Systematic Review

Sensor Applications in Mass Timber Buildings: A Comprehensive Review

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Mass timber is increasingly adopted as a sustainable construction material, closely aligned with circular economy principles that emphasize durability, resource efficiency, and extended service life. However, the structural and environmental performance of mass timber buildings remains strongly influenced by moisture exposure, environmental variability, and time-dependent material behavior, necessitating reliable monitoring strategies. This study presents a systematic review of sensor-based monitoring applications in mass timber buildings through a PRISMA-guided literature review combined with scientometric and thematic analyses. In total, 64 publications published between 2015 and 2025 were systematically examined to identify prevailing research trends, dominant sensing technologies, and primary application domains. The results reveal a rapidly expanding research landscape, with moisture monitoring and vibration-based Structural Health Monitoring (SHM) emerging as the most extensively investigated areas, particularly in cross-laminated timber systems. While a broad range of sensing technologies has been deployed, challenges related to sensor installation, calibration, environmental coupling, and data interpretation continue to limit cross-study comparability and large-scale implementation. The findings highlight the need for more standardized, integrated, and field-ready monitoring frameworks to support durability assessment, performance-based design, and lifecycle management of mass timber buildings.

Keywords: *mass timber, sensor, CLT, Cross Laminated Timber, SHM, monitoring, data logger, digital twin, GLT*

Introduction

The rising popularity of mass timber in construction has been substantially influenced by the growing awareness and application of Circular Economy (CE) principles, which prioritize sustainability and resource efficiency (Hasani and Riggio 2025). Over the past decade, the rising volume of mass timber projects, enabled by improved regulations and advances in fire safety and structural design, has accelerated interest and investment in sustainable construction practices, reinforcing timber's growing role within a circular economy framework (Abad et al. 2024; Nepal et al. 2024). In contrast to conventional construction materials, which typically demonstrate more uniform and predictable mechanical properties, mass timber, derived from a natural biological material, exhibits inherent variability and anisotropy, even when manufactured into engineered products such as Cross Laminated Timber (CLT) and glulam (GLT) ; Brandner et al. 2016; Grönquist et al. 2019). These inherent material characteristics introduce time-dependent and environment-sensitive performance variations, making long-term behavior less predictable and reinforcing the need for systems to track and manage durability and performance over time. Accordingly, a key strategy for supporting the environmental and economic sustainability goals inherent in circular economy frameworks, particularly in sectors such as mass timber construction where longevity and material reuse are prioritized, is the implementation of Structural Health Monitoring (SHM) systems. These systems enable ongoing assessment of structural performance and timely maintenance interventions that can extend service life and reduce resource consumption (Bocken et al. 2016; Payawal and Kim 2024; Wang and Ke 2024).

Over the past decade, SHM has gained increasing attention from both academic researchers and industry practitioners, driven by the rise of digital twins, smart buildings, and sustainability-driven performance metrics (Katam et al. 2023). The three pillars of sustainability are environmental, economic, and social, which also form the basis of the circular economy (Wang and Ke 2024). To achieve this, SHM encompasses a suite of strategies aimed at capturing and analyzing structural parameters, such as displacement, strain, acceleration, and vibration, under various loading and environmental conditions (Payawal and Kim 2024). In the context of mass timber construction, SHM is typically implemented through embedded or surface-mounted sensors that provide continuous or event-triggered data on moisture content, temperature, stress, and overall structural performance (Hnat et al. 2011; Riggio et al. 2019). This real-time information enables timely detection of integrity issues,

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facilitates proactive maintenance, and extends the service life of timber components, thereby slowing material flows and contributing to improved circular economy outcomes (Bocken et al. 2016). Advanced technologies, including distributed fiber-optic sensors, accelerometers, and moisture sensing systems, further support the calibration of analytical models, tracking of damage progression, and development of effective retrofit strategies (Golovastikov et al. 2025; Wang et al. 2020). As mass timber is increasingly deployed in more complex and large-scale applications, such monitoring remains essential for ensuring structural resilience, durability, and regulatory confidence.

Despite growing scholarly attention, there remains a limited consolidated understanding of the sensor technologies used in mass timber construction and how their applicability varies across monitoring scenarios. Accordingly, the objective of this study is to systematically review and synthesize sensor-based monitoring technologies used in mass timber buildings, with particular attention to sensor types, monitoring objectives, application domains, and their associated advantages and limitations. The study further examines how monitoring strategies vary across mass timber systems in order to identify dominant methodological patterns, research gaps, and practical considerations for effective sensor selection. To support methodological rigor and reproducibility, the review adopts a PRISMA-based approach to identify, screen, and select the relevant literature.

2 Method

To achieve the aims of this study, a Systematic Literature Review (SLR) methodology was employed, integrating scientometric analysis with qualitative thematic synthesis. Given the rapidly expanding and methodologically diverse literature on sensor-based monitoring in mass-timber structures, a comprehensive review is needed to develop a coherent understanding of the field. Accordingly, a scientometric analysis was conducted to provide a high-level overview of research growth, dominant themes, and frequently used sensor technologies. Building on this perspective, a qualitative thematic analysis was performed to organize the reviewed studies into coherent groups based on their primary monitoring objectives and sensor applications, thereby identifying the main application domains in mass-timber systems. These themes were then examined through representative use-case analyses to illustrate how they manifest in practical mass-timber monitoring scenarios. This approach is particularly appropriate for multidisciplinary domains such as mass timber monitoring, where sensor technologies, structural engineering, building science, and data analytics intersect.

Following established SLR protocols, the review process was designed to (1) comprehensively identify relevant studies, (2) filter them using objective screening rules, and (3) synthesize findings through both quantitative mapping and qualitative thematic analysis. The workflow aligns with PRISMA 2020 guidelines for systematic reviews, ensuring methodological transparency and replicability (Page et al. 2021).

2.1 Early Reviews

To situate this review within the current state of research, we begin by evaluating recent literature on SHM sensor technologies. Riggio and Dilmaghani (2020) provide an early, wide-ranging survey of SHM in timber buildings, reviewing studies across historic and contemporary structures. Their taxonomy, classifying SHM efforts by project scope, monitored phenomena, and measurement types, offers a useful foundation, though its relevance to modern engineered mass timber is limited by the period studied and the absence of contemporary system-scale challenges. While this early work establishes an important foundation, more recent reviews have shifted toward challenges unique to modern engineered mass timber systems.

In a more related study, Johns et al. (2024b) offer a state-of-the-art review explicitly targeting Moisture-Content (MC) monitoring in mass timber. Their analysis of sensor types, installation practices, and data acquisition for CLT and Glulam highlights MC measurement as a central determinant of long-term durability. They identify a lack of standardization across case studies and propose best-practice recommendations, positioning conductance-based sensing as the most reliable technique for in-situ monitoring. This review is technically detailed, though broader integration with structural performance monitoring could further strengthen its impact.

Building on this emphasis on moisture-related durability risks, Ayanleye et al. (2022) focus specifically on durability and protection strategies for mass timber systems such as CLT, Glulam, LVL, and MPP. Their review emphasizes moisture-driven degradation in tall mass timber applications and critically evaluates preservative treatments and modification techniques. However, the work also highlights unresolved issues, including the lack of standardized protection protocols and limited understanding of treatment compatibility with adhesives and manufacturing processes, key gaps for current practice.

While the above studies emphasize what needs to be monitored, another body of work focuses on how monitoring is achieved through sensing technologies. Mardanshahi et al. (2025) introduce a unified, multi-criteria evaluation framework for seven major SHM sensing families, including infrared thermography, strain sensing, electrochemical sensors, ultrasonic testing, visual inspection, vibration analysis, and acoustic emission. Their framework, organized around SHM suitability, signal characteristics, hardware requirements, feature sensitivity, and Digital Twin integration, offers a transparent basis for examining how each technology performs in terms of scalability, environmental robustness, feature richness, and readiness for real-time monitoring. However, although mass timber has gained significant traction in recent structural and infrastructure developments, the scope of this paper is limited to large-scale steel and concrete infrastructure, and mass timber is notably absent from the discussion.

