Discover Sustainability

RESEARCH Open Access

Potential for wider adoption of wood fiber insulation in building construction

Jami Pentti Joonatan Järvinen[1*], Hüseyin Emre Ilgın[1], Markku Karjalainen[1] and Henrik Heräjärvi[2]

*Correspondence:
Jami Pentti Joonatan Järvinen
jami.jarvinen@tuni.fi
[1]Faculty of Built Environment, School of Architecture, Tampere University, Tampere, Finland
[2]Faculty of Science, Forestry and Technology, School of Forest Sciences, University of Eastern Finland, Joensuu, Finland

Abstract
As Europe advances toward low-carbon construction, bio-based materials like wood fiber insulation (WFI) are gaining traction as viable alternatives to conventional insulations. Industrial timber construction presents a strategic context for deploying WFI due to its compatibility with prefabrication and sustainability goals. This study explores the adoption potential of fire-retardant WFI through a qualitative, grounded theory approach based on expert interviews conducted in six European countries. The objective is to examine the relationship between WFI's technical performance and the regulatory frameworks that govern its approval and market entry. The research offers a novel contribution by identifying critical gaps between WFI's documented strengths, including fire resistance, thermal regulation, and moisture buffering—and regulatory assessment methods that were developed with non-bio-based materials in mind. These systemic mismatches create significant barriers to innovation and material diversification in sustainable construction. Three key findings emerged: (1) Current technical assessment protocols inadequately capture the real-world performance of WFI; (2) Environmental sustainability acts as a catalyst for innovation and material substitution; (3) Education and policy alignment are crucial to overcoming institutional inertia and advancing market uptake. A conceptual model is developed to illustrate the barriers and enablers influencing WFI integration. This study concludes that performance-based evaluation systems and policy incentives are essential to unlocking the full potential of WFI in climate-responsive construction. These insights are intended to inform regulators, industry stakeholders, and researchers, contributing to the broader discourse on ecological material transitions.

Keywords Wood fiber insulation (WFI), Low carbon construction, Fire retardancy, Bio-based materials, Sustainable building regulations

1 Introduction

Addressing climate change requires urgent, cross-sectoral reductions in greenhouse gas emissions, with the built environment constituting a key intervention point [1]. Within the European Union, construction activities, including the erection of new buildings and the operation and demolition of existing ones, account for approximately 40% of total

energy consumption and contribute to over one-third of greenhouse gas emissions [2]. This substantial footprint underscores the sector's role as both a significant contributor to anthropogenic climate change and a critical focus for decarbonization efforts [3]. Consequently, the European Green Deal and legislative instruments such as the Energy Performance of Buildings Directive (EPBD) have set targets for improving energy efficiency, integrating renewable energy, and promoting the use of bio-based, recyclable, and low-emission construction materials [4]. These initiatives aim to achieve a climate-neutral building stock by 2050 [5].

Among various strategies for reducing buildings' operational emissions, improving thermal insulation performance is particularly effective. High-performance insulation reduces energy use over a building's lifetime by minimizing heating and cooling demands [6, 7]. As operational efficiencies improve, however, the relative significance of embodied emissions—from material extraction, manufacturing, transportation, installation, and disposal—increases. Materials should therefore be assessed holistically, considering both operational and life-cycle impacts [8]. Bio-based insulation materials, such as wood fiber insulation (WFI), can offer lower global warming potential (GWP) than conventional alternatives like mineral wool, expanded polystyrene, and polyurethane, particularly when their capacity for biogenic carbon storage is considered [9, 10]. In this article, WFI refers broadly to both virgin wood fiber products and cellulose-based insulation from recycled paper or cardboard, unless otherwise specified. Environmental Product Declarations (EPDs indicate that Steico wood fiber insulation boards generally show lower cradle-to-gate GWP values than Isover mineral wool products, though the relative advantage depends on density, functional unit, and end-of-life assumptions [11, 12]. At the same time, comparative LCA results vary depending on boundaries, energy mixes, transport distances, and formulations, and in some cases bio-based materials may even show higher GWP values. Despite these variations, the dominant environmental benefit of insulation is its capacity to reduce operational energy consumption, which typically outweighs embodied differences and complements the additional advantages of bio-based materials, including renewable sourcing, improved recyclability [13], and contributions to healthier indoor air quality [14].

Despite Finland's abundant forest resources, the shift toward high-value, low-emission wood products has been limited. The Finnish Forest Bioeconomy Science Panel reports declining market value for several wood products, indicating challenges in advancing the value chain [15]. Simultaneously, climate change, forest aging, and intensive harvesting have reduced the carbon sink capacity of Finnish forests [16]. These trends highlight the need for climate-aligned wood innovations that do not exacerbate forest pressures.

WFI, produced either from mechanically processed wood residues or from recycled paper and cardboard, presents a renewable, recyclable, and low-carbon alternative to conventional insulation. It also offers favorable hygrothermal properties that enhance building durability and occupant comfort [17, 18]. Its hygroscopicity suits breathable wall systems increasingly used in ecological designs emphasizing moisture regulation and energy efficiency. These properties make WFI suitable for both new construction and retrofitting in sustainable building projects.

WFI's potential is shaped not only by technical performance but also by evolving market and policy frameworks. The EU's Circular Economy Action Plan and sustainable taxonomy favor materials that are renewable, low-emission, and recyclable [19, 20]. This alignment facilitates green financing and market incentives. Public procurement policies increasingly require life-cycle assessments (LCA) and environmental product declarations (EPD), promoting transparency in material choices [21].

Wider adoption of WFI could improve energy performance, lower emissions, and increase economic returns from domestic wood. It supports EU decarbonization goals and Finland's ambition to enhance the sustainability of its wood industries. Nevertheless, challenges persist. Concerns about fire safety, moisture behavior, and installation sensitivity are especially relevant in regions with strict regulations. Conservative interpretations of fire codes can hinder the use of bio-based materials and limit ecological innovation [22].

In Finland, these constraints are evident in multi-story timber buildings. National regulations require that insulation used in P2 fire class buildings over two storeys must meet at least class A2-s1, d0 for reaction to fire [23]. In the Euroclass system, construction materials are ranked from A1 (non-combustible) to F (easily flammable), with A1 and A2 indicating minimal combustibility. The suffixes denote smoke production and flaming droplets,for example, A2-s1, d0 indicates low smoke and no flaming droplets.

Wood fiber insulation (WFI) typically attains Euroclass E in its untreated form, reflecting its inherent combustibility. With the application of fire-retardant treatments, WFI products can improve significantly, achieving Euroclass B-s1, d0 under standardized testing. For comparison, structural timber used in load-bearing applications typically achieves Euroclass D, which further highlights the relative position of WFI within the Euroclass spectrum. Despite these improvements, Finnish regulations for multi-story P2 buildings effectively exclude WFI from unprotected use, as only A2-class or better insulations are permissible unless adequate fire performance can be demonstrated through certified assemblies or protective cladding. While grounded in safety, these requirements complicate the adoption of low-carbon, bio-based materials in building types where their environmental benefits could be most substantial. Recent innovations offer solutions.

Fire-retardant treatments for WFI are showing promise in meeting strict fire standards without undermining environmental performance [24]. Research into hygrothermal modeling supports better installation practices and moisture management [25, 26]. Nonetheless, key knowledge gaps remain in long-term durability, standardized fire testing, and comparative life-cycle impacts. Bridging these gaps requires interdisciplinary collaboration among researchers, industry, and regulators. Fire-retardant WFI uniquely combines renewable sourcing, technical performance, and policy alignment, making it a strategic material in the low-carbon transition. These systemic barriers and enabling levers are summarized in Fig. 1.

