies), office (43), commercial (20), and public, institutional or educational contexts (19). These categories are non-exclusive and encompass both constructed building case studies and conceptual or numerical assessments. In terms of building scale, 60 studies were coded as addressing high-rise contexts, including numerical investigations of buildings reaching 40 storeys. This range illustrates the relevance of hybrid timber-based systems across different building types and scales, while the applicability of individual findings remains dependent on the investigated configuration and assessment conditions.

The following results present the reviewed literature through three main aspects: recurrent hybrid structural combinations, reported benefits and limitations, and the roles assigned to timber-based, other bio-based and conventional materials.

3.2. Main Recurrent Hybrid Structural Combinations

Four main recurrent building- and frame-level hybrid structural combinations were identified in the reviewed literature (Table 1). These combinations describe the dominant ways in which timber-based or other bio-based components are combined with conventional structural materials at the building, frame, or major-element level.

Table 1. Main recurrent building- and frame-level hybrid structural combinations.

Hybrid Structural Combination	n	Structural Interpretation	Representative References
Steel frame/bracing/beams + timber-based components	50	Steel remains the primary frame, bracing, beam or stability system; timber-based components are introduced as wall panels, infill panels, floors, roof elements, shear-wall components or other hybrid structural parts.	[53,101,115,120]
Mass timber load-bearing structures + RC core/shear walls	34	Mass timber forms the main load-bearing structure; reinforced concrete provides stiffness, lateral stability and robustness through cores, shear walls, podiums or base elements.	[36,68,108,110]
Timber/bio-based façade or envelope + conventional frame	13	The main frame remains conventional, usually reinforced concrete or steel; timber or other bio-based components are introduced through façade, external wall, insulation, infill or envelope systems.	[83,140–142]
RC frame/core/shear walls + timber-based components	12	Reinforced concrete remains the primary vertical or stability system; timber-based components are introduced in selected parts such as floors, walls, infill panels, modules, roof elements or envelope components.	[12,32,117,131]

Note: The categories summarise recurrent building- and frame-level combinations identified in the reviewed literature. They are review categories rather than standardised structural typologies. The counts refer only to studies assigned to the four main recurrent building- and frame-level categories and therefore do not sum to the full set of 141 included studies.

The largest group consists of systems in which steel remains the primary framing, bracing, beam, or stability component, while timber-based elements are introduced as floors, walls, infill panels, roof elements, or hybrid shear-wall components. This indicates that steel–timber hybridisation is frequently addressed through interactions between steel framing or stability systems and timber-based panels, floors, or wall elements.

The second-largest group includes mass-timber load-bearing structures combined with reinforced concrete (RC) cores, shear walls, podiums, or base elements. In these cases, timber-based components form a major part of the load-bearing structure, while reinforced concrete is used for stiffness, lateral stability, robustness or lower-level structural support.

Two smaller but structurally relevant groups were also identified. The façade and envelope group usually retains a reinforced concrete or steel primary structure and introduces timber-based or other bio-based components through external walls, façade panels, insulation, infill or envelope systems. The RC frame, core, or shear-wall group includes systems in which reinforced concrete remains the primary vertical or stability system, while timber-based components are added in selected parts of the building.

The distribution of combinations indicates that the reviewed literature most often addresses hybridisation at the frame, core, façade, or major-element level, rather than as a single, uniform building-system type.

3.3. Reported Benefits and Limitations of the Main Hybrid Combinations

The reported benefits and limitations were coded for each of the four main hybrid structural combinations. Table 2 summarises the most frequently reported benefit and limitation categories within each group.

Table 2. Reported benefits and limitations of the main recurrent hybrid combinations.

Hybrid Structural Combination	Group n	Most Reported Benefits	Most Reported Limitations
Steel frame/bracing/ beams + timber-based components	50	improved seismic behaviour (n = 30); structural efficiency (n = 26); prefabrication (n = 15); lower GWP/embodied carbon (n = 11); improved stiffness (n = 11)	connection complexity (n = 34); seismic demand (n = 19); design-code/regulatory uncertainty (n = 18); data uncertainty (n = 18); modelling uncertainty (n = 14)
Mass-timber load-bearing structures + RC core/shear walls	34	lower GWP/embodied carbon (n = 20); structural efficiency (n = 16); prefabrication (n = 14); reduced weight (n = 11); faster construction (n = 10)	data uncertainty (n = 17); connection complexity (n = 16); design-code/regulatory uncertainty (n = 16); fire safety (n = 12); vibration/serviceability (n = 8); cost (n = 8)
Timber/bio-based façade or envelope + conventional frame	13	thermal performance (n = 9); lower GWP/embodied carbon (n = 5); reduced operational energy (n = 2); local availability (n = 2); energy efficiency (n = 2)	data uncertainty (n = 6); moisture/durability (n = 4); scope limitation (n = 3); scale limitation (n = 3); modelling uncertainty (n = 3)
RC frame/core/shear walls + timber-based components	12	improved seismic behaviour (n = 7); reduced weight (n = 6); improved stiffness (n = 4); structural efficiency (n = 4)	connection complexity (n = 9); seismic demand (n = 5); data uncertainty (n = 4); design-code/regulatory uncertainty (n = 3); scope limitation (n = 3); modelling uncertainty (n = 3)

Note: Values in brackets indicate the number of studies within each group that reported the respective benefit or limitation. Categories are non-exclusive; one study may report several benefits or limitations.