Regarding monitoring technologies, Nasir et al. (2022) offer a focused critique of Acoustic Emission (AE) as a non-destructive evaluation method for wood and timber structures. They examine AE signal physics, propagation behavior in anisotropic wood materials, and practical limitations compared with other NDE methods such as infrared spectroscopy and stress-wave analysis. Their review identifies significant research gaps in signal processing, machine learning integration, and sensor fusion, areas that remain underdeveloped for mass timber applications and could benefit from additional recent citations if available.

2.2 Review Design and Scope

The scope of this review is restricted to sensor-based monitoring applications in mass timber buildings, with an emphasis on implemented sensing systems rather than conceptual or purely numerical studies. The review focuses on publications from 2015 to 2025, reflecting the period in which mass timber adoption and sensor-enabled monitoring matured into building-scale research and practice. Both journal articles and conference proceedings were included to capture emerging technologies and experimental studies that may not yet appear in archival journals, an approach commonly adopted in technology-driven systematic reviews (Snyder 2019). The overall review workflow follows the PRISMA guideline (Page et al. 2021) as illustrated in Figure 1.

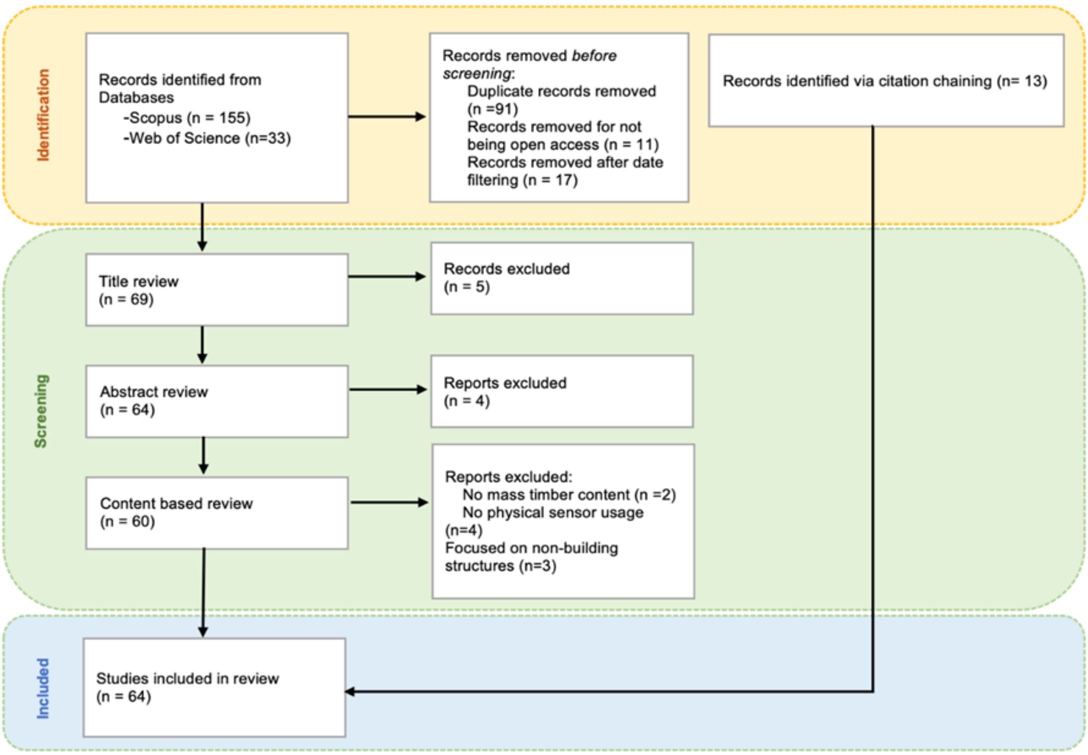

Figure 1 PRISMA diagram of the study selection process.

2.3 Preparation Stage: Search Strategy Development

The preparation stage established the search string, databases, and temporal boundaries of the review. Keyword selection followed an iterative process informed by 1) prior mass timber reviews, 2) pilot searches, and 3) domain expertise in structural health monitoring and building science. The finalized search query was:

((CLT) OR (cross laminated timber) OR (GLT) OR (glued laminated timber) OR (glue laminated timber) OR (mass timber)) AND ((monitoring) OR (sensor) OR (digital twin) OR (SHM) OR (data logger) OR (field study) OR (field experiment))

The first keyword group captures the dominant engineered timber systems used in contemporary practice, while the second ensures inclusion of studies involving in-situ sensing, real-time monitoring, or data-driven evaluation. Two major bibliographic databases were selected: 1) Scopus – searched using indexed keywords 2) Web of Science – searched using author keywords. These databases are widely acknowledged for their comprehensive coverage, citation tracking, and relevance in construction, structural engineering, and materials science research.

2.4 Identification Stage: Literature Retrieval

Database searches were conducted using the predefined search string without applying an initial publication-year filter. The search retrieved 155 records from Scopus and 33 records from Web of Science, resulting in a total of 188 publications.

Following the PRISMA identification stage, duplicate records (n = 91) were removed. Records without accessible full texts (n = 11) were excluded, as full-text availability was required for detailed analysis. Subsequently, publication-year filtering (2015–2025) was applied, resulting in the removal of additional records (n = 17). After these initial filtering steps, the remaining records were advanced to the screening stage.

2.5 Screening Stage: Inclusion and Exclusion Criteria

The screening phase applied both automated and manual review procedures, consistent with best practices in SLR research (Tranfield et al. 2003). A three-step screening process was implemented, consisting of title review, abstract review, and full-text content assessment.

During title screening, 5 publications were excluded due to lack of relevance to sensor-based monitoring in mass timber buildings. During abstract screening, 4 additional studies were excluded because they did not report implemented sensor systems or monitoring applications.

Each remaining paper was then assessed through full-text content review, where explicit exclusion criteria were applied. Publications were excluded if they:

- did not involve mass timber materials (n = 2)
- did not employ physical sensor systems (n = 4)
- focused on non-building infrastructure such as bridges or towers (n = 3)

After screening, 51 studies met all inclusion requirements. To reduce publication bias and capture influential work potentially missed by database indexing, 13 additional publications were included through backward citation chaining, an accepted enhancement to database-driven SLRs (Webster and Watson 2002). This resulted in a final dataset of 64 publications included in the analysis.

2.6 Scientometric Analysis

Scientometric analysis was conducted to quantitatively map research evolution, thematic density, and conceptual relationships within the selected literature. Publication trends were analyzed to identify growth patterns and periods of intensified scholarly focus. Analysis of keyword frequency and structural relationships enables identification of dominant themes and conceptual linkages within a research domain (Weismayer and Pezenka 2017). Keyword co-occurrence analysis was performed using VOSviewer (version 1.6.20), a widely adopted tool for bibliometric visualization and network analysis (Eck and Waltman 2009). Author-provided keywords were extracted and normalized to reduce variability caused by synonyms and spelling differences.

The co-occurrence network visualizes: 1) keyword frequency (node size), 2) strength of thematic linkage (edge thickness), and 3) thematic clusters (color coding). This analysis informed the identification of dominant research domains and guided the subsequent thematic classification of studies.

2.7 Thematic Analysis of Reviewed Studies

To synthesize the technical content of the selected studies beyond bibliometric mapping, this review employed Thematic Analysis (TA) as a structured qualitative synthesis method. Thematic analysis offers a flexible and robust framework for the identification, analysis, and interpretation of patterns of meaning within textual datasets and is well suited for systematic literature reviews that integrate heterogeneous methodologies and application contexts. In this study, the qualitative dataset consisted of the full texts of the 64 selected publications, including descriptions of sensor technologies, monitoring objectives, deployment strategies, and performance outcomes.

Data analysis was conducted using the six-phase reflexive thematic analysis framework (Braun & Clarke, 2006). Microsoft Excel served as the primary tool for data organization and coding, and all authors participated in the analytical process: (1) get familiarized with the data, (2) generate initial codes, (3) search for themes, (4) review the themes, (5) define and name the themes, and (6) report the results. Coding was conducted manually through systematic extraction of relevant text segments, assignment to initial codes, and iterative refinement through cross-study comparison until consistent themes were established. During the familiarization phase, each paper was read in full to develop a comprehensive understanding of its scope and technical focus. These codes captured meaningful text segments related to sensor types, monitored phenomena, data usage, and application objectives.