The socio-economic benefits of expanding bio-based insulation should also be considered. Local WFI manufacturing can stimulate rural economies, create green jobs, and improve regional material self-sufficiency [27]. These benefits align with EU goals under the Just Transition Mechanism [28]. Additionally, WFI can enhance indoor

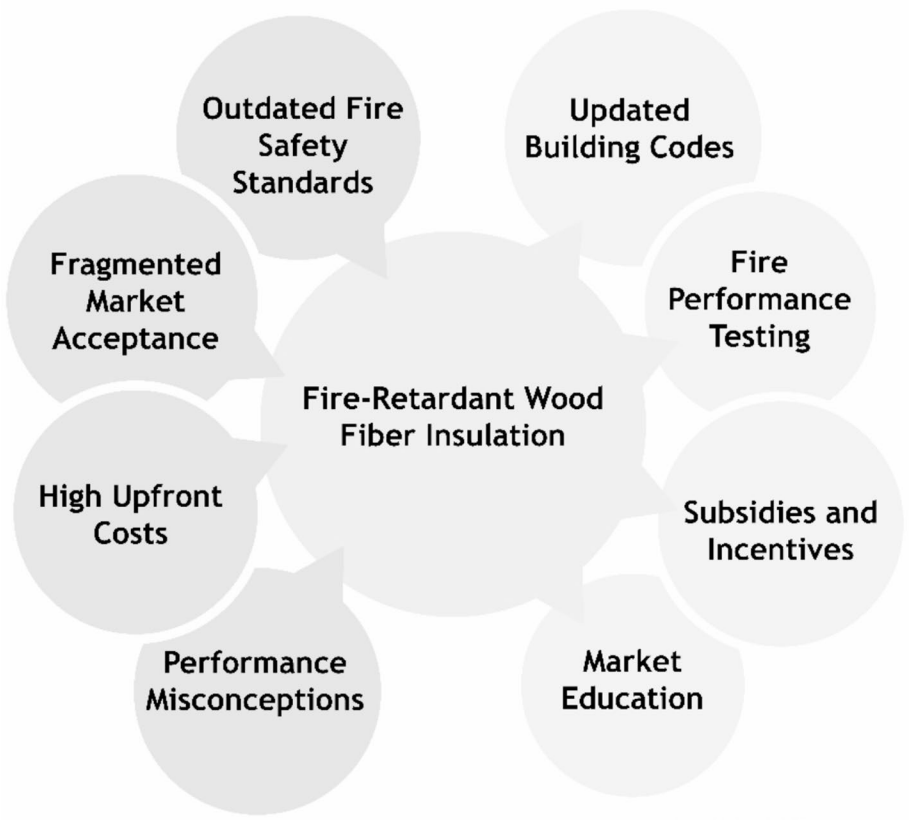

Fig. 1 Systemic Barriers and Enabling Levers for the Adoption of Fire-Retardant WFI

environmental quality, which is increasingly critical under climate change-driven extreme weather.

Cost remains a barrier. WFI typically has higher upfront costs than mineral wool, limiting competitiveness in cost-sensitive projects [22]. Addressing this challenge requires further R&D, standardized performance assessments, and more case studies demonstrating WFI's efficacy across varying conditions.

Despite its low-carbon potential and favorable physical properties, WFI adoption is hindered by outdated standards and fragmented acceptance. This research addresses how promising materials can be sidelined by legacy frameworks and socio-technical inertia. It hypothesizes that fire-retardant WFI, when evaluated through assembly-based and performance-oriented criteria, can meet or exceed conventional benchmarks for fire, thermal, and moisture performance. The study investigates: (1) how current regulatory and technical systems constrain WFI adoption; (2) which socio-institutional barriers perpetuate biases against bio-based materials; and (3) which strategies—including regulatory reform, technical innovation, and stakeholder education—can most effectively enable scaling. The goal is to develop a conceptual model diagnosing systemic barriers and proposing pathways for material innovation and sustainable integration.

2 Methodology

2.1 Research approach and rationale

This study adopts a qualitative grounded theory methodology to explore the factors shaping the adoption of fire-retardant wood fiber insulation (WFI) in low-carbon construction. Grounded theory is particularly suitable for examining under-theorized topics where complex socio-technical interactions exist [29, 30]. Its iterative and emergent structure supports the development of conceptual models grounded in empirical reality, making it well-suited for capturing stakeholders lived experiences across diverse regulatory, climatic, and market contexts.

While grounded theory provides the primary methodological foundation, the study is also informed by Rogers' Diffusion of Innovations framework [31]. This framework was not imposed as a priori theory but used as a sensitizing concept to guide aspects of the research design and subsequent interpretation. Key constructs—such as relative advantages, compatibility, and complexity—were incorporated into the interview protocol to stimulate reflection among participants and later served as interpretive lenses during analysis.

In this way, grounded theory ensured that categories and themes emerged inductively from the data, while Rogers' framework supported the contextualization and theoretical enrichment of these findings. The two approaches are thus complementary: grounded theory anchored the study in participants' perspectives, and the Diffusion of Innovations framework provided a structured vocabulary to situate the emergent categories within established scholarship on innovation adoption. This dual-framework strategy enhanced analytical robustness while minimizing the risk of theoretical imposition.

2.2 Sampling strategy and participant recruitment

A purposeful and theoretically informed sampling strategy was employed to capture a broad range of perspectives across geographies, professions, and institutional contexts. Participants were selected from six countries—Finland, Norway, Sweden, Denmark, Germany, and Poland—to reflect both regional diversity and regulatory variation in fire safety and building standards. The sample also spanned professional domains including manufacturing, fire safety engineering, and academic research, ensuring a cross-sectional representation of the construction ecosystem.

Inclusion criteria required participants to have a minimum of five years' professional experience with insulation materials or timber construction, and to be affiliated with an institution actively engaged in sustainable building practices. Initial participants were identified via industry networks and academic partnerships, and a snowball sampling approach was used to reach further respondents with specialized knowledge. In total, 15 expert participants were interviewed. While the study does not claim theoretical saturation, the sample size is considered sufficient for an exploratory study aimed at identifying key themes and developing initial conceptual insights. Prior qualitative research suggests that similar sample sizes are adequate for capturing major themes and generating robust exploratory findings [32]. The distribution of participants by country and role is presented in Table 1. As shown in Table 1, the sample includes representatives from

Table 1 Participant overview – geographical and professional distribution

Interviewee specialization	Country	Code
Cellulose insulation industry representative	Finland	FI1
Cellulose insulation industry representative	Finland	FI2
Wood fiber insulation industry representative	Finland	FI3
Wood fiber insulation industry representative	Finland	FI4
Wood fiber insulation industry representative	Norway	NO1
Wood fiber insulation industry representative	Germany	GER1
Company representative – fire safety consultancy	Finland	FI5
Company representative – fire safety consultancy	Norway	NO2
Researcher – fire safety of wood-based materials	Sweden	SE1
Company representative – fire safety consultancy	Denmark	DK1
Researcher – building physics	Finland	FI6
Researcher – building physics	Finland	FI7
Researcher – wood science	Germany	GER2
Researcher – materials engineering	Germany	GER3
Researcher – wood preservation and conservation	Poland	POL1

Table 2 Interview guide themes, subtopics and key sources

Theme	Example subtopics	Key sources
Applications and uses	Current uses, recent innovations, future potential	[17], [18]
Market situation and demand	Market share, drivers and barriers, trends	[15], [16], [27]
Legislation and standards	Fire and energy regulations, future policy	[23], [4], [2, 19, 20]
Environmental Impact and sustainability	Advantages, lifecycle benefits, circular economy	[9], [10], [11, 12], [13], [14]
User attitudes and awareness	Awareness, misconceptions, perception shifts	[22]
Challenges and solutions	Cost, compliance, availability, recommendations	[6], [24], [26], [25], [22]

both wood fiber and cellulose (recycled paper/cardboard) industries; in this study, both groups are considered within the scope of WFI.

2.3 Data collection

Data was collected through semi-structured interviews, enabling in-depth exploration while maintaining consistency across participants. The interview guide was developed from a literature review and refined following two pilot interviews. The pilots indicated that the number of subtopics was extensive, prompting us to structure them into six overarching thematic domains for clarity and consistency. They also confirmed the relevance of the themes identified through the literature review, while highlighting the need for refinements: awareness and misconceptions were treated as distinct subtopics, costs were separated from broader adoption barriers, and several questions were rephrased to improve clarity and flow. This ensured that interviews remained within a reasonable duration while still covering all relevant issues and allowed the emphasis to be tailored to each participant's expertise. The final guide comprised six domains—Applications and Uses, Market Situation and Demand, Legislation and Standards, Environmental Impact and Sustainability, User Attitudes and Awareness, and Challenges and Solutions—with associated subtopics and key sources summarized in Table 2. Each participant received the guide in advance, enhancing transparency and enabling reflective engagement.