The benefit patterns differ between the four groups. Steel–timber combinations are mainly associated with seismic behaviour, structural efficiency, prefabrication, and stiffness, whereas mass timber systems with RC cores or shear walls are more strongly linked to lower GWP or embodied carbon, reduced weight, and faster construction. Façade and envelope systems present a different profile, with benefits primarily related to thermal performance, operational energy, and embodied carbon.

The reported limitations also vary by configuration. Steel–timber and RC–timber combinations raise recurring concerns regarding connection complexity, seismic demand, and modelling assumptions. Mass timber systems with RC stability elements are more often associated with data uncertainty, design-code uncertainty, fire safety, serviceability and cost. In façade and envelope applications, the main limitations are linked to data uncertainty, moisture, durability and scale of application.

Overall, Table 2 shows that benefits and limitations should be interpreted in relation to the specific hybrid configuration rather than as general properties of all timber-based or bio-based systems.

3.4. Material Roles in the Identified Hybrid Combinations

The material coding was used to identify how timber-based, other bio-based and conventional materials are assigned different functions within the reviewed hybrid combinations. The main material groups and their typical roles are summarised in Table 3.

Table 3. Material groups and their roles in the reviewed hybrid configurations.

Material Side	Material Group	n	Typical Role in the Reviewed Hybrid Combinations
Bio-based/timber-based	CLT	102	Floors, walls, infill panels, slabs and horizontal load-transfer panels; also part of mass timber systems.
Bio-based/timber-based	Other engineered timber: glulam, LVL, PSL, mass timber	116	Beams, columns, frames, roof members and mass timber load-bearing structures.
Bio-based/timber-based	Light timber frame/OSB/wood-based panels	46	Light shear walls, infill panels, façade panels, envelope systems and renovation modules.
Bio-based/non-timber	Non-timber bio-based materials	7	Mainly envelope, insulation, infill and non-load-bearing applications; rarely addressed as primary structural systems.
Conventional	Steel	80	Frames, bracing, beams, plates, connectors, reinforcement and ductile lateral systems.
Conventional	Concrete layers	71	Concrete toppings, compression layers and slabs used mainly in timber–concrete composite floors and hybrid horizontal systems.
Conventional	Reinforced concrete	62	RC cores, shear walls, frames, foundations, podiums and other primary structural or stability elements.
Conventional/connection-related	Mechanical fasteners/ steel connectors	24/16	Connection detailing between timber, steel and concrete components; critical in hybrid structural behaviour.
Conventional	Masonry	6	Limited use as a conventional counterpart in selected hybrid wall or building configurations.

Note: Categories are non-exclusive; a single study may include multiple material groups. Therefore, values should not be summed. Engineered timber categories partly overlap with CLT and other timber product codes. Concrete layers refer to toppings, compression layers, or slabs in hybrid floor systems, whereas reinforced concrete refers to coded RC structural elements such as cores, shear walls, frames, and foundations.

The material-role distribution shows that the reviewed hybrid systems are dominated by timber-based components, particularly engineered timber products. CLT is most commonly used as a plate-type component in floors, walls, infill panels, and horizontal load-transfer elements. Other engineered timber products, including glulam, LVL, PSL and broader mass timber categories, are mainly reported as primary structural members or mass timber load-bearing components.

In the reviewed hybrid configurations, light timber-frame systems, OSB and other wood-based panels were represented in a range of panelised applications, including light shear walls, infill and façade panels, envelope systems and renovation modules. Non-timber bio-based materials were reported much less frequently and appeared mainly in envelope, insulation, infill or other non-load-bearing applications.

On the conventional material side, steel, concrete layers and reinforced concrete were the most frequently reported groups. Steel and reinforced concrete retain key structural and stability-related functions, while concrete layers are mainly associated with timber–concrete composite and other hybrid horizontal systems.

The material-role distribution therefore shows a clear contrast between the frequent structural use of engineered timber and the limited structural-system role of non-timber bio-based materials. The main material-role logic of the recurrent hybrid combinations is summarised conceptually in Figure 3.