A hybrid deductive–inductive approach guided theme development. Deductive coding was informed by established performance domains in mass timber research, such as structural health monitoring, hygrothermal performance, structural strengthening, fire safety, and Indoor Environmental Quality, while inductive coding allowed additional patterns related to sensor deployment practices and use cases to emerge from the literature. In the subsequent phases, related codes were clustered into candidate themes and subsequently reviewed to ensure internal coherence within themes and clear distinction between themes.

In the final phases, themes were clearly defined, named, and organized into a coherent narrative structure. Although some studies addressed multiple monitoring domains, each publication was classified according to its dominant analytical focus to preserve conceptual clarity. This process resulted in five primary thematic categories that underpin the thematic analysis and use-case exploration presented in Section 4. The entire procedure was iterative and transparent, consistent with recommended practices for ensuring rigor and reliability in thematic analysis (Braun & Clarke 2006).

2.8 Use Cases

Following the scientometric and thematic analyses, a use-case analysis was conducted to further examine the identified thematic categories. Representative studies within each theme were selected to synthesize key findings and sensor applications, providing insight into how these themes are operationalized in mass-timber monitoring contexts. This approach explicitly connects thematic classifications to practical implementations and supports an application-oriented interpretation of the reviewed literature.

3 Scientometric Analysis

Scientometric analysis consists of systematic quantitative assessment of bibliographic records, citation networks, and keyword relationships to evaluate the structural dynamics, intellectual evolution, and research performance of a scientific domain over time (Hood and Wilson 2001; Raan 2006).

3.1 Publication Trends

Figure 2 illustrates the overall publication trend related to sensor applications in the mass timber industry from 2015 to 2025. Despite some year-to-year fluctuations, a general upward trajectory is evident, indicating a growing research interest in this domain. A significant surge occurred in 2023, where publication volume peaked. This increase coincides with intensified research activity in moisture and hygrothermal performance monitoring and structural health monitoring in mass timber systems. Outside of this notable peak, the trend demonstrates a steady increase over the years, underscoring the progressively widespread adoption of sensor technologies in mass timber research and practice.

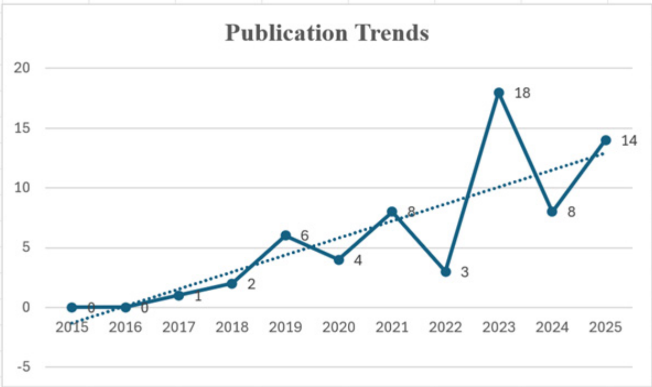

Figure 2 Publication Trends

3.2 Keyword Co-Occurrence Mapping

Keyword co-occurrence analysis plays a pivotal role in this study by revealing the core thematic structure of the reviewed literature. Figure 3 illustrates a keyword co-occurrence analysis used to identify the inclusive thematic areas related to sensor applications in mass timber research. The thickness of the connecting lines indicates the strength of the co-occurrence between keywords. The size of each keyword reflects its frequency of occurrence within the analyzed literature. Central research foci are represented by prominent terms such as "mass timber," "laminated timber," "moisture," and "structural health monitoring". Alongside dominant themes like "structural health monitoring" and "moisture monitoring," the prominence of keywords such as "modal analysis" and "stress analysis" highlights additional focal points in the academic discourse on sensor integration in mass timber systems.

3.3 Sensor Technologies for Monitoring Mass Timber Buildings

This section presents a synthesis of sensor technologies identified in the reviewed literature, examining their measurement principles, deployment contexts, and practical limitations in mass timber buildings. To better introduce the scope of this study, a sensor is defined as a physical device that detects or measures a physical, environmental, or mechanical phenomenon and converts it into a quantifiable electrical or digital signal that can be recorded and analyzed (Abdulhussain et al. 2025; Fraden 2004; Javaid et al. 2021). Accordingly, the sensor-centric synthesis presented in this section includes only primary sensing devices that directly transduce physical phenomena (e.g., moisture, temperature, strain, displacement, acceleration, airflow, or heat flux), and excludes downstream data acquisition systems, control hardware, or analytical software unless explicitly treated as sensing elements in the original studies.

Across the studies, a wide range of sensing technologies were

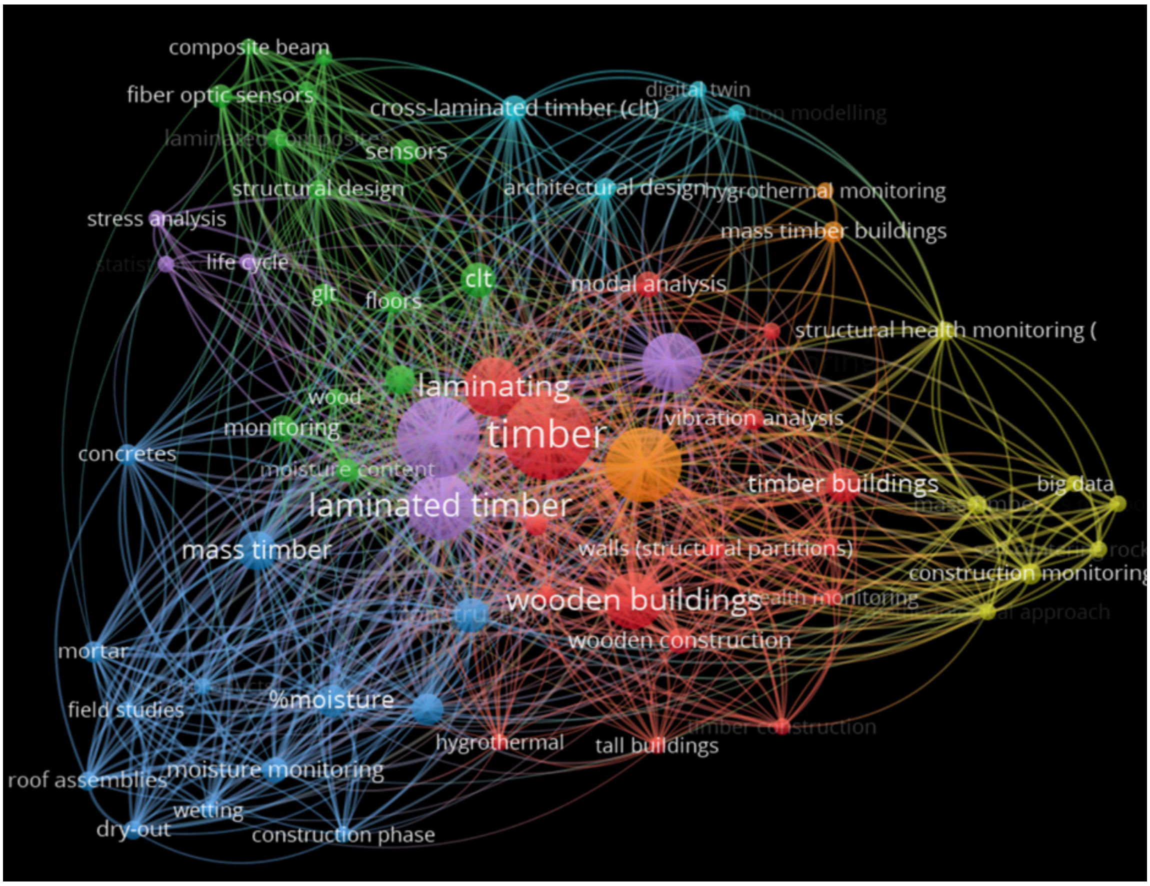

Figure 3 Keywords Co-Occurrence

adopted to capture structural, hygrothermal, environmental, and fire-related responses at both component and building scales. This sensor-centric synthesis provides the technical foundation for the subsequent section, which reframes the same evidence around use cases and performance objectives. To provide a structured overview of sensing technologies reported in the reviewed literature, Table 1 summarizes sensor types, underlying measurement technologies, and representative references, serving as a technical map for the sensor-specific discussions that follow. Some monitoring setups consist of individually installed single-parameter sensors, while others integrate multiple measurements within a single device. In Table 1, we prioritize