Interviews were conducted remotely via Microsoft Teams between October 2024 and January 2025. Each session lasted 45–75 min, balancing open-ended exploration with comparability across participants, in line with qualitative best practices [33]. Most interviews were conducted in English, with occasional use of participants' native languages for clarification. Three interviews included two participants with complementary expertise. All sessions were audio-recorded with prior consent and transcribed verbatim, and interviews with multiple participants were treated as single data units during analysis.

2.4 Ethical considerations and researcher reflexivity

Participants received detailed consent information via email, outlining the study's objectives, data management procedures, and their right to withdraw without consequence. Consent was obtained through written confirmation prior to participation. Anonymity was maintained using coded pseudonyms (e.g., FI1, GER3), and interview transcripts were securely stored on encrypted drives in accordance with the General Data Protection Regulation (GDPR).

Reflexive memoing was employed throughout the coding process to critically examine assumptions and track theoretical sensitivity, in line with grounded theory principles [29, 34]. Regular peer debriefings supported the development of axial categories and enhanced interpretive credibility [35].

2.5 Data analysis: grounded theory coding

The data were analyzed through a three-phase grounded theory process using ATLAS.ti 24 software. During open coding, transcripts were examined line-by-line to generate over 50 initial codes spanning performance, knowledge, regulation, and sustainability. In the axial coding phase, these codes were iteratively compared, clustered around central concepts, and refined into broader analytical categories. Selective coding then identified a unifying core category—"systemic influences on material adoption"—which served as the foundation for theory generation.

To ensure reliability, two researchers independently coded three transcripts, reaching 85% agreement after calibration; disagreements were resolved through consensus and memo comparison. A detailed codebook, including code definitions, usage rules, and

Table 3 Sample open coding – categories, codes, and illustrative quotes

Category	Key concepts (codes)	Frequency	Illustrative quotes
Knowledge of WFI	Awareness	59	'Bio-based materials are not well domesticated' (DK1)
	Misconceptions	23	
	Research & education	24	
Regulatory landscape	Fire standards	92	'Fire and carbon efficiency legislation are key' (FI2)
	Technical regulation	12	
	Low carbon guidance	46	
Material performance	Fire resistance	68	'Good in fire resistance, but can still burn' (NO2)
	Moisture handling	28	
	Thermal value	37	
Adoption Barriers	Costs	33	'Main obstacles: high cost and low awareness' (PL1)
	Conservatism	38	
	Compliance gaps	24	
	Lack of awareness	33	
Sustainable Development	Circular use	53	'Recyclability is a key advantage' (DE1)
	Environmental trends	61	

illustrative examples, is provided in Appendix 1 to enhance transparency of the coding process. Representative codes and illustrative quotes are presented in Table 3.

2.6 Thematic development and conceptual framing

The coding process yielded three central themes capturing the main dimensions influencing the uptake of WFI:

1 Deficiencies in the Assessment of Technical Performance and Safety,
2 Sustainability as a Driver for Adoption and Innovation, and
3 Policy and Education Guidance: Structural Enablers for Market Integration.

Together, these themes illustrate the interplay between technical legitimacy, environmental value, and socio-regulatory acceptance. Axial categories were mapped onto the three themes to build a comprehensive conceptual model of adoption drivers (see Table 4). The final stage of analysis synthesized them into an explanatory framework—depicted in Fig. 2—that shows how structural, epistemic, and institutional forces converge to shape adoption trajectories in industrial timber construction.

3 Results and discussion

3.1 Deficiencies in the assessment of technical performance and safety

3.1.1 Fire performance and safety

Interview findings suggest that one of the primary barriers to the wider use of WFI in fire-regulated construction is the perceived incompatibility between prescriptive Euroclass requirements and the material's demonstrated behavior in protected assemblies. Standard, untreated WFI generally receives a Euroclass E classification, indicating a high contribution to fire. Even with advanced, non-toxic fire-retardant treatments, experts noted that WFI products usually achieve Euroclass B-s1, d0, signifying a limited contribution to fire. By contrast, Finnish regulations for insulation in multi-story timber buildings require at least class A2-s1, d0—defined as "limited combustibility" and approaching non-combustible performance. According to several Finnish interviewees,

Table 4 Core themes, subcategories, and linked codes

Core theme	Subcategories	Linked codes	Subcategory frequency
Deficiencies in the assessment of technical performance and safety	Material performance	Fire resistance (68) moisture handling (28) thermal value (37)	133
	Regulatory landscape	Fire standards (92) technical regulation (12)	104
	Adoption barriers	Misconceptions (23) compliance gaps (24)	47
Sustainability as a driver for adoption and innovation	Sustainable Development,	Circular use (53) environmental trends (61)	114
	Regulatory landscape	Low carbon guidance (46)	46
Policy and education guidance: structural enablers for market integration	Knowledge of WFI	Awareness (59) misconceptions (23) research & education (24)	106
	Regulatory landscape	Fire standards (92) technical regulation (12) low carbon guidance (46)	150

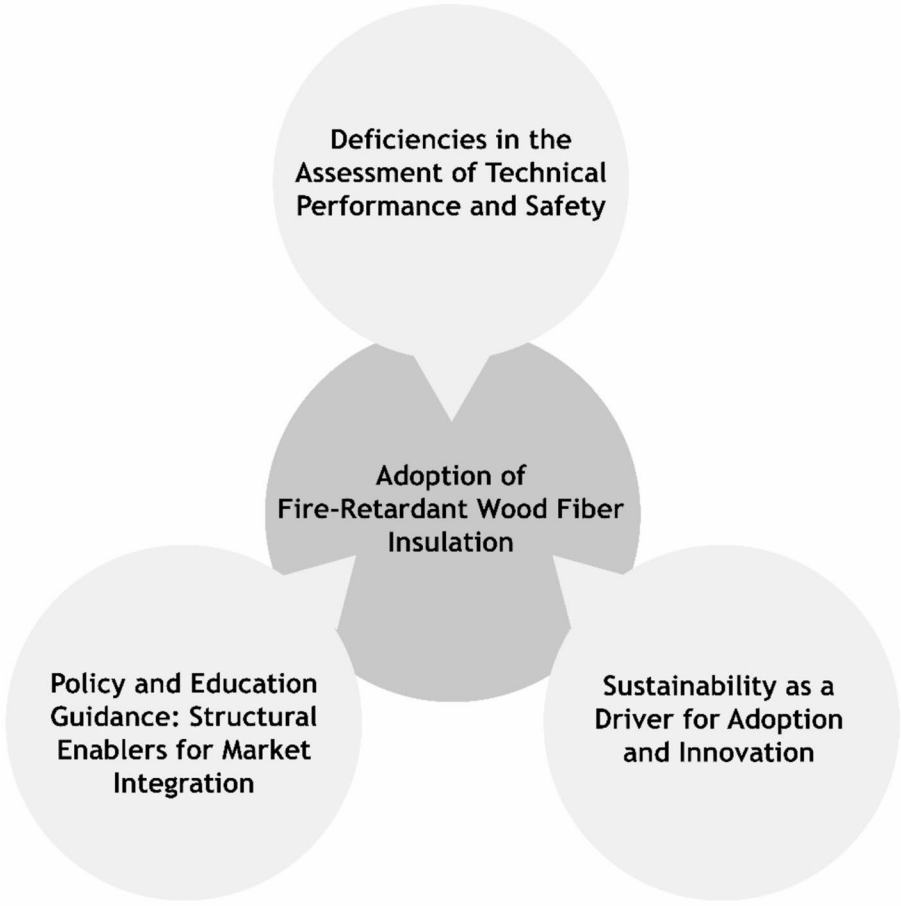

Fig. 2 Conceptual Framework of Interrelated Factors Influencing WFI Adoption

this gap illustrates the scale of the regulatory challenge: WFI cannot realistically meet the A2 requirement on a material basis, regardless of chemical treatment (FI1, FI2, FI5).