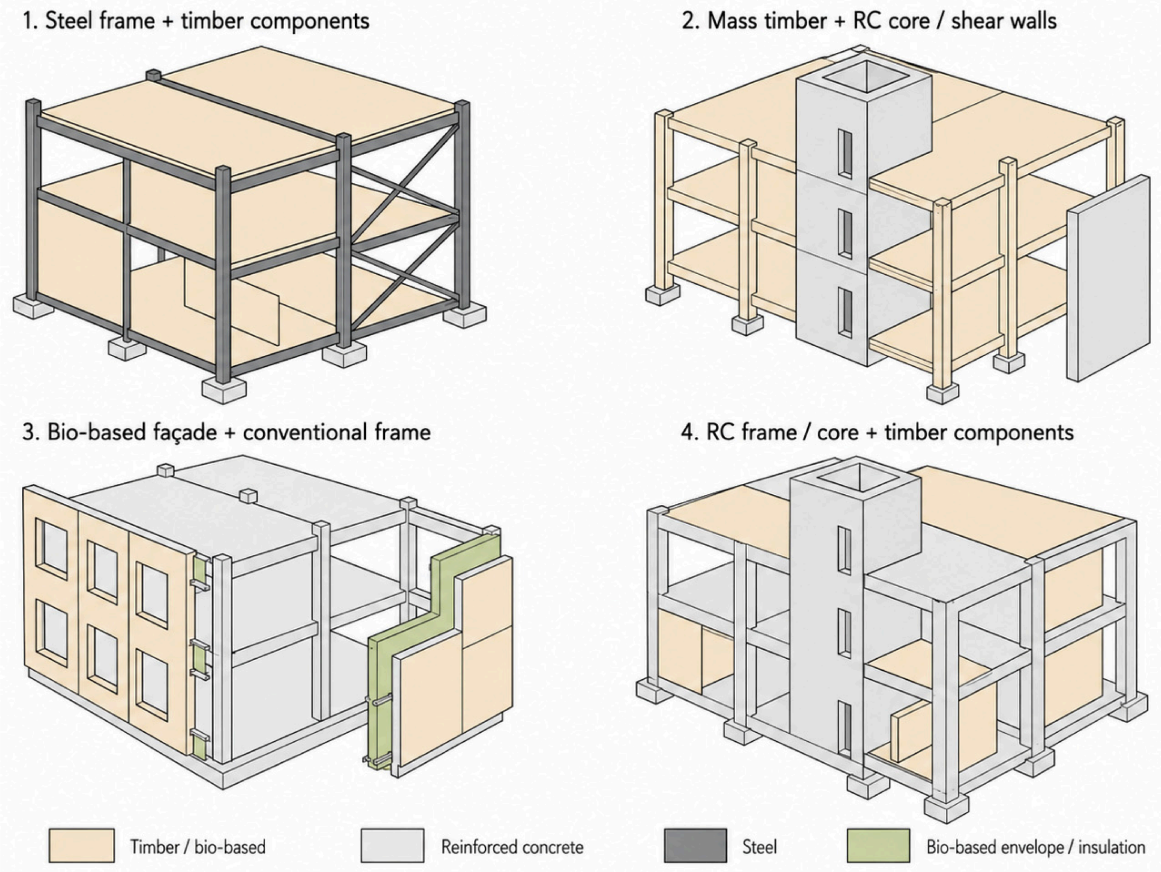


Figure 3. Conceptual representation of the main recurrent hybrid timber-based and conventional building system configurations identified in the review.

4. Discussion

4.1. From Material Substitution to Function-Based Hybrid Design

The results suggest that hybrid timber-based and conventional building systems are not only about replacing reinforced concrete or steel with timber. More often, they combine different materials in different parts of the building according to their structural or envelope function. In this sense, hybrid design is a question of system configuration rather than material substitution alone.

The four main configurations identified in this review represent recurrent building- and frame-level arrangements, distinguished by how timber-based components are combined with the primary structural or envelope system. These categories describe how materials are arranged within hybrid building systems, while functional analysis explains the specific contribution of each material. For example, timber in steel-framed systems may act as floors, walls or infill elements contributing to lateral resistance [54,92,128]. In mass timber structures combined with reinforced concrete cores or shear walls, timber generally carries gravity loads, while reinforced concrete provides lateral stability [80,94]. Timber and other bio-based materials incorporated into conventional-frame envelopes primarily serve thermal, environmental or enclosure functions [83,140], whereas timber components in reinforced-concrete-dominant systems can contribute to seismic strengthening or reduced structural mass [32,117,137].

The main design question is therefore not only how much bio-based material is used, but where it is used and what function it performs.

This interpretation also explains the dominant role of engineered timber in the reviewed literature. Products such as CLT, glulam and LVL can be assigned clear structural roles in

primary building elements. By contrast, non-timber bio-based materials appear mainly in envelope and non-load-bearing applications. Their contribution to hybrid building systems is therefore different from that of structural timber products and should be assessed accordingly.

Accordingly, classification by recurrent system configuration and interpretation by material function are complementary rather than competing approaches. The four groups accommodate different component functions and design strategies within the same broader configuration. These differences do not undermine the classification; instead, they help explain why the benefits and design considerations vary across individual studies. This functional interpretation connects the identified configurations with the practical design implications synthesised in Section 4.4.