Table 1 Overview of sensor technologies used in mass-timber buildings

Sensor Type	Technology	References
Moisture		(Riggio et al. 2019), (Longman et al. 2023), (Baas et al. 2021b), (Baas et al. 2021a), (Wang et al. 2025), (Aloisio et al. 2025), (Greffier et al. 2024), (Fast et al. 2017), (Flexeder et al. 2021), (Schmidt et al. 2019), (O'Brien et al. 2025), (Strang et al. 2023), (Civera et al. 2025), (Coelho et al. 2024), (Zelinka et al. 2018), (Schmidt and Riggio 2019), (Flexeder et al. 2022), (Tamagnone et al. 2023), (Riggio et al. 2023), (Shirmohammadi et al. 2025), (Humar et al. 2020), (Pei et al. 2021), (Poblete et al. 2022), (Imamura et al. 2024), (Olsson 2021), (Johns et al. 2024a), (Johns and Richman 2025), (Kotlarewski et al. 2025), (Stolze et al. 2021), (Zanni et al. 2023)
Temperature	Thermistors	(Riggio et al. 2019), (Longman et al. 2023), (Baas et al. 2021b), (Baas et al. 2021a), (Schmidt and Riggio 2019), (Schmidt et al. 2019)
	Thermocouples	(Greffier et al. 2024), (Imamura et al. 2025), (Imamura et al. 2024), (Hwang et al. 2022), (Pope et al. 2023), (Koklas et al. 2023)
	RTD	(Flexeder et al. 2021)
	Other / Integrated / Unspecified	(Jockwer et al. 2021), (Greffier et al. 2024), (Zhang et al. 2024), (Wang et al. 2025), (Aloisio et al. 2025), (Humar et al. 2020), (Adekunle 2020), (Olsson 2021), (Stolze et al. 2021), (Johns and Richman 2025), (Flexeder et al. 2022), (Tamagnone et al. 2023), (Riggio et al. 2023), (Shirmohammadi et al. 2025), (Coelho et al. 2024), (Strang et al. 2023), (O'Brien et al. 2025), (Sciomenta et al. 2023), (Johns et al. 2024a)
RH		(Longman et al. 2023), (Baas et al. 2021b), (Baas et al. 2021a), (Wang et al. 2025), (Aloisio et al. 2025), (Aloisio et al. 2023), (Zhang et al. 2024), (O'Brien et al. 2025), (Strang et al. 2023), (Coelho et al. 2024), (Flexeder et al. 2022), (Tamagnone et al. 2023), (Riggio et al. 2023), (Shirmohammadi et al. 2025), (Imamura et al. 2025), (Humar et al. 2020), (Adekunle 2020), (Imamura et al. 2024), (Olsson 2021), (Johns and Richman 2025), (Flexeder et al. 2021), (Stenson et al. 2019), (Hwang et al. 2022), (Stolze et al. 2021), (Sciomenta et al. 2023), (Greffier et al. 2024), (Johns et al. 2024a)
Weather Station		(Riggio et al. 2019), (Baas et al. 2021b), (Baas et al. 2021a), (Janot et al. 2024), (O'Brien et al. 2025), (Coelho et al. 2024), (Schmidt and Riggio 2019), (Tamagnone et al. 2023), (Riggio et al. 2023), (Zanni et al. 2023), (Aloisio et al. 2025)
Potentiometer	String	(Baas et al. 2021b), (Baas et al. 2021a), (Fast et al. 2017), (Deeves and Woods 2025), (Longman et al. 2023), (Hwang et al. 2022)
	Linear	(Čápová et al. 2020), (Goodwin and Woods 2025), (Deeves and Woods 2025), (Ernewein and Woods 2023), (Sciomenta et al. 2023)
LVDT		(Zhang et al. 2024), (Schmidt et al. 2019), (Imamura et al. 2025), (Masoudnia et al. 2018)
Strain	Distributed Fiber Optic Sensor	(Jockwer et al. 2021), (Münzer and Dill-Langer 2023), (Goodwin and Woods 2025), (Frohnmüller et al. 2023), (Deeves and Woods 2025), (Ernewein and Woods 2023)
	Electrical Resistance	(Greffier et al. 2024), (Münzer and Dill-Langer 2023), (Imamura et al. 2025), (Čápová et al. 2020)
	FBG	(Čápová et al. 2020)
Load Cell		(Baas et al. 2021b), (Baas et al. 2021a), (Schmidt et al. 2019), (Goodwin and Woods 2025), (Deeves and Woods 2025), (Ernewein and Woods 2023), (Longman et al. 2023), (Frohnmüller et al. 2023)

Table 1 Continued Overview of sensor technologies used in mass-timber buildings

Accelerometer	Ceramic shear piezoelectric (PCB Piezotronics/ICP)	(Kurent et al. 2024), (Wang et al. 2025), (Aloisio et al. 2025), (Amaddeo et al. 2025), (Guo et al. 2025), (Opazo-Vega et al. 2023), (Jara-Cisterna et al. 2025), (Mugabo et al. 2019a), (Stenson et al. 2019),
	Piezoelectric	(Tamagnone et al. 2023)
	Force-balance accelerometers (FBA)	(Aloisio et al. 2023), (Ao et al. 2023)
	MEMS	(Ao et al. 2023), (Jara-Cisterna et al. 2025)
	Capacitive	(Peña-Lasso et al. 2020)
	Other/Unspecificed	(Fast et al. 2017), (Zanni et al. 2023), (Longman et al. 2023), (Mugabo et al. 2019b), (Zhang et al. 2024), (Genç et al. 2021)(Wang et al. 2023)
Velocimeter	Electrodynamic	(Janot et al. 2024), (Miyazu and Loss 2023)
PZT Transducers	Stress Wave	(Gao et al. 2022), (Chen et al. 2023)
AE		(Manthei et al. 2024), (He and Zhu 2024)
Extensometer		(Čápová et al. 2020), (Ernewein and Woods 2023)
Anemometer	Ultrasonic	(Wang et al. 2025), (Aloisio et al. 2025),
Air Velocity	pressure-based	(Pope et al. 2023), (Koklas et al. 2023), (Stenson et al. 2019), (Adekunle 2020), (Coelho et al. 2024), (Flexeder et al. 2021)
Air Quality / Gas Monitoring Sensors		(Stenson et al. 2019), (Flexeder et al. 2021), (Coelho et al. 2024), (Humar et al. 2020), (Adekunle 2020), (Koklas et al. 2023)
Heat Flux		(Pope et al. 2023), (Koklas et al. 2023), (Flexeder et al. 2021), (Longman et al. 2023)

distinct sensor types and include multi-parameter devices only where relevant to the focus of this review.

3.3.1 Moisture

Electrical resistance–based pin-type moisture sensors are commonly used for in-situ monitoring of moisture content in mass-timber elements (Baas et al. 2021a; b; Fast et al. 2017; Johns et al. 2024a; Riggio et al. 2019). Across laboratory, field, and long-term monitoring studies, authors consistently report limitations including reduced accuracy above the fiber saturation point, species-dependent calibration uncertainty, temperature sensitivity requiring correction, probe–wood contact instability, electrical noise and short-circuiting under liquid water exposure, installation damage, sensor failure and data loss, restricted measurement range, and the inherently localized, one-dimensional nature of point measurements that cannot capture multidimensional moisture transport (Flexeder et al. 2022; Humar et al. 2020; Imamura et al. 2024; Johns et al. 2024a; Johns and Richman 2025; O'Brien et al. 2025; Olsson 2021; Pei et al. 2021; Riggio et al. 2023; Schmidt and Riggio 2019; Shirmohammadi et al. 2025; Strang et al. 2023; Zelinka et al. 2018).