At the same time, participants emphasized that Euroclass ratings primarily capture the reaction to fire of exposed materials, while not adequately reflecting how WFI behaves when installed within multilayered, protected assemblies. Tests such as EN 13823 (Single Burning Item) were viewed as overlooking properties that can enhance fire safety in practice, including delayed ignition, protective charring, and thermal inertia. In contrast, full-scale assembly tests (e.g., SP Fire 105, REI-rated wall assemblies) were reported by interviewees to show that when installed behind protective linings such as gypsum board, WFI can maintain compartmentation and effectively limit thermal transfer (FI1, FI2, FI5, DK1). As several interviewees pointed out:

> *"Although wood fiber is classified as Euroclass E, its performance in construction can be much better. Current small-scale tests and classifications are not well suited to such materials, as they overlook beneficial properties like charring, which both indicates burning and simultaneously protects the material in real fire scenarios." -NO2.*
>
> *"In ISO 834 fire resistance tests, wood fiber insulation can perform comparably to non-combustible stone wool, as performance is measured by heat transfer through the construction—reflecting its inherent insulating capacity." -DE1.*

From the interviewees' perspective, this disconnect reflects both a mismatch in test philosophy and the prescriptive emphasis on non-combustibility in regulatory frameworks. Structural timber was cited as a relevant comparison: although it is classified as Euroclass D (combustible), it is permitted in load-bearing applications when adequately protected and assessed at the assembly level (FI5). Extending a similar performance-based design philosophy to insulation was seen as a potential pathway for bio-based materials like WFI. However, experts also stressed that broader adoption of performance-based fire design remains limited, constrained by procedural complexity, liability concerns, and the lack of institutional guidance (FI1, FI7, NO2, DK1).

Interviewees also acknowledged important limitations. Smoldering combustion, particularly in concealed cavities, was highlighted as a significant hazard due to its potential for delayed ignition and post-suppression re-ignition (DK1, FI5). While EN 16733 provides a method for assessing smoldering, participants observed that its implementation remains uneven across Europe. Germany's stricter requirements for evaluating smoldering in WFI were identified by some experts as a useful reference (DK1, FI5).

Concerns were further raised regarding fire-retardant additives. Although chemical treatments can elevate WFI's classification, participants noted potential drawbacks related to toxicity, recyclability, and long-term durability, especially under tightening restrictions on substances such as boric acid (POL1, SE1). In this context, mineral-based insulation materials, which more readily achieve A2 without additives, were perceived as maintaining a regulatory advantage.

In summary, the experts consulted in this study emphasized that WFI's inherent combustibility prevents it from reaching the A2 requirement currently applied to insulation in multi-story timber construction (FI1, FI2, FI5). At the same time, they argued that prescriptive classifications do not fully capture the safety of WFI within protected assemblies (FI1, FI2, FI5, DK1). From their perspective, a more balanced regulatory approach—integrating performance-based assessment of assemblies alongside material-level classification—would better reflect actual building conditions and could enable renewable materials such as WFI to contribute more safely to low-carbon construction (FI1, FI7, NO2, DK1, POL1, SE1). This argument is consistent with the broader literature on performance-based fire safety design, which emphasizes system-level analysis as an alternative to prescriptive material classifications [36].

3.1.2 Thermal efficiency

Interview data suggest that existing thermal performance assessments may not adequately capture the multifunctional behavior of WFI. According to several experts, standard metrics such as steady-state thermal conductivity overlook the dynamic thermal responses of bio-based materials in real building conditions. While WFI was described as having moderate thermal conductivity, high specific heat capacity, and significant air flow resistance, participants noted that these attributes are often disregarded in formal evaluation frameworks (FI1, FI2).

A critical aspect repeatedly highlighted by interviewees was WFI's hygrothermal responsiveness. As the material absorbs moisture due to seasonal humidity changes,

its thermal conductivity can increase, thereby reducing insulation effectiveness (GER2, GER3). As one interviewee noted:

> *"Wood fiber boards offer pros and cons: they can buffer indoor humidity to some extent, contributing to a more stable indoor climate, whereas elevated moisture content increases their thermal conductivity and reduces insulation performance." -GER2.*

Experts argued that this underscores the need for moisture-adaptive evaluation methods to ensure reliable long-term performance.

Several participants also emphasized WFI's high specific heat capacity, which contributes to thermal buffering by moderating temperature fluctuations within the building envelope (FI1, FI2, GER1). This observation aligns with previous research, which highlights that the thermal inertia of wood fiber insulation can mitigate summertime overheating through phase-shift effects [10, 18]. This property was seen as supporting passive thermal regulation and reducing reliance on mechanical heating and cooling systems. While interviewees acknowledged that WFI's thermal conductivity is broadly comparable to that of mineral wool (e.g., 0.038 W/mK in Hunton products), they viewed its thermal inertia as particularly beneficial in lightweight timber structures prone to rapid temperature shifts.

Another underappreciated attribute, according to experts, is WFI's air flow resistance. Its dense, fibrous structure was described as limiting internal convection and thereby helping to maintain thermal transmittance over time. This was regarded as especially relevant in contrast to low-density mineral insulation, which was seen as more susceptible to performance degradation via natural convection. Despite its significance for energy performance and durability, participants noted that air flow resistance is not typically included in product documentation or U-value calculations, leading to biased comparisons between materials (FI1, FI2, FI6).

Interviewees also pointed to regulatory changes that exacerbate these shortcomings. In Finland, for instance, the repeal of national insulation regulations in 2017 shifted reliance to generalized EN standards, which do not reflect local climatic conditions such as freeze–thaw cycles or high humidity gradients (FI1, FI2). As one interviewee explained:

> *"Building performance is assessed mainly through conductivity and thickness, yet natural convection within insulation can cause far greater heat losses than U-value calculations suggest, a factor overlooked in Finnish regulations." -FI2.*

While the RIL 225–2023 guideline provides more detailed thermal modeling [37], experts stressed that its lack of enforceability limits its impact. Stakeholders advocated for the reintroduction of national oversight, particularly regarding metrics like air flow resistance and moisture buffering, to enable more accurate and context-specific energy assessments (FI1, FI2).

Participants also recognized an inherent limitation of WFI: its volumetric requirement. They noted that greater thickness is needed to achieve the same thermal resistance (R-value) as plastic-based insulations such as polyurethane or XPS (FI2, FI5, POL1, GER2, GER3). This was seen as a potential barrier in space-limited applications like

renovations or certain prefabricated systems. However, in prefabricated timber elements where insulation is integrated into the same structural layer as the load-bearing timber frame, the increased thickness was often not considered a constraint, since the element depth is designed to accommodate both structural and thermal functions. Moreover, experts emphasized that this drawback should be weighed against WFI's broader benefits, including improved phase shift performance, reduced risk of summertime overheating, and compatibility with net-zero energy targets.

In summary, the interviewees stressed that current thermal assessment methods tend to favor conventional materials not because of inherently superior performance, but because the metrics used fail to account for the specific strengths of bio-based alternatives like WFI (FI1, FI2, FI6, FI5, POL1, GER1, GER2, GER3).

3.1.3 Moisture performance

From a hygrothermal perspective, interviewees suggested that the moisture buffering capacity of bio-based insulations can contribute to the resilience of building assemblies and may reduce the risk of mold growth. Wood fiber insulation (WFI) was described as having high sorption capacity and vapor permeability, enabling it to moderate indoor humidity fluctuations in airtight, diffusion-open constructions (FI1, FI2, FI6, GER1, POL1). This observation is consistent with experimental findings reported in previous studies, which demonstrate the strong moisture-buffering capacity and hygroscopic behavior of bio-based insulations such as WFI [25]. According to experts, this dynamic moisture responsiveness helps reduce peak humidity levels and can support mold resistance in well-ventilated assemblies. Under suitable drying conditions, participants noted that WFI may also tolerate minor leaks or condensation without structural degradation or microbial growth (FI2, FI6).