4.2. Component-Level Evidence and the System-Level Gap

A clear pattern in the reviewed literature is the strong focus on components, sub-systems and specific structural mechanisms. Many studies address specific component or sub-system types, including timber–concrete composite floors [65,81,146], CLT infill panels and hybrid shear-wall systems [12,53,101,115,117,120], and steel–timber frame interaction or connection behaviour [31,38,70,138]. Other studies focus on timber-based façade or envelope systems [83, 140–142], or on mass timber structures combined with reinforced concrete cores or shear walls [58,108,110]. This type of evidence is important because hybrid systems depend on the performance of interfaces, connections and element-level interaction between materials.

At the same time, this component-level focus creates a system-level gap. Individual studies often provide detailed evidence on one element, connection or structural mechanism, but few studies explain how different hybrid components are combined into complete building configurations. For larger and public buildings, this distinction is important. A structurally efficient floor system, façade panel, wall element or connection detail does not automatically define a feasible whole-building solution.

The distinction concerns the scale and scope of the investigated findings rather than the research method itself. For example, experimental studies of CLT infill panels establish their contribution to the lateral response of the tested structural arrangements [54,117], while building-level seismic behaviour also depends on diaphragm flexibility, connections and the interaction of the complete lateral-resisting system [92]. Similarly, measurements from constructed hybrid buildings provide valuable evidence of overall dynamic behaviour, although the observed response remains linked to the specific building configuration [50]. These findings can therefore be synthesised across different research approaches while retaining the conditions under which individual results were obtained.

The overall configuration also depends on span arrangement, stability strategy, vertical load transfer, fire-safety strategy, acoustic and vibration requirements, construction sequence and regulatory acceptance. The contribution of this review is therefore to organise the fragmented evidence into recurrent building- and frame-level combinations. This helps to move the discussion from isolated hybrid components towards the structural logic of combined building systems.

4.3. System-Dependent Benefits and Implementation Barriers

The reported benefits and limitations show that hybrid systems cannot be evaluated by a single general performance claim. Lower embodied carbon, reduced weight, prefabrication, improved stiffness or improved seismic behaviour appear in the reviewed literature, but their relevance depends on the specific hybrid combination and on the role assigned to each material.

These benefits are conditional rather than independent of other design requirements. For example, steel–timber floor configurations can reduce embodied carbon compared with selected conventional alternatives [22,128], but the inclusion of additional concrete layers or

measures required for vibration and fire performance can influence the overall environmental balance. Similarly, mass timber structures combined with reinforced concrete cores can achieve lower embodied carbon under the investigated design conditions [94], while their lateral and dynamic response remains dependent on the stiffness and arrangement of the stabilising system [50,80]. These findings highlight trade-offs between environmental, structural and serviceability objectives rather than a uniform advantage associated with a particular material combination.

The same applies to implementation barriers. Connection and interface behaviour are recurring concerns in steel–timber, timber–concrete and RC–timber configurations [30,31,38,53,70,117]. Fire safety and serviceability issues appear in more specific steel–timber and timber–concrete floor or building contexts [44,50,61–63,79,86,146]. Data uncertainty and assessment-boundary choices are particularly relevant in environmental and life-cycle studies [6,16,17,23,26,100,110,128]. These issues become critical in different ways depending on the structural configuration and assessment boundary.

The same interdependence is evident in envelope and retrofit applications. External wall assemblies with similar thermal transmittance can exhibit different annual heating and cooling demands because of differences in thermal mass and climatic conditions [141]. The environmental benefits of bio-based insulation can be partly offset by the additional framing, supporting elements and other materials required in the complete wall assembly [83]. In reinforced concrete frames incorporating CLT infill walls, improved lateral resistance must be considered together with the response of the connections and the capacity of the RC members transferring the additional forces [32,117]. Accordingly, the significance of each benefit or limitation depends on the complete assembly, the interaction between materials and the conditions investigated in the original study.

4.4. Implications for Larger and Public Building Applications

For larger and public building applications, the findings support an early-stage design approach based on the intended function of timber within the overall building configuration, rather than on material selection or substitution alone. The suitability of a hybrid solution depends on how the primary load-bearing structure, lateral stability system, floors, building envelope and connections interact. The four recurrent configurations identified in this review provide a basis for relating the purpose of timber integration to the principal findings in the literature and the conditions that require attention during design. These relationships are summarised in Table 4 and illustrated schematically in Figure 4.

Table 4. Evidence-based design implications of the main hybrid timber-based building configurations.

Hybrid Structural Combination	Why Is Timber Integrated?	What Are the Main Findings?	What Should Be Considered During Design?
Steel frame/bracing/ beams + timber-based components (n = 50)	To combine steel framing with timber-based floors, walls, infill panels or roof elements, assigning timber a defined structural function while reducing structural mass or embodied impacts where the configuration allows.	CLT wall infills increase lateral stiffness and energy dissipation in the investigated steel-frame configurations [54,101,112]. Selected steel–timber building and floor solutions show lower embodied carbon than their specified steel–concrete alternatives [22,128]. The interaction between timber and steel affects overall structural response [92].	Define whether timber acts as a load-bearing element, a lateral-resisting component or an infill panel. Verify connection stiffness and slip, force transfer and floor diaphragm flexibility [54,92,101]. Assess walking-induced floor vibrations, fire resistance and the environmental effects of concrete toppings or protective layers [22,128].