3.3.2 Temperature

In mass-timber monitoring, thermistors are used to temperature-correct resistance-based moisture readings, though delayed availability of temperature data and reliance on species-based correction factors and manufacturer calibration can introduce systematic offsets and uncertainty in MC estimates (Riggio et al. 2019; Schmidt and Riggio 2019). In compartment fire testing, thermocouples are subject to reported uncertainties related to calibration, signal conversion, and extension wiring (Koklas et al. 2023), as well as sensor diameter effects, radiative influence resulting from the absence of radiation correction, and potential failure at very high temperatures (Pope et al. 2023). RTD-based monitoring further shows that in-situ reliability depends strongly on installation and environmental conditions in addition to specified sensor accuracy (Flexeder et al. 2021).

3.3.3 Relative Humidity

Across mass-timber monitoring studies, RH is almost always measured together with temperature, typically via integrated thermo-hygrometers and, in some cases, combined with electrical-resistance moisture-content sensing. RH–T data are used both to characterize ambient or boundary climates and to infer in-wood equilibrium moisture content or mould risk, with most reported challenges stemming from equilibrium assumptions, sorption hysteresis, hygroscopic buffering, sensor placement, and temporal lag, while a smaller number of studies also note calibration drift and temperature sensitivity in RH hardware (Flexeder et al. 2022; Hwang et al. 2022; Imamura et al. 2024, 2025; Shirmohammadi et al. 2025).

3.3.4 Weather Station

Weather stations are commonly used to provide outdoor boundary conditions in mass-timber monitoring studies, but reported limitations relate to data gaps and representativeness. Several studies noted the need to supplement missing records with nearby stations or external sources, introducing spatial uncertainty (Baas et al. 2021a; b; O'Brien et al. 2025; Schmidt and Riggio 2019). Additionally, outdoor macroclimate measurements may not fully capture localized or rapidly changing microclimatic conditions during construction (Baas et al. 2021a).

3.3.5 Potentiometer

Linear and string potentiometers are commonly used in mass-timber studies to measure deflection and slip at laboratory and building scales. In laboratory tests, linear potentiometers can exhibit distorted early load–displacement responses if specimens are not preloaded due to seating or stabilization effects (Deeves and Woods 2025). In field monitoring, string potentiometers are suitable for large-scale displacement tracking but are sensitive to environmental conditions and construction effects, requiring post-processing and careful interpretation (Baas et al. 2021a; b).

3.3.6 LVDT

Linear Variable Differential Transformers (LVDTs) are commonly used in mass timber studies to monitor structural response. Imamura et al. (2025) report several practical limitations, including sensitivity to alignment, expansion and contraction of mounting components that may introduce apparent movement, reliance on stable reference configurations, and delayed installation that can restrict interpretation of early-stage behavior. In addition, single-point measurement layouts may limit assessment of spatial variability and inter-panel effects within floor systems (Zhang et al. 2024).

3.3.7 Strain

Strain sensing in mass-timber research commonly relies on distributed fiber optic sensors (DFOS), conventional electrical resistance strain gauges, and fiber Bragg grating (FBG) sensors. DFOS provide continuous, high-resolution strain measurements, but their application is constrained by installation-related vulnerabilities, including cable damage, fiber fragility, and slip in high strain zones, which can reduce data continuity and accuracy (Ernewein and Woods 2023; Jockwer et al. 2021).In timber structures, interpretation is further complicated by material heterogeneity, environmental effects (moisture, temperature, creep), and sensitivity to fiber placement that may produce apparent strain discontinuities (Deeves and Woods 2025; Münzer and Dill-Langer 2023).

Electrical resistance strain gauges are widely used for localized strain measurement; however, they are constrained by installation and positioning limitations in timber joints (Greffier et al. 2024) and by sensitivity to temperature variation and lead-wire length, which require calibration and correction for accurate interpretation (Imamura et al. 2025). FBG sensors enable multiplexed point strain monitoring with good agreement to reference measurements, but they measure only at discrete locations and require careful installation because the fibers can be fragile and susceptible to mechanical damage (Čápová et al. 2020).

3.3.8 Load Cells

Load cells have been used in mass-timber research for both construction-phase monitoring and laboratory-based measurements. Reported limitations include sensitivity to environmental fluctuations, creep of axially loaded timber, load-bearing distribution effects at the timber–sensor interface, and data gaps caused by temporary power supply interruptions (Baas et al. 2021a), as well as temperature-induced measurement drift requiring thermal correction (Schmidt et al. 2019).

3.3.9 Accelerometer

Vibration monitoring of mass-timber and glulam structures has employed a range of accelerometer technologies, including capacitive, MEMS, force-balance, and piezoelectric accelerometers. Capacitive accelerometers have been used in laboratory vibration testing of glulam components (Peña-Lasso et al. 2020), while force-balance accelerometers have been applied in long-term ambient vibration monitoring of large structures (Aloisio et al. 2023). MEMS accelerometers have been used for continuous monitoring with low-cost instrumentation (Jara-Cisterna et al. 2025), and they have also been deployed alongside force-balance accelerometers in CLT building testing (Ao et al. 2023). Piezoelectric accelerometers are consistently treated as reliable reference instruments for ambient vibration monitoring of CLT buildings and floors (Kurent et al. 2024).

3.3.10 Velocimeter

Velocity sensors are used in mass-timber vibration studies for ambient and human-powered excitation testing to capture low-amplitude building response. While they are applied for modal identification, one study reports that a sensor record exceeded the measurable amplitude range during human-powered excitation, and the affected data were excluded from the dataset (Miyazu and Loss 2023).

3.3.11 PZT Transducer

Piezoceramic (PZT) wafers have been used in mass-timber research to monitor connection behavior, providing a low-cost, sensitive, and non-destructive approach for detecting stiffness changes and localized joint damage (Chen et al. 2023; Gao et al. 2022). Reported limitations include reliance on intact-state baseline signals in traditional PZT approaches (Chen et al. 2023) and limitations of conventional PZT-enabled active sensing for stage monitoring under reciprocating loading, motivating machine-learning–based approaches (Gao et al. 2022).

3.3.12 AE

Acoustic emission (AE) sensing has been applied in mass-timber research to monitor internal damage using surface-mounted sensor networks. Manthei et al. (2024) note that AE source localization in CLT is complicated by complex geometry and direction-dependent wave velocity. He and Zhu (2024) further show that anisotropy, heterogeneity, and wave reflections in layered engineered wood complicate localization and arrival-time interpretation, motivating machine-learning–based approaches.

3.3.13 Extensometer

Mechanical clip-on extensometers have been used as reference instruments in laboratory testing to measure strain over a defined gauge length and to support comparison with fiber-optic sensing data in timber beam experiments (Čápová et al. 2020).

3.3.14 Ultrasonic Anemometer

Ultrasonic anemometers were used in rooftop weather stations to measure outdoor wind speed and direction during long-term monitoring of multi-story CLT buildings (Aloisio et al. 2025; Wang et al. 2025).

3.3.15 Air Velocity

Air-velocity sensors, including bi-directional probes and

Pitot-static tubes, are used in mass-timber fire experiments to measure opening inflow and outflow and characterize ventilation conditions (Koklas et al. 2023; Pope et al. 2023). However, these pressure-based devices may exhibit reduced reliability at low velocities and near the neutral plane, requiring cautious interpretation and supporting measurements (Pope et al. 2023).

3.3.16 Air Quality

Air-quality monitoring in mass-timber buildings primarily relies on CO^2 sensing to assess occupancy and ventilation (Adekunle 2020; Flexeder et al. 2021; Humar et al. 2020; Stenson et al. 2019), with some studies also measuring VOC/TVOC concentrations(Coelho et al. 2024; Flexeder et al. 2021; Stenson et al. 2019). Reported limitations show that gas concentrations are influenced by ventilation operation(Humar et al. 2020; Stenson et al. 2019) and occupancy-related disturbances (Flexeder et al. 2021), while VOC attribution is complicated by multiple sources and secondary reactions (Stenson et al. 2019). Fixed-location measurements may also limit spatial representativeness (Adekunle 2020; Humar et al. 2020).

3.3.17 Heat flux

Heat-flux measurements in mass-timber fire experiments provide important insight into thermal exposure but require careful interpretation. In fully developed compartment fires, thin-skin calorimeters are primarily sensitive to radiative heat transfer and exhibit increased uncertainty when convective contributions are significant (Pope et al. 2023).