However, interviewees consistently emphasized that this buffering capacity should not be seen as a substitute for appropriate vapor control. In cold climates, they argued that adequate vapor resistance on the interior side of the assembly remains critical, particularly since untreated WFI—like many organic insulation materials—is inherently susceptible to mold growth under prolonged moisture exposure. When treated with biocidal agents such as borates, WFI's resistance to microbial degradation was reported to improve. At the same time, some participants pointed to uncertainties regarding the long-term effectiveness of such treatments. They noted that boron compounds may leach out over time or that microbes may adapt, raising questions about durability under real-world conditions (FI6, FI7). Consequently, several experts advised caution in relying solely on treatments to ensure biological stability over the lifespan of a building.

A significant barrier to wider market uptake, in the view of interviewees, is the mismatch between WFI's actual hygrothermal behavior and the standardized methods used to assess material performance. Current European frameworks rely predominantly on static metrics such as vapor diffusion resistance (μ-values), which are derived under laboratory conditions and were seen as failing to capture dynamic in situ phenomena. Participants highlighted processes such as capillary redistribution, time-dependent sorption hysteresis, and moisture buffering under variable humidity loads and pressure differential factors they considered highly relevant in real-world applications (FI2,

FI6). From this perspective, WFI and similar materials are systematically undervalued in product comparisons, despite what experts described as context-sensitive performance advantages.

Interviewees also highlighted persistent misconceptions, particularly the conflation of vapor permeability with air leakage. Ambiguous terms like "breathable walls" were said to contribute to confusion and, in some cases, to inadequate airtightness detailing. These misunderstandings have, according to participants, undermined confidence in WFI and indirectly impeded its broader adoption (FI6, SE1).

Specific concerns were raised regarding wet-sprayed WFI products, which some experts associated with slow drying times and increased mold risk in cold climates if drying is insufficient. At the same time, interviewees emphasized that such risks are application-specific rather than intrinsic to the material itself. Dry-installed WFI products were not seen as exhibiting the same vulnerabilities, provided they are installed correctly and not exposed to moisture on site, underscoring the importance of distinguishing between material properties and implementation quality (GER2, FI6, FI7). As one interviewee explained:

> *"There is also a risk of mold growth—none if construction is done correctly, but if not, problems can occur early on when materials are still wet." -GER2*

Looking ahead, participants suggested that as climate change increases the frequency of extreme rainfall events, ambient humidity, and condensation risks, the relevance of materials capable of buffering, storing, and redistributing moisture—such as WFI—is likely to grow (FI6). Despite this, experts observed that current regulatory frameworks rarely account for advanced hygrothermal behavior. They called for the development of improved assessment methods and simulation tools that incorporate transient moisture transport, coupled heat and mass transfer, and non-linear sorption phenomena (FI2, FI6).

In summary, the interviewees characterized WFI as exemplifying a shift from static, resistive moisture control toward more adaptive, system-integrated hygrothermal strategies. However, they stressed that realizing its full potential for enhancing building durability, indoor environmental quality, and climate resilience will require not only more refined design practices but also substantive reforms in regulation and performance assessment (FI1, FI2, FI6, GER1, GER2, FI7, SE1, POL1).

3.2 Sustainability as a driver for adoption and innovation

3.2.1 Sustainability performance and systemic barriers

Interviewees emphasized that sustainability has become a central consideration in material innovation for the construction sector. From their perspective, WFI illustrates this shift through its renewable origin, relatively low embodied energy, and role as medium-term carbon storage (FI1, FI2, FI3, FI4, NO1, GER1, GER2, GER3, POL1). This view is consistent with life cycle assessment evidence: Environmental Product Declarations (EPDs) for wood fiber insulation report lower embodied energy and favorable carbon storage compared to conventional mineral insulations (e.g., [9]). Experts noted that its production is based on by-products from the wood industry and requires comparatively

minimal processing, which they viewed as aligning well with circular economic principles. At the same time, participants highlighted that evolving regulatory frameworks—such as REACH, toxicity restrictions, and recyclability demands—are continuously reshaping the criteria for what counts as sustainable performance (FI1–FI4, NO1, POL1). This is consistent with recent literature showing that compounds like boric acid are now classified under REACH as substances of very high concern for reproduction, and that many conventional flame retardants face increasing restrictions due to toxicity concerns [38]. This regulatory context underscores the need for ongoing innovation, particularly in relation to non-toxic binders and fire retardants (SE1, FI6, NO1, GER2).

Despite the availability of life cycle assessments and environmental product declarations, interviewees stressed that sustainability is not yet systematically rewarded in regulatory or procurement contexts. According to several participants, these tools currently have limited impact on permitting processes, subsidies, or material selection (FI1, FI3, FI7). As a result, materials such as WFI, which were perceived as technically and environmentally sound, remain underutilized. From the experts' perspective, system-level changes—such as integrating carbon accounting into building regulations and incentivizing low-impact materials—are needed to unlock their potential more fully (NO1, FI1–FI3, FI7).

One Finnish interviewee, for example, pointed out that low-carbon calculations will become mandatory in Finland at the beginning of 2026, yet such requirements are still absent in most European countries. While bio-based materials were generally expected by participants to perform well in such assessments, they also noted challenges. In Finland, the carbon storage potential of biogenic carbon over a 50-year horizon is not recognized in the national calculation method—unlike in the dynamic climate impact framework of the French RE2020 regulation (FI7).

3.2.2 Challenges in circularity and raw material availability

Interviewees noted that although WFI aligns with circular economic goals, several practical challenges remain—particularly regarding raw material availability and logistics. According to participants, the dispersed nature of supply sources, combined with the material's low bulk density, was seen as increasing transportation complexity, costs, and emissions (FI1–FI4, NO1, POL1, GER2).

A recurring concern among experts was the competition between material and energy uses of wood. Following the reduction of energy wood imports from Russia, domestic biomass was reported to have been increasingly directed toward energy production, constraining availability for insulation manufacturing (FI3). Some participants suggested that transitions toward diversified renewable energy sources may ease this pressure over time (FI3, FI4, GER3).

Recycled fiber availability was also identified as a limitation. Interviewees pointed out that declining paper production has reduced access to recycled paper, which historically served as a feedstock for cellulose-based insulation. Manufacturers were said to have responded by shifting to recycled cardboard, which is more widely available due to the growth of e-commerce packaging (FI1, FI2, NO1). Recent industry statistics similarly indicate that while newsprint production in Europe continues to decline, containerboard

output increased in 2024, reflecting a broader shift from paper toward cardboard feedstocks [39]. As one interviewee pointed out:

> *"A persistent concern in the cellulose insulation industry has been the sufficiency of paper as a raw material. At the same time, the growing demand for cardboard packaging—driven by efforts to reduce plastic use and by paper mills converting production lines to cardboard—has created alternative paper-based feedstocks suitable for similar products." -FI2.*

While recycled wood was viewed as having potential, participants emphasized that its heterogeneous quality and energy-intensive processing present barriers to broader adoption (FI3, FI4). They suggested that advancements in recycling systems and fiberization methods would be required to enable consistent, low-emission reuse. Several experts anticipated that the use of recycled wood would increase in the future as part of extended material life cycles.

Regional variation in virgin material availability was also mentioned as affecting sourcing strategies. In Central Europe, for example, bark beetle damage has reduced softwood supply, prompting interest in hardwoods and stimulating research into the suitability of alternative species for insulation production (GER2, GER3). These issues were discussed in relation to wood-fiber–based WFI rather than cellulose insulation, which relies on recycled paper and cardboard as raw material.