Table 4. *Cont.*

Hybrid Structural Combination	Why Is Timber Integrated?	What Are the Main Findings?	What Should Be Considered During Design?
Mass timber load-bearing structures + RC core/shear walls (n = 34)	To use mass timber as the primary gravity-load-bearing structure while reinforced concrete cores or shear walls provide lateral stiffness and stability.	Building-level comparisons identify reductions in embodied carbon for particular timber–concrete configurations [94] and changes in seismic demand [113]. Core stiffness and the resulting dynamic response remain decisive for whole-building performance [80]. Monitoring and analytical studies identify important vibration and differential-deformation considerations [41,50].	Check RC-core stiffness, lateral drift and occupant comfort under wind-induced building movements [50,80]. Assess the transfer of horizontal forces through floor diaphragms and diaphragm-to-core connections. Account for differential shortening and moisture-related movements between timber and concrete [41], alongside fire resistance and serviceability requirements.
Timber/bio-based façade or envelope + conventional frame (n = 13)	To integrate timber and other bio-based materials into façades and external walls, improving the environmental or thermal performance of the envelope while retaining a conventional primary frame.	Selected timber-based and bio-based envelope alternatives reduce cooling demand or embodied impacts under the examined building and climate conditions [23,49,142]. Equal thermal transmittance does not necessarily mean equal annual energy demand: thermal mass and climate can reverse the comparison [141]. Supporting components can offset material-level environmental gains [83].	Assess the performance of the full wall assembly, including fixings, secondary supports, insulation and finishes [83]. Check climate-specific heating and cooling demand, thermal inertia [49,141], rain exposure, moisture accumulation and the capacity of the assembly to dry [140].
RC frame/core/shear walls + timber-based components (n = 12)	To introduce timber walls, floors or other components into an RC-dominant structure for a defined function, including lateral strengthening, lower structural mass or adaptation of existing buildings.	CLT wall infills improve lateral response in the RC-frame arrangements investigated in experimental and numerical studies [12,32,117]. Replacing heavier concrete floors with timber components reduces mass and seismic demand in specified numerical comparisons [137]. A monitored hybrid building illustrates that acceptable structural response does not itself ensure satisfactory floor vibration comfort [13].	Verify existing RC-member capacity and load transfer through timber–concrete connections [12,117]. Examine changes in stiffness, deformations and local failure mechanisms [32,109]. For timber floors, assess diaphragm behaviour and vibrations felt by occupants during walking [13]. Distinguish new-build details from retrofit conditions [32,117].

Note: The table synthesises recurring findings and design considerations in the reviewed literature. Individual results apply to the investigated configurations, loading conditions and assessment boundaries rather than constituting universal design rules. The four main groups comprise 109 studies; the remaining 32 studies are included in the wider systematic review but are not assigned to these four groups.

A further implication concerns the interaction between individual components and the complete building system. Improvements in the lateral response of timber infill walls or hybrid connections do not, by themselves, establish the seismic performance of an entire building [54,92,109,117]. Similarly, the use of lighter timber floor components requires consideration of diaphragm action and vibration comfort under occupant movement [13]. These findings highlight the need to assess how component-level improvements influence the behaviour of the primary structure and its connections.

The relevance of these findings to larger buildings is supported by studies addressing both constructed multi-storey hybrid buildings and numerical assessments of taller structural configurations [50,80,94,113,134]. However, results obtained for a particular building,

structural arrangement or loading scenario cannot be directly generalised to other building types and scales. This distinction is especially important for public buildings, where structural safety, vibration and acoustic comfort, fire resistance, durability and operational requirements must be addressed together. Accordingly, the findings provide configuration-specific design considerations rather than universal limits for building height, structural spans or material substitution.

At the early design stage, the findings summarised in Table 4 can help compare hybrid configurations against project objectives and identify the structural, environmental and serviceability requirements to be verified before selecting a solution. These requirements must then be assessed for the specific building configuration, loading conditions and intended use.