3.4 Temporal Distribution of Sensor Technologies

To complement the qualitative assessment of individual sensor technologies, Table 2 presents a temporal overview of sensor adoption across the reviewed literature from 2015 to 2025. The distribution illustrates a clear expansion in monitoring scope over time, with early studies relying primarily on moisture, temperature, and basic displacement sensing, followed by increasing diversification toward environmental, mechanical, and dynamic sensing technologies. In particular, the growing adoption

Table 2 Temporal distribution of sensor technologies in mass timber monitoring studies (2015–2025).

Sensor/Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Moisture			1	1	3	1	6	2	5	4	7
Thermistors					3		2		1		
Thermocouples								1	2	2	1
RTD							1				
Other Temp						2	3	1	4	4	5
RH					1	2	5	2	5	5	5
Weather Station					2		2		3	2	2
String Potentiometer			1				2	1	1		1
Linear Potentiometer						1			2		2
LVDT				1	1					1	1
DFOS							1		3		2
Electrical resistance						1			1	1	1
FBG						1					
Load Cell					1		2		3		2
Piezoelectric					2				2	1	5
FBA									2		
MEMS									1		1
Capacitive						1					
Other Accelerometer			1		1		1		3	1	
Velocimeter									1	1	
PZT Transducers								1	1		
AE										2	
Extensometer						1			1		
Anemometer											2
Air velocity					1	1	1		2	1	
Air Quality					1	2	1		1	1	
Heat flux							1		3		
Overall	0	0	3	2	16	13	28	8	47	26	37

of structural and dynamic sensing systems, including distributed fiber-optic sensing (DFOS), capacitive strain sensors, load cells, accelerometers, and especially piezoelectric sensors, reflects a rising emphasis on structural response and vibration-based assessment in recent mass-timber research. At the same time, the continued prevalence of moisture and hygrothermal monitoring indicates that environmental exposure and moisture-related risks continue to receive attention comparable to long-term, multi-physics monitoring approaches in mass-timber buildings. This temporal perspective highlights the progressive maturation of sensing strategies in the field and provides quantitative context for the sensor-specific discussions presented in this section.

4 Use Cases: Mass Timber Performance Improvement

This section presents a case-based synthesis of the studies identified through the systematic literature review, focusing on how sensor technologies are applied and evaluated in real mass timber projects. Each selected study was examined in detail to assess its methodological approach, sensing strategy, monitoring context, and reported outcomes. This evaluation enabled a critical interpretation of common practices, recurring challenges, and technical contributions across both laboratory experiments and field-scale case studies.

To structure the analysis, the reviewed case studies were grouped into five primary thematic domains: (1) SHM and Dynamic Behavior, (2) Moisture Monitoring and Hygrothermal Performance, (3) Structural Strengthening and Retrofit Evaluation, (4) Fire Dynamics and Compartment Behavior, and (5) Indoor Environmental Quality and Comfort. Each domain reflects a distinct performance objective frequently addressed through sensor deployment in mass timber research and practice. Table 3 provides an overview of these domains and lists the associated studies grouped under each category, illustrating the distribution and breadth of research across the identified themes. Several case studies addressed multiple performance domains through integrated monitoring strategies. Because many studies could reasonably fall into more than one category, we assigned each reference to the domain that best matched the primary monitoring objective based on our interpretation of the work. This classification approach enabled a focused analysis of sensor use and performance within each domain while preserving clarity across overlapping applications.

4.1 SHM and Dynamic Behavior

SHM is widely applied to track the evolution of modal properties in mass-timber and hybrid structures under real service and environmental conditions. Early building-scale studies described the implementation of accelerometers, moisture meters, and displacement sensors to monitor in-situ damping, column

Table 3 Case studies categorized by monitoring domain

Category	Reference
SHM and Dynamic Behavior	(Aloisio et al. 2023, 2025; Amaddeo et al. 2025; Ao et al. 2023; Baas et al. 2021a; b; Čápová et al. 2020; Chen et al. 2023; Civera et al. 2025; Fast et al. 2017; Frohnmüller et al. 2023; Gao et al. 2022; Genç et al. 2021; Guo et al. 2025; He and Zhu 2024; Janot et al. 2024; Jara-Cisterna et al. 2025; Kurent et al. 2024; Longman et al. 2023; Manthei et al. 2024; Miyazu and Loss 2023; Mugabo et al. 2019b; a; Münzer and Dill-Langer 2023; Opazo-Vega et al. 2023; Peña-Lasso et al. 2020; Sciomenta et al. 2023; Wang et al. 2023, 2025; Zhang et al. 2024)
Moisture Monitoring and Hygrothermal Performance	(Coelho et al. 2024; Flexeder et al. 2021, 2022; Greffier et al. 2024; Humar et al. 2020; Hwang et al. 2022; Imamura et al. 2024, 2025; Jockwer et al. 2021; Johns et al. 2024a; Johns and Richman 2025; Kotlarewski et al. 2025; O'Brien et al. 2025; Olsson 2021; Pei et al. 2021; Poblete et al. 2022; Riggio et al. 2019, 2023; Schmidt et al. 2019; Schmidt and Riggio 2019; Shirmohammadi et al. 2025; Stolze et al. 2021; Strang et al. 2023; Tamagnone et al. 2023; Zelinka et al. 2018)
Structural Strengthening and Retrofit Evaluation	(Deeves and Woods 2025; Ernewein and Woods 2023; Goodwin and Woods 2025; Masoudnia et al. 2018; Zanni et al. 2023)
Fire Dynamics and Compartment Behavior	(Koklas et al. 2023; Pope et al. 2023)
Indoor Environmental Quality and Comfort	(Adekunle 2020; Stenson et al. 2019)

shortening, and moisture-related effects in a tall hybrid timber building (Fast et al. 2017). At the member scale, vibration-based investigations of glulam and CLT beams show that localized damage such as cracking or stiffness degradation produces measurable changes in natural frequencies and mode shapes, supporting vibration response as a reliable indicator for damage detection in timber components (Genç et al. 2021; Peña-Lasso et al. 2020).

At the building-system scale, ambient-vibration studies show that global modal properties vary during construction and move-in phases and with added mass and finishing works (Janot et al. 2024), while decade-scale remeasurements in completed CLT buildings indicate broadly stable modal characteristics over time (Amaddeo et al. 2025). Ambient testing also provides benchmark modal datasets, and modeling demonstrates that exterior wall cladding and glazing can significantly influence modal response at ambient excitation levels, supporting repeated modal identification as an SHM baseline (Mugabo et al. 2019a). Sciomenta et al. (2023) combined in-field load testing and thermal imaging to document moisture presence and associated stiffness loss in CLT floors and proposed a vibration-based diagnostic protocol relying on professional and Bluetooth accelerometers for future implementation. Related studies show that support stiffness and beam-supported configurations significantly influence system-level modal behavior in mass-timber floors (Guo et al. 2025).

With the growth of continuous monitoring, research increasingly highlights environmental and time-dependent effects. Long-term studies show that temperature drives seasonal frequency variations (Aloisio et al. 2023), that moisture-related variables significantly influence modal properties (Civera et al. 2025), and that creep under sustained loading alters dynamic characteristics over time (Zhang et al. 2024). Extreme-event monitoring shows temporary reductions in fundamental frequencies during seismic loading, followed by recovery to initial values (Jara-Cisterna et al. 2025). Additional studies have advanced modal identification and validation through forced excitation with synchronized sensing (Ao et al. 2023), Bayesian model updating (Kurent et al. 2024), long-term automated modal tracking with data-driven analysis (Wang et al. 2025), and open vibration datasets from a tall timber–concrete hybrid building for benchmarking (Miyazu and Loss 2023).

Recent SHM studies employ distributed fiber-optic sensing (DFOS) and acoustic emission (AE) to assess damage in engineered timber systems. DFOS provides spatially resolved strain measurements, enabling detection of localized strain irregularities in glulam members and monitoring of bond integrity and shear transfer in adhesively bonded timber–concrete composite elements (Frohnmüller et al. 2023; Münzer and Dill-Langer 2023). AE monitoring captures damage-related activity during loading, interpreted as associated with cracking and screw-connection regions in CLT–steel composite beams (Manthei et al. 2024). At CLT connections, PZT-based active sensing combined with machine learning can classify elastic, yielding, and failure stages, with performance influenced by sensor placement and feature selection (Chen et al. 2023; Gao et al. 2022). Data-driven methods enable localization using different modalities: machine-learning analysis of AE signals supports 2D source localization in an LVL plate (He and Zhu 2024), while time-series analysis of vibration-response data supports damage identification and localization in a large-span timber lattice shell system (Wang et al. 2023).