3.2.3 End-of-life possibilities

Interviewees consistently highlighted WFI's recyclability as a perceived competitive advantage over many conventional insulations. According to participants, surplus material and removed insulation can, under suitable conditions, be reintegrated into manufacturing processes. Although current standards were said to restrict recycled content in certified products to approximately 10%, experts pointed to recent legislative developments—including Finland's Building Act (751/2023) and the revised EU Construction Products Regulation (2024/3110)—that aim to increase the use of secondary raw materials [40, 41]. At the same time, interviewees stressed that recycling remains logistically feasible primarily within a limited radius of production facilities, highlighting the need for improved collection systems (NO1, GER1).

Participants also identified several potential end-of-life uses that they viewed as consistent with circular economy principles. These included utilization in asphalt binders, pellet production, and, increasingly, biochar conversion. Experts emphasized that biochar could act both as a form of long-term carbon storage and as a substitute for fossil coal in industrial applications. While regulations were noted to prohibit the use of fire-retardant-treated materials in food-related value chains, interviewees suggested that they may be suitable for non-food horticultural purposes—where additives like boron could even be beneficial. In their view, such multifunctional reuse pathways represent both ecological and economic opportunities (FI1, FI2, FI4, GER1).

3.3 Policy and education guidance: structural enablers for market integration

3.3.1 Policy foundations for bio-based construction integration

Interviewees emphasized that the integration of WFI into mainstream construction depends not only on its technical and ecological performance but also on policy

structures and knowledge dissemination. According to participants, current regulatory frameworks were perceived as fragmented and insufficiently aligned with the requirements of bio-based construction.

At the EU level, experts noted that efforts are underway to incorporate carbon sequestration and life cycle environmental impacts into policy. However, they also stressed that existing LCA methodologies often omit biogenic carbon storage and phase shift performance, leading to what they viewed as the underrepresentation of bio-based materials in environmental assessments (FI1–FI3, FI7, NO1). Several participants argued that more inclusive LCA tools could help correct these imbalances and support evidence-based policymaking. One interviewee pointed out that while such limitations persist in current LCA standards, the recently adopted EU Regulation on the Certification Framework for Carbon Removals (CRCF) introduces a voluntary scheme that does acknowledge the value of biogenic carbon stored in long-life products such as wood-based construction materials [42]. From their perspective, such developments could, over time, strengthen the policy relevance of carbon storage in materials and support national measures—such as mandatory carbon footprint limits for small- and medium-scale residential projects—that could incentivize the use of low-impact materials (FI1, DK1).

National reforms were also highlighted as important drivers. For example, Poland's promotion of timber construction was described as indirectly supporting related materials like WFI (POL1). Similarly, interviewees suggested that performance-based technical codes, which prioritize functional outcomes over material classifications, could help remove long-standing barriers to innovation (FI1, FI2, NO1, NO2, FI7).

Finally, participants underscored the importance of coordinated industry action, particularly among small and medium-sized enterprises, which they saw as key actors in the bio-based sector. Collaborative lobbying, participation in standards development, and strategic alliances were viewed as essential for ensuring that emerging materials are not disadvantaged by protocols developed primarily for conventional products (FI1, FI3, NO1).

3.3.2 Regulatory alignment and incentivization strategies

A consistent theme across interviews was the perceived disconnect between sustainability goals and their operational implementation. While environmental objectives were acknowledged as being embedded in policy strategies, participants reported that supportive mechanisms—such as subsidies, tax incentives, or procurement rules—are often lacking or inconsistently applied (FI1, FI3, GER1, POL1, DK1).

Experts called for stronger regulatory alignment across scales. At the EU level, they suggested that harmonized carbon accounting, recyclability criteria, and toxicity regulations could enhance market transparency and reduce cross-border barriers (NO1, FI3). At the local level, several interviewees argued that adapting building codes to recognize the properties of WFI would facilitate its use in varied contexts, ranging from renovations to new ecological developments (FI7).

In terms of market development, participants emphasized that incentives should also target underutilized segments such as small-scale residential construction, renovations, and commercial retrofits. They proposed tailored instruments—such as green loans,

retrofit subsidies, or performance-linked grants—as ways to stimulate demand in these areas (FI1, FI3, GER1, DK1). In addition, demonstration projects, including public-sector pilot sites and living labs, were frequently cited as critical for validating WFI's performance and reducing perceived risk (FI3, GER1, POL1, DK1).

3.3.3 Educational outreach and professional training

Interviewees emphasized that knowledge gaps and misconceptions regarding WFI's performance, durability, and installation continue to limit its uptake, even among industry professionals (FI2, FI5, FI6, GER1, POL1, SE1, DK1). From their perspective, addressing these gaps requires both comprehensive professional education and proactive public engagement.

Participants suggested that training should combine theoretical understanding with practical skills, covering appropriate use cases, compliance strategies, and real-world applications. Several interviewees observed that performance failures are often linked more to incorrect installation than to inherent material shortcomings (DK1). Updating vocational curricula and offering targeted continuing education programs were seen as effective ways to mitigate this issue (GER1, POL1, NO1, FI1, FI3, FI5, DK1).

Education was also described as playing a reputational role. According to experts, informed professionals are more likely to specify bio-based materials, thereby contributing to wider adoption. Certification schemes, credits for continuing education, and manufacturer-led workshops were identified as practical tools to improve sector-wide competence and confidence (GER1, POL1, NO1, FI5, DK1).

3.3.4 Consumer awareness and demand activation

Interviewees noted that although end-users have limited influence in large-scale construction projects, their role is more pronounced in residential and self-build markets. From their perspective, targeted public awareness campaigns could highlight the environmental and health benefits of WFI, thereby stimulating demand from the bottom up (FI1, NO1).'

Participants emphasized the importance of countering persistent myths—such as doubts regarding WFI's fire or moisture resistance—with empirical evidence and accessible success stories. They suggested that positive user experiences, disseminated via social media, community platforms, or local demonstrations, may help shift perceptions (NO1, NO2, FI5).

Consumer-facing incentives were also identified as potential drivers. According to experts, tax deductions for sustainable retrofits or rebates for certified materials could support informed purchasing decisions (GER1, POL1). In this view, engaged consumers may act as active market drivers, influencing both supply chains and innovation trajectories.

4 Conclusions

This study suggests, based on expert perspectives, that the primary barriers to the broader adoption of fire-retardant WFI in industrial timber construction lie less in the material's technical performance than in the structural misalignment between emerging

material capabilities and existing evaluation systems. According to the interviewed experts, conventional assessment methods across fire safety, thermal efficiency, and moisture performance do not sufficiently capture WFI's dynamic behavior in real-world building assemblies. Properties such as protective charring, phase-shift capacity, vapor buffering, and air flow resistance were described as undervalued or excluded in current classification systems, particularly those designed around static, material-level testing.

These perceived gaps in evaluation were interpreted by experts as reflecting a broader systemic issue: bio-based materials like WFI continue to be assessed against standards originally developed for mineral-based or petrochemical products. As a result, their actual performance in context-sensitive and climate-adaptive applications is often not recognized, reinforcing a regulatory and market environment that favors conventional solutions regardless of their suitability for contemporary building and climate policy goals.

From the perspective of participants, addressing these challenges requires a shift from static, prescriptive frameworks to more dynamic, performance-based assessment models. In fire safety, this would mean prioritizing system-level resistance to fire rather than solely reaction-to-fire classifications. In thermal performance, experts emphasized the importance of integrating phase shift, convective stability, and thermal inertia alongside steady-state conductivity. Moisture assessment, in turn, should evolve to capture buffering capacity, capillarity, and sorption hysteresis under varying climatic and use conditions. Such changes would require test protocols and simulation tools that reflect how materials interact with other components over time, rather than in isolation.

Policy development was repeatedly highlighted as a central factor in enabling such transitions. Although high-level goals such as decarbonization and circularity are increasingly embedded in EU and national agendas, experts observed that practical implementation through incentives, certification systems, and building codes remains fragmented. Current policy instruments were seen as rarely rewarding the full sustainability performance of WFI—particularly its role in long-term carbon storage, resource circularity, and low-toxicity material cycles. Harmonized standards for carbon accounting, recyclability, and safe additive use were regarded as steps that could support a more consistent regulatory environment across EU member states.