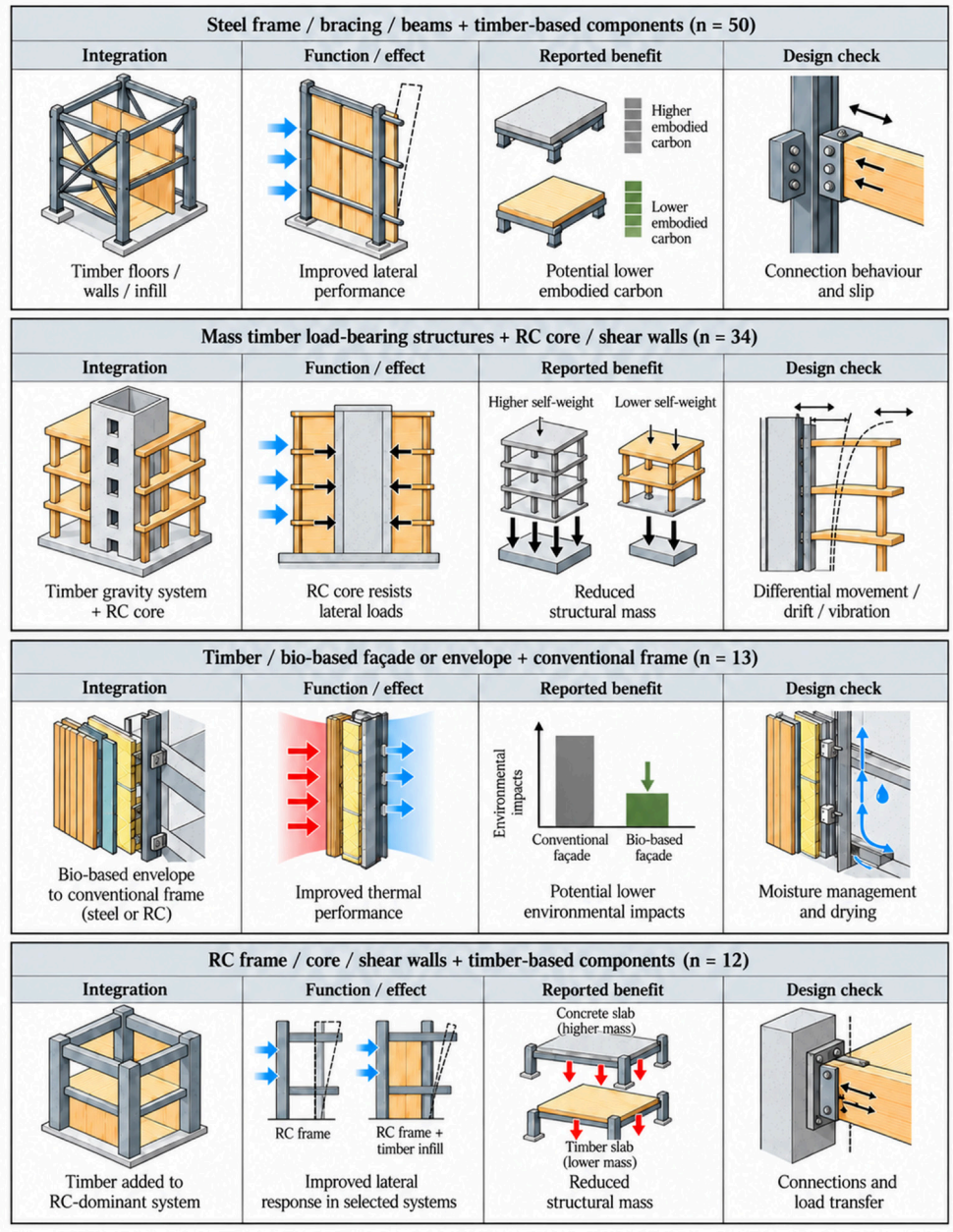


Figure 4. Schematic comparison illustrating material integration, structural and envelope functions, reported benefits and design considerations.

4.5. Limitations of the Review

The review has several limitations. The analysis is based on Scopus and Web of Science records, English-language publications, and journal articles or full conference/proceeding papers. The coding process involved interpretation, especially when studies addressed multiple materials, elements, or performance aspects. The frequency counts describe the distribution of topics in the reviewed literature and should not be interpreted as direct measures of technical performance or practical suitability.

The reviewed studies also differ in their research methods, investigated structural scales and assessment conditions. Consequently, the identified design considerations reflect recurring findings in the literature rather than universally applicable performance estimates or prescriptive design rules.

The review identifies recurrent hybrid configurations and their reported benefits and limitations. However, the suitability of each solution still needs to be assessed at project level using the relevant structural, fire, acoustic, cost and life-cycle analyses.

5. Conclusions

This systematic review analysed 141 studies on hybrid building systems combining timber-based or other bio-based components with conventional construction materials. Four main configurations were identified: steel structures incorporating timber components; load-bearing timber structures with reinforced concrete cores or shear walls; timber or other bio-based building envelopes combined with conventional frames; and reinforced concrete structures incorporating timber components (Table 1).

Hybrid building systems are not simply about replacing steel or concrete with timber, but about combining materials according to their functions within the building. The comparison of the four configurations shows how these different material roles are associated with specific benefits, limitations and design considerations.

The main benefits and design considerations differ across the four configurations. In steel–timber systems, CLT wall infills can improve lateral response, while timber floor solutions can reduce embodied carbon in selected designs. Their performance depends on connection behaviour, load transfer and diaphragm flexibility. In mass timber structures with RC cores or shear walls, the division of load-bearing and lateral-stability functions can support structurally efficient solutions with lower embodied carbon, but requires consideration of core stiffness, differential deformation and vibrations. Timber and other bio-based façade systems offer thermal and environmental benefits, although these depend on climate, moisture behaviour and the composition of the complete wall assembly. In RC-dominant systems, timber components can improve seismic response or reduce structural weight, provided that load transfer, the capacity of RC members and the connections between materials are adequately verified. Structural efficiency and prefabrication also emerge as recurring benefits across several configurations (Tables 2 and 4).