Finally, integrated SHM frameworks combining hygrothermal sensors, mechanical measurements, and weather data enable environmental correction of measured responses and tracking of conditions such as post-tensioning force loss and localized wetting during construction (Baas et al. 2021a; b). Digital-twin–based monitoring highlights the importance of accounting for hygrothermal conditions in mass-timber systems by linking temperature and moisture measurements with structural response data (Longman et al. 2023).

4.2 Moisture Monitoring and Hygrothermal Performance

This category synthesizes studies examining how mass-timber systems, primarily CLT and glulam, respond to moisture exposure during construction and service. Across the literature, sensor-based monitoring combined with hygrothermal modeling has been used to assess risks related to decay, deformation, and stiffness evolution, and to validate durability-oriented design strategies.

Field monitoring shows that CLT elements can be exposed to precipitation during construction, with case studies reporting elevated or highly variable moisture content when weather protection is limited (Olsson 2021; Zelinka et al. 2018). Detailed measurements further indicate that moisture-trapping details, particularly at edges and connections, tend to dry more slowly and can develop persistent moisture gradients, including slower drying in interior plies (Schmidt and Riggio 2019). Roof studies highlight the importance of construction exposure protection, air/ventilation layers, and membrane permeability for promoting dry-out, and they show that CLT end-grain/edge regions remain particularly vulnerable to moisture uptake and slower drying (Johns et al. 2024a; Johns and Richman 2025).

Studies on hybrid timber–concrete slabs show that concrete placement can affect dimensional response (Hwang et al. 2022), while moisture uptake after capping depends on the hybrid interface and exposure conditions (Kotlarewski et al. 2025). Monitoring of below-grade CLT assemblies further indicates that internal moisture sources, drainage performance, and heating conditions affect moisture levels and mould-growth risk (Imamura et al. 2024). Moisture gradients and climate-driven moisture changes can generate swelling–shrinkage stresses between laminated layers and promote delamination; in glulam, joint-strength loss may occur even without clear surface indicators (Greffier et al. 2024; Stolze et al. 2021).

Seasonal relative-humidity variations drive continued mechano-sorptive strain in timber members (Jockwer et al. 2021), while indoor monitoring studies show that temperature and relative humidity patterns are reflected in measured wood moisture-content trends (Humar et al. 2020). Long-term monitoring of an eight-story mass timber building reported that construction-phase moisture exposure was associated with elevated wood moisture contents that decreased after enclosure as drying progressed (Pei et al. 2021).

Recent studies combine field monitoring of temperature, relative humidity, and moisture content with calibrated hygrothermal simulations to evaluate moisture performance and mold risk under real or experimentally tested conditions (O'Brien et al. 2025; Shirmohammadi et al. 2025; Strang et al. 2023). Coelho et al. (2024) outline workflows integrating WUFI-based tools with whole-building and HAM modeling for hygrothermal and energy assessment. The monitored case studies analyze exterior wall assemblies with water-resistive barriers and ventilated cavities to assess drying behavior, moisture risk, and the effects of construction-phase exposure and assembly design (O'Brien et al. 2025; Shirmohammadi et al. 2025; Strang et al. 2023).

4.3 Structural Strengthening and Retrofit Evaluation

Research in this category examines how strengthening and retrofit interventions improve the mechanical performance of mass-timber systems, with monitoring tools used to quantify changes in stiffness, strength, and deformation under service or loading conditions. Early studies focused on mobilizing composite action within timber systems, showing that fastening CLT panels to LVL beams can enhance flexural performance by engaging the slab as an effective flange (Masoudnia et al. 2018). At the connection scale, Ernewein and Woods (2023) employed distributed fiber-optic strain sensing (DFOS) to measure full strain profiles along glued-in steel rods and the adhesive interface, enabling inference of stress/force transfer and characterization of bond–slip behavior and localized response.

More recent work has explored hybrid and externally bonded strengthening strategies. Deeves and Woods (2025) experimentally evaluated CLT–steel composite beams using post-installed self-tapping screw connections, with and without adhesive, and instrumented the specimens with distributed fiber optic strain sensors to obtain high-resolution strain distributions and evaluate composite action. Similarly, Goodwin and Woods (2025) showed that externally bonded FRP systems substantially increase the strength and ductility of glulam beams, with DFOS measurements revealing detailed strain distributions, interfacial strain-transfer behavior, and failure mechanisms critical for validating retrofit performance.

At the building scale, Zanni et al. (2023) proposed a prefabricated CLT exoskeleton retrofit for existing masonry buildings, combining seismic strengthening, energy upgrading, and functional improvements. Their use of embedded structural, moisture, and environmental monitoring enabled continuous assessment of both mechanical and hygrothermal performance, illustrating an integrated approach to mass-timber retrofit evaluation.

4.4 Fire Dynamics and Compartment Behavior

Research in this category shows that exposed mass-timber surfaces contribute additional combustible fuel in compartment fires, leading to increased heat flux and more heterogeneous temperature distributions. Experimental studies report higher in-compartment heat fluxes and greater spatial temperature variability when CLT surfaces are exposed, underscoring the need to account for timber contribution in performance-based fire design (Koklas et al. 2023; Pope et al. 2023).

4.5 Indoor Environmental Quality and Comfort

Indoor environmental quality (IEQ) in mass-timber buildings includes indoor air quality and thermal comfort, as defined in building IEQ literature (Stenson et al. 2019). Field measurements in a CLT school building indicate that mean indoor temperatures during the cold season were generally within ASHRAE comfort-temperature thresholds (Adekunle 2020). In an occupied mass-timber office building, CO^2 levels reflected occupancy and ventilation performance, and some measured pollutants, including formaldehyde and monoterpenes, were higher in spaces with little or no mechanical ventilation (Stenson et al. 2019). Stenson et al. (2019) also report that indoor microbial communities are primarily sourced from occupants and outdoor air introduced via ventilation and traffic, and that it remains uncertain whether CLT materials directly contribute to the indoor microbial community.

4.6 Temporal distribution of use cases

To better situate the reviewed studies within the broader landscape of mass timber research, it is useful to examine both the types of structural systems that have been investigated and the contexts in which empirical evidence has been generated. In this regard, Figures 4(a) and 4(b) summarize two key characteristics of the reviewed literature: the structural timber systems investigated and the experimental settings in which studies were conducted. Figure 4(a) shows that cross-laminated timber (CLT) dominates the literature, appearing in the majority of studies either as a standalone system or in combination with other timber types, while glued-laminated timber (glulam) is also frequently examined, particularly in component-level and hybrid system investigations. In contrast, other mass timber typologies, such as NLT, LVL, and mixed assemblies, are comparatively underrepresented and are rarely studied as primary systems at the building scale.

Complementing this material distribution, Figure 4(b) indicates a strong prevalence of field-based investigations, reflecting the emphasis on in-situ monitoring of real structures during construction and service. Laboratory studies constitute a substantial portion of the literature and are typically used to evaluate material behavior, connections, and sensor performance under controlled conditions, whereas relatively few studies integrate laboratory and field approaches. Together, these distributions highlight a CLT-centric body of research that is strongly grounded in field deployment while revealing opportunities for broader coverage of alternative mass timber systems and for more systematic linkage between laboratory calibration and long-term in-service monitoring.