Beyond regulation, participants emphasized education and market awareness as essential enablers. Persistent misconceptions about the technical feasibility of WFI, especially in fire and moisture performance, were seen as underscoring the need for professional training and curricular reform. Suggested measures included certification programs, case study dissemination, and manufacturer-led workshops to close knowledge gaps. In addition, consumer-facing communication that highlights available empirical evidence and use-case benefits was viewed as potentially strengthening demand in sectors where individual decision-making plays a greater role, such as residential retrofits and self-build housing.

The study also brought forward expert concerns about challenges specific to material supply and end-of-life use. Logistics, fiber availability, and the competition between material and energy uses of wood were perceived as affecting the scalability of WFI. At the same time, opportunities were identified in increasing the use of recycled cardboard,

developing techniques for recycled wood fiber processing, and investing in end-of-life applications such as biochar production.

It is important to emphasize that these findings are derived from qualitative interviews with experts in six European countries and should be interpreted within the exploratory scope of the study. Several limitations must be acknowledged. First, the sample size was relatively small and unevenly distributed across countries and professional roles, which limits the breadth of perspectives. Second, participants were recruited primarily through professional networks, which may have introduced selection bias by favoring individuals already engaged with WFI-related topics. Third, certain key stakeholder groups—such as developers, insurers, and regulatory authorities—were not represented, leaving important decision-making perspectives unaddressed. Finally, as with all interview-based research, the findings reflect subjective interpretations and experiences rather than universal or directly generalizable evidence.

Further research should therefore complement these insights with quantitative performance testing, broader stakeholder engagement, and system-level assessments. Areas such as smoldering risk, additive toxicity, long-term hygrothermal modeling, and cost–benefit analyses merit closer examination to validate and extend the perceptions reported here.

Despite these limitations, the findings provide useful insights for different stakeholder groups. Regulatory agencies may draw on the results when considering revisions to fire safety and energy performance standards toward more functional, assembly-based approaches. Product developers could refine formulations and documentation to align with evolving regulatory, and procurement demands. Building professionals may use these insights to support the justification of WFI in design and specification, advancing climate-responsive construction practices. Researchers, meanwhile, are encouraged to close remaining knowledge gaps and further validate WFI's performance in diverse use scenarios.

Taken together, the perspectives collected in this study suggest that climate-resilient construction will require integrating novel material performance into equally adaptive regulatory, educational, and market systems. Unless reform occurs in how materials like WFI are evaluated, communicated, and supported, their potential to contribute to ecological and policy targets risks remaining unrealized—not due to intrinsic performance deficits, but due to the structural lag of the systems that define what performance means. It should also be noted that WFI, as defined in this study, encompasses both virgin wood fiber and cellulose-based insulation from recycled paper or cardboard; while many of the identified barriers and opportunities apply to both, certain aspects such as raw material availability are more material-specific.

Appendix

See Table 5

Table 5 Code definitions, rules, and sample quotations

Code	Definition	Inclusion rules	Exclusion rules	Example quotation
Awareness	Mentions of stakeholders knowing or not knowing about WFI as a material or technology	Use when participant describes general recognition or visibility	Don't use if focused specifically on *incorrect* knowledge → code as Misconceptions	"Knowledge of wood fibre insulation is limited among many builders." -SE1
Misconceptions	Incorrect assumptions or misunderstandings about WFI properties	Use when a participant highlights a misconception present in the market	Don't use if issue is lack of exposure/knowledge → awareness	"There are misconceptions about fire performance, such as the belief that cellulose-based products cannot be made fire-safe." -FI2
Research & education	References to need for studies, data, or training to support adoption	Include calls for more scientific validation or educational programs	Exclude if comment is only about regulation	"The rise of timber construction brings inexperienced actors, highlighting the need for education." -GER1
Fire standards	Mentions of national or EU fire standards constraining or guiding WFI use	Use when participant names specific fire classifications, standards, or approvals	Don't use for general conservatism	"Fire regulations group all combustible insulation together, although wood fibre chars and can remain undamaged behind gypsum, unlike plastics that melt and spread fire." -NO2
Technical regulation	Broader building regulations affecting WFI beyond fire (structural, acoustic, etc.)	Use when participant cites codes or official requirements	Don't use for voluntary sustainability guidance → Low carbon guidance	"The industry sees a need for specific regulations on thermal insulation, covering thermal and moisture performance in more detail." -FI2
Low carbon guidance	References to climate targets, embodied carbon standards, or LCA requirements	Use when participant links adoption to carbon reduction rules	Don't use if only about technical performance	"Changes in energy efficiency regulations and green building certification support the broader use of wood fibers." -POL1
Fire resistance	Comments on WFI's tested or perceived resistance to fire	Use when participant highlights performance test results	Exclude if focus is on regulation/standard, code separately	"Tests have shown that wood fibre can achieve high fire resistance ratings (EI 60–120) and maintain insulation performance under fire." -NO2
Moisture handling	Descriptions of WFI's capacity to buffer or manage humidity	Use when participant discusses technical behavior in moisture	Don't use for sustainability-only narratives	"A further advantage is that wood fibre can absorb moisture from surrounding materials." -GER2
Thermal value	References to insulation's thermal conductivity and energy performance	Include U-value, lambda, or energy comparisons	Don't use for moisture-related comments	"One advantage of wood fibre insulation is its capacity to store heat and release it later." -GER1
Costs	Economic aspects of WFI production, installation, or market competitiveness	Include affordability, subsidies, or life-cycle cost	Exclude if about risk-averse investment → Conservatism	"A key difficulty concerns initial costs" -POL1

Table 5 (continued)

Code	Definition	Inclusion rules	Exclusion rules	Example quotation
Conservatism	Attitudes of risk aversion among designers, regulators, or clients	Use for cultural, habitual, or organizational resistance	Don't use if constraint is explicitly regulation → Fire standards / Technical regulation	"The construction industry remains highly conservative, relying on familiar solutions that have been used for the past century." -FI3
Compliance gaps	Mentions of unclear or missing pathways for WFI to meet current rules	Use when participants note inconsistencies between rules and product	Exclude if general conservatism or lack of awareness	"Although fire class P0 allows project-specific assessments, it is rarely applied in industrial house production due to cost and regulatory uncertainty." -FI1
Lack of awareness	Overlaps with Awareness but specifically emphasizes absence of information	Use when explicitly framed as missing knowledge	Avoid duplicating "awareness" unless absence is stressed	"Unfamiliar timber solutions are priced higher, but costs decrease once experience is gained." -FI5
Circular use	References to recyclability, reuse, or end-of-life benefits of WFI	Include when circular economy concepts arise	Don't use for carbon-only talk → Low carbon guidance	"Some users are reluctant to adopt it, but recycling requirements provide an argument for wood fibre insulation." -SE1
Environmental trends	Broader societal or market movements toward sustainability influencing adoption	Use when participant points to external pressure from trends	Don't use if only about specific guidance → Low carbon guidance	"The green transition has renewed interest in circular practices, highlighting long-standing sustainable solutions."—FI2

Author Contribution
J.J. developed the research design, collected and analyzed the data, and prepared the first draft of the manuscript. E.I. contributed to the conceptual framing, provided methodological guidance, and co-wrote sections of the manuscript. M.K. and H.H. participated in the conceptual design of the study, supervised the research process, contributed to the interpretation of results, and provided critical revisions to the manuscript. All authors reviewed and approved the final version of the manuscript.

Funding
Open access funding provided by Tampere University (including Tampere University Hospital). This work was a part of the Ministry of Education and Culture's Doctoral Education Pilot under Decision No. VN/3137/2024-OKM-6 (Circular Materials Bioeconomy Network, CIMANET).

Data availability
Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate
In Finland, ethical review is not required for studies involving interviews with adult participants about their professional expertise, provided that informed consent is obtained and participants' rights (e.g., anonymity and the option to withdraw) are respected.Informed consent was obtained from all individual participants included in the study.

Consent to Publish
Consent for publication was obtained from all participants whose data or information is presented in a form that could potentially identify them.

Human or Animal Rights
All procedures involving human participants were conducted in accordance with the guidelines of the Finnish National Board on Research Integrity (TENK).