Engineered timber remains the principal bio-based structural material in the reviewed systems, particularly CLT, glulam and LVL. Other bio-based materials were identified in only seven studies and were used mainly for insulation, infill and building envelopes (Table 3). Their role in the reviewed applications is therefore generally complementary to the main load-bearing structure.

The performance of individual components does not necessarily reflect the performance of the complete building. A stiffer wall does not automatically ensure better seismic performance of the entire structure; a lighter floor may still experience excessive vibrations under walking loads; and the environmental advantage of a bio-based material can be reduced when additional supporting elements and layers are included. These findings highlight the importance of considering how different components interact within the complete building system.

Together, these findings provide a literature-based foundation for evaluating hybrid solutions during the early stages of building design. By linking the intended role of timber with the benefits and limitations identified for each configuration, the review helps designers compare alternative structural approaches and determine which performance requirements must be verified before selecting a solution (Table 4). Further research should focus on complete building systems, combining structural performance, fire safety, serviceability, durability, cost and life-cycle environmental impacts to develop more comprehensive design guidance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16214325/s1. Table S1. Characteristics of studies included in the systematic review; Table S2, Full-text records excluded from the systematic review and reasons for exclusion.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Search Strategy and Database Filters

The database search was conducted on 12 May 2026. Two Boolean search strings were used in both Web of Science and Scopus. Search 1 targeted hybrid timber-based systems combined with conventional materials; Search 2 targeted hybrid systems involving other bio-based materials and conventional counterparts.

Table A1. Search strings.

Search ID	Purpose	Boolean Search Expression
Search 1	Hybrid timber-based systems and conventional materials	(hybrid* OR “multi-material” OR “multi-materials” OR “mixed material” OR “mixed materials” OR “timber-concrete” OR “wood-concrete” OR “steel-timber” OR “timber-steel”) AND (“building system” OR “building systems” OR “structural system” OR “structural systems” OR “hybrid building” OR “hybrid buildings” OR “building element” OR “building elements” OR floor* OR slab* OR roof* OR wall* OR facade* OR façade* OR envelope*) AND (“mass timber” OR CLT OR “cross-laminated timber” OR “cross laminated timber” OR glulam OR “glued laminated timber” OR LVL OR “laminated veneer lumber” OR “engineered wood” OR timber) AND (concrete OR “reinforced concrete” OR steel OR masonry OR brick)
Search 2	Hybrid other bio-based systems and conventional materials	(hybrid* OR “multi-material” OR “multi-materials” OR “mixed material” OR “mixed materials”) AND (“building system” OR “building systems” OR “structural system” OR “structural systems” OR “hybrid building” OR “hybrid buildings” OR “building element” OR “building elements” OR floor* OR slab* OR roof* OR wall* OR facade* OR façade* OR frame* OR infill OR envelope OR insulation) AND (“bio-based” OR biobased OR “bio based” OR “plant-based” OR “natural fibre” OR “natural fiber” OR hemp OR hempcrete OR straw OR flax OR cork OR cellulose OR bamboo OR mycelium OR “sheep wool” OR “wood fibre” OR “wood fiber”) AND (concrete OR “reinforced concrete” OR steel OR masonry OR lime OR “mineral binder”) AND (building* OR construction)

Note: The expressions are reported as Boolean logic strings. Database-specific field tags and export settings were applied according to the fields reported in Table A2. The asterisk (*) is used as a wildcard to capture different word endings.

Table A2. Database-specific application and filters.

Database	Record Set	Search String	Search Field	Search Date	Applied Limits	Records Retrieved
Web of Science	WoS-1	Search 1	Topic	12 May 2026	Language: English; Document types: Article or Proceeding Paper; Web of Science categories: Engineering Civil and Construction Building Technology.	644
Web of Science	WoS-2	Search 2	Topic	12 May 2026	Language: English; Document types: Article or Proceeding Paper; Web of Science categories: Engineering Civil and Construction Building Technology.	124
Scopus	Scopus-1	Search 1	Title, abstract and keywords	12 May 2026	Subject areas: Engineering and Materials Science; Document types: Article or Conference Paper; Language: English.	1010
Scopus	Scopus-2	Search 2	Title, abstract and keywords	12 May 2026	Subject areas: Engineering and Materials Science; Document types: Article or Conference Paper; Language: English.	182

Note: Record counts are reported as recorded in the review protocol before deduplication. The full study selection process is reported in the PRISMA flow diagram in the main manuscript.

Appendix B. Coding Categories and Definitions

The coding framework was used to support the structured categorisation and frequency-based synthesis. Codes were non-exclusive where applicable; one study could therefore be assigned to more than one category. The table defines the coding categories used in the review and does not provide study-level coding records.

Table A3. Coding categories and definitions.