5 Challenges and Future Research Needs in Sensor-Based Monitoring of Mass Timber Buildings

The practical implementation of sensor technologies in mass timber buildings faces persistent challenges related to deployment quality, calibration uncertainty, environmental sensitivity, and multi-sensor data interpretation. Across displacement, strain, moisture, temperature, and vibration monitoring, mass-timber studies consistently report limitations related to installation quality, sensor robustness, calibration requirements, and data interpretability. Displacement and strain sensing systems are strongly influenced by installation and material effects. Potentiometers and LVDTs depend on precise alignment and

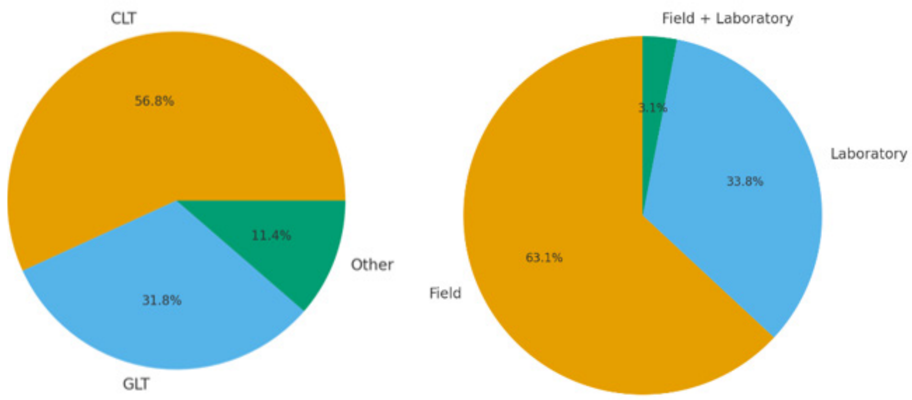

Figure 4 Overview of literature characteristics: (a) distribution of experimental settings across the reviewed studies (field-based, laboratory, and combined approaches), and (b) distribution of structural timber systems investigated, categorized as CLT, glulam, and other mass timber typologies.

stable reference conditions, while fiber-optic and electrical resistance strain sensors are challenged by installation robustness and complex strain interpretation in timber's heterogeneous and moisture-sensitive material. Moisture sensors pose substantial deployment challenges due to temperature sensitivity, species-dependent calibration uncertainty, probe–wood contact instability, and vulnerability to liquid water exposure, which can result in sensor failure or unreliable data. Their reduced accuracy above the fiber saturation point, combined with their inherently localized measurement nature, further limits their capacity to capture critical wetting events or deep moisture gradients in thick CLT panels.

Additional limitations arise from measurement characteristics and deployment scale. Extensometers and FBG sensors provide high-accuracy strain data but are inherently localized, while DFOS offers continuous strain profiling along structural members but remains sensitive to installation robustness and interpretation challenges in heterogeneous timber materials. String potentiometers are suitable for building-scale displacement monitoring but are affected by environmental sensitivity and sensor dynamic behavior in field applications. In vibration monitoring, piezoelectric accelerometers are commonly used as reliable reference instruments, whereas MEMS and capacitive accelerometers are typically employed in complementary or laboratory-focused roles. Weather stations further introduce uncertainty due to data continuity issues and the limited representativeness of macro-climate measurements for site-specific microclimatic conditions.

Interpretation challenges are further amplified by calibration demands and environmental coupling. Electrical resistance strain gauges are sensitive to moisture and temperature effects that complicate long-term strain interpretation, while RH–temperature measurements, commonly used to infer equilibrium moisture conditions or mould risk, are affected by equilibrium assumptions, sorption hysteresis, hygroscopic buffering, sensor placement, and temporal lag. In damage monitoring applications, AE sensing is challenged by anisotropic and layered wave propagation in timber, complicating source localization and interpretation of damage mechanisms, while PZT wafers rely on baseline signals from intact states and exhibit high variability in signal features under sustained or cyclic loading, potentially reducing robustness in real structural applications. Collectively, these limitations, together with heterogeneous datasets, missing data, and inconsistent processing workflows, constrain cross-sensor interpretation and limit the effectiveness of multi-sensor structural assessment in mass-timber buildings.

Future work in mass-timber monitoring should prioritize standardized installation and calibration protocols for moisture, displacement, strain, and temperature sensors to reduce variability and ensure comparability across projects. Robust hardware development is essential, including rugged embedded packages for fiber-optic, moisture, and vibration sensors that can withstand thermal swings, construction-phase damage, and long-term environmental exposure. Improvements in compensation models are also needed, particularly for moisture sensors operating above the fiber saturation point, RH sensors under high-humidity conditions, and temperature probes influenced by localized microclimates.

A major research direction is the advancement of unified data-fusion frameworks that integrate heterogeneous sensor streams through BIM and digital-twin platforms, enabling real-time interpretation, automated model updating, and improved decision-making. Such frameworks can help reconcile heterogeneous sensor resolutions, sampling rates, and uncertainties that currently limit cross-sensor interpretation. Wireless smart-sensor systems, IoT-enabled nodes, and event-triggered sampling strategies can reduce data loss and extend service life, aligning with the SHM research trajectory described by (Mardanshahi et al. 2025). Developing shared, labeled datasets is equally important, especially for AE, PZT, DFOS, and vibration-based diagnostics, to support machine-learning-based detection, classification, and prognostic modeling.

Progress in advanced analytics, including modal decomposition, feature-selection techniques, and image- or waveform-based fusion, will help address noise, anisotropy, and environmental coupling that obscure structural signals. Hybrid sensing approaches, such as combining DFOS with localized point sensors or exploring complementary imaging techniques (e.g., infrared thermography), offer a promising pathway to improve anomaly detection in large members and complex joints. Finally, expanded field trials and long-term monitoring campaigns are needed to validate new sensing strategies, quantify durability, and evaluate the cost-effectiveness of next-generation systems. These priorities closely align with the future research needs identified in recent SHM reviews, reinforcing the importance of scalable algorithms, multisensory data fusion, wireless integration, and digital-twin–based model updating for the next phase of mass-timber structural monitoring.

From an industry perspective, the findings of this review suggest that sensor-based monitoring in mass timber buildings should be approached not as an experimental add-on, but as a practical risk-management and asset-management strategy across the project lifecycle. For designers and engineers, the reviewed studies indicate that monitoring data can support more informed detailing decisions in moisture-sensitive zones, improve understanding of structural response under service conditions, and strengthen confidence in performance-based design approaches. For contractors, the evidence highlights the value of construction-phase monitoring for identifying wetting events, drying delays, and installation-related vulnerabilities before they develop into costly durability or remediation problems. For owners and facility managers, long-term sensing systems offer a pathway toward condition-based maintenance, earlier detection of abnormal behavior, and more reliable documentation of building performance over time. However, the review also makes clear that broader industry adoption will depend on moving beyond isolated pilot deployments toward standardized sensor selection, installation protocols, data interpretation workflows, and integration with BIM or digital-twin-based facility management environments. In this sense, the practical value of monitoring lies not only in data collection itself, but in its ability to support timely decisions, reduce uncertainty, and improve the long-term reliability, maintainability, and insurability of mass timber buildings.

6 Conclusion

This study presents a comprehensive synthesis of sensor-based monitoring applications in mass timber buildings through combined scientometric and thematic analyses of 64 publications published between 2015 and 2025. The results reveal a rapidly expanding research landscape driven by the growing adoption of mass timber within sustainability- and circular-economy–oriented construction. Consistent with early foundational reviews on timber structural health monitoring (Riggio and Dilmaghani 2020), the findings confirm that moisture exposure and environmental variability remain the dominant drivers of performance risk in engineered timber systems, underpinning the continued emphasis on hygrothermal monitoring and vibration-based assessment. At the same time, the scientometric trends demonstrate a clear diversification of sensing strategies in recent years, with increasing adoption of distributed fiber-optic sensing, vibration-based monitoring, and active sensing techniques to capture structural response at both component and building scales.

Despite this technological expansion, the review identifies persistent barriers that continue to limit scalable and comparable implementation in practice. These challenges - including installation sensitivity, calibration requirements, environmental coupling of sensor signals, and fragmented data-processing workflows - closely align with the multi-criteria SHM limitations identified by (Mardanshahi et al. 2025), particularly regarding field robustness and readiness for digital twin integration. The recurrence of these issues across mass timber case studies indicates that current limitations stem less from sensor availability than from the absence of standardized deployment protocols and unified multi-sensor interpretation frameworks. Advancing mass timber monitoring therefore requires a transition toward field-robust sensing systems, uncertainty-aware calibration strategies, and digital twin enabled architectures capable of integrating heterogeneous sensor streams into actionable performance indicators. Addressing these needs is essential for strengthening durability assessment, enabling performance-based design, and supporting mass timber's long-term role as a resilient construction system within a circular built environment.

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