Competing Interests
The authors declare no competing interests.

Received: 18 August 2025 / Accepted: 10 October 2025
Published online: 07 November 2025

References

1. Karjalainen M, Ilgın HE, Somelar D. Wooden extra stories in concrete block of flats in Finland as an ecologically sensitive engineering solution In ecological engineering addressing climate challenges and risks. InTech Open. 2021. https://doi.org/10.5772/intechopen.101171.
2. European Commission, 2024. Energy Performance of Buildings Directive. Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en
3. Häkkänen L, Ilgın HE, Karjalainen M. The current state of the Finnish cottage phenomenon: perspectives of experts. Buildings. 2022;12(3):260. https://doi.org/10.3390/buildings12030260.
4. European Parliament and Council, 2024. Directive (EU) 2024/1275 of 24 April 2024 on the energy performance of buildings (recast). Official Journal of the European Union L 1275, 1–35. https://eur-lex.europa.eu/eli/dir/2024/1275/oj
5. Ilgın, H.E., Karjalainen, M., Koponen, O-P., 2021. Dovetailed massive wood board elements for multi-story buildings. In: LivenARCH VII: Livable environments & architecture: Other architect/ure(s): Proceedings, vol. 1, pp. 47–60.
6. Far C, Far H. Improving energy efficiency of existing residential buildings using effective thermal retrofit of building envelope. Indoor Built Environ. 2019;28(6):744–60.
7. ICF, 2024. Impact of building envelope thermal insulation on use-phase emissions – Final report. Insulation Industry. Available at: https://www.americanchemistry.com/content/download/16324/file/Impact-of-Building-Envelope-Thermal-Insulation-on-Use-Phase-Emissions.pdf
8. Ibn-Mohammed T, Greenough R, Taylor S, Ozawa-Meida L, Acquaye A. Operational versus embodied emissions in buildings—a review of current trends. Energy Build. 2013;66:232–45. https://doi.org/10.1016/j.enbuild.2013.07.026.
9. Hill C, Norton A, Dibdiakova J. A comparison of the environmental impacts of different categories of insulation materials. Energy Build. 2018;162:12–26. https://doi.org/10.1016/j.enbuild.2017.12.009.
10. Latif, E.H., 2020. A review of low energy thermal insulation materials for building applications. International Journal of Mechanical and Production Engineering 8(5), 84–88. Available at: http://iraj.in
11. Institut Bauen und Umwelt e.V. (IBU). (2018). EPD for Steico wood fibre insulation boards (EPD-STC-20190209-IBE1-DE). Berlin: IBU.
12. Institut Bauen und Umwelt e.V. (IBU). (2019). EPD for Isover mineral wool products (EPD-Isover-MW-2018). Berlin: IBU.
13. Rabbat C, Awad S, Villot A, Rollet D, Andrès Y. Sustainability of biomass-based insulation materials in buildings: current status in France, end-of-life projections and energy recovery potentials. Renew Sustain Energy Rev. 2022;156:111962.
14. Fuczek D, Czajka M, Szuta J, Szutkowski K, Kwaśniewska-Sip P. VOC emission from lightweight wood fiber insulation board. Forests. 2023;14(7):1300. https://doi.org/10.3390/f14071300.
15. Österberg, M., Karjalainen, M., Lintunen, J., Tammelin, T., Asikainen, A., Vakkilainen, E., Toivonen, R., Virta, P., Henn, A., Nuutinen, E.-M., Kohl, J., Hassinen, J., 2024. From timber to medicine: Value added for the forest sector through broadening the product portfolio. Report of the Finnish Forest Bioeconomy Science Panel 1/2024. http://urn.fi/URN:ISBN:978-952-65456-3-9
16. Natural Resources Institute Finland, 2025. Preliminary greenhouse gas inventory results for 2023: Forest land has turned into an emission source because the carbon sink of trees no longer cover emissions from forest soil. Available at: https://www.luke.fi/en/news/preliminary-greenhouse-gas-inventory-results-for-2023-forest-land-has-turned-into-an-emission-source-because-the-carbon-sink-of-trees-no-longer-cover-emissions-from-forest-soil
17. Asdrubali F, D'Alessandro F, Schiavoni S. A review of unconventional sustainable building insulation materials. Sustain Mater Technol. 2015;4:1–17.
18. Raja P, Murugan V, Ravichandran S, Behera L, Mensah RA, Mani S, et al. A review of sustainable bio-based insulation materials for energy-efficient buildings. Macromol Mater Eng. 2023;308(10):2300086.
19. European Commission, 2020. Circular economy action plan: For a cleaner and more competitive Europe. Available at: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
20. European Commission, 2021. EU taxonomy for sustainable activities. Available at: https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en
21. Scherz M, Wieser AA, Passer A, Kreiner H. Implementation of life cycle assessment (LCA) in the procurement process of buildings: a systematic literature review. Sustainability. 2022;14(24):16967.
22. Zerari S, Franchino R, Pisacane N, Llatas C, Soust-Verdaguer B. Addressing the difficulties and opportunities to bridge the integration gaps of bio-based insulation materials in the European construction sector: a systematic literature review. Sustainability. 2024;16(19):8711. https://doi.org/10.3390/su16198711.
23. Ministry of the Environment, 2017. Decree of the Ministry of the Environment on the fire safety of buildings (848/2017). Finnish Statute Book. Available at: https://www.finlex.fi/fi/lainsaadanto/saadoskokoelma/2017/848
24. Park SH, Lee M, Kang EC, Lee SM, Shim K. Manufacture of semi non-combustible wood-fiber insulation boards by inorganic fire-retardant treatment. Bioresour. 2020;15(4):8235.
25. Asli M, Sassine E, Brachelet F, Antczak E. Hygrothermal behavior of wood fiber insulation, numerical and experimental approach. Heat Mass Transfer. 2021;57:1069–85.
26. Ranefjärd O, Strandberg-de Bruijn PB, Wadsö L. Hygrothermal properties and performance of bio-based insulation materials locally sourced in Sweden. Materials. 2024;17(9):2021.
27. European Wood Policy Platform, 2024. A wood-based circular bioeconomy for a sustainable Europe: Green construction and innovative wood solutions (Policy Paper 2024, Final Version High-Level Meeting). International Union of Forest Research Organizations (IUFRO). Available at: https://woodpop.eu
28. European Commission, n.d. Just Transition Mechanism. Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_en
29. Charmaz K. Constructing grounded theory. 2nd ed. London: SAGE; 2014.
30. Corbin J, Strauss A. Basics of qualitative research: Techniques and procedures for developing grounded theory. 4th ed. Los Angeles: SAGE; 2014.
31. Rogers EM. Diffusion of innovations. 5th ed. New York: Free Press; 2003.
32. Guest G, Bunce A, Johnson L. How many interviews are enough? An experiment with data saturation and variability. Field Methods. 2006;18(1):59–82. https://doi.org/10.1177/1525822X05279903.
33. Silverman D. Interpreting qualitative data. 6th ed. London: SAGE; 2024.
34. Birks M, Mills J. Grounded theory: A practical guide. London: SAGE; 2015.

35. Tracy SJ. Qualitative quality: Eight "big-tent" criteria for excellent qualitative research. Qual Inquiry. 2010;16(10):837–51.
36. Buchanan, A. H., & Abu, A. K. (2017). *Structural design for fire safety* (2nd ed.). John Wiley & Sons. https://doi.org/10.1002/9781118700402
37. Finnish Association of Civil Engineers RIL, 2023. RIL 225–2023: Calculation of thermal transmittance of building components. RIL, Helsinki.
38. Gebke S, Thümmler K, Sonnier R, Tech S, Wagenführ A, Fischer S. Suitability and modification of different renewable materials as feedstock for sustainable flame retardants. Molecules. 2020;25(21):5122. https://doi.org/10.3390/molecules252151222.
39. Taylor, B. (2025, February 18). Europe's paper and board industry rebounds in 2024. Recycling Today. https://www.recyclingtoday.com/news/paper-containerboard