Coding Dimension	Category	Definition/Use in This Review
Study/evidence type	Numerical study	Study using numerical modelling, simulation or computational analysis as a main source of evidence.
	Experimental study	Study reporting laboratory, full-scale, quasi-static, dynamic, material, component or system testing.
	Case study	Study based on a realised or designed building, project, prototype or documented application.
	Design-oriented study	Study focused on design strategies, structural concepts, feasibility, detailing or configuration development.
	Comparative assessment	Study comparing two or more material, structural or design alternatives.
	Life-cycle assessment	Study reporting LCA, embodied carbon, GWP or related environmental performance indicators.
Main hybrid combination	Steel frame/bracing/ beams + timber-based components	Steel remains the primary framing, bracing, beam, or stability system; timber-based components are used for floors, walls, panels, roof elements, or other hybrid structural parts.
	Mass timber load-bearing structures + RC core/shear walls	Mass timber forms a major part of the load-bearing structure; reinforced concrete provides stability, stiffness, robustness or lower-level structural support.

Table A3. *Cont.*

Coding Dimension	Category	Definition/Use in This Review
	Timber/bio-based façade or envelope + conventional frame	A conventional frame is combined with timber-based or other bio-based façade, envelope, insulation, infill or external wall components.
	RC frame/core/shear walls + timber-based components	Reinforced concrete remains the main vertical or stability system; timber-based components are used in selected parts of the building.
Material group	CLT	Cross-laminated timber used as floor, wall, slab, infill, panel or horizontal load-transfer component.
	Other engineered timber	Glulam, LVL, PSL, mass timber or related engineered timber products used in beams, columns, frames, roof members or load-bearing systems.
	Light timber frame/OSB/wood-based panels	Light timber frame systems, oriented strand board or other wood-based panels used in shear walls, infill, façade panels, envelope systems or renovation modules.
	Non-timber bio-based materials	Bio-based materials other than timber, including hemp, straw, flax, cork, cellulose, bamboo, mycelium, sheep wool or related organic products.
	Steel	Steel used in frames, bracing, beams, plates, connectors, reinforcement or ductile lateral systems.
	Concrete layers	Concrete toppings, compression layers or slabs, mainly in timber-concrete composite floors or hybrid horizontal systems.
	Reinforced concrete	Reinforced concrete elements such as cores, shear walls, frames, foundations, podiums or other stability and load-bearing components.
	Mechanical fasteners/ steel connectors	Fasteners, plates, bolts, screws, pins or connector systems used to transfer forces between timber, steel and concrete components.
	Masonry	Brick, block or masonry components used as a conventional counterpart in selected hybrid wall or building configurations.
Reported benefit	Improved seismic behaviour	Reported improvement or favourable performance related to lateral, seismic, cyclic or dynamic behaviour.
	Structural efficiency	Reported improvement in structural performance, load-bearing efficiency, material efficiency or composite action.
	Prefabrication	Reported benefit related to off-site production, modularity, industrialised construction or simplified assembly.
	Lower GWP/embodied carbon	Reported reduction or favourable result related to global warming potential, embodied carbon or life-cycle environmental impact.
	Improved stiffness	Reported improvement in stiffness, lateral resistance or deformation control.
	Reduced weight	Reported reduction in structural weight, dead load or foundation demand.
	Faster construction	Reported reduction in construction time, assembly time or site operations.
	Thermal performance	Reported improvement in thermal resistance, thermal inertia, thermal comfort or heat-transfer behaviour.
	Energy efficiency/reduced operational energy	Reported reduction in operational energy demand or improvement in energy efficiency.

Table A3. *Cont.*

Coding Dimension	Category	Definition/Use in This Review
	Local availability	Reported benefit related to local material availability, regional supply chains or local sourcing.
Reported limitation	Connection complexity	Limitation related to connection design, detailing, force transfer, construction tolerances, modelling or constructability of interfaces.
	Seismic demand	Limitation related to high seismic actions, drift demand, lateral deformation or seismic design requirements.
	Design-code/regulatory uncertainty	Limitation related to design rules, standards, approvals, regulatory acceptance or lack of established design guidance.
	Data uncertainty	Limitation related to incomplete, inconsistent or unavailable technical, environmental, cost or performance data.
	Modelling uncertainty	Limitation related to modelling assumptions, simplifications, boundary conditions, validation or numerical uncertainty.
	Fire safety	Limitation related to fire resistance, charring, encapsulation, detailing, approval or fire design requirements.
	Vibration/serviceability	Limitation related to vibration, deflection, acoustic comfort or other serviceability requirements.
	Cost	Limitation related to material cost, construction cost, economic feasibility or market conditions.
	Moisture/durability	Limitation related to moisture sensitivity, biological degradation, durability, hygrothermal performance or long-term exposure.
	Scope limitation	Limitation indicating restricted study scope, simplified assumptions, narrow system boundary or limited set of investigated performance criteria.
	Scale limitation	Limitation related to small-scale testing, prototype scale, limited building scale or uncertain transferability to larger buildings.

Note: Study-level coding records, coding notes and full source mapping are retained as working records and are not included in this article.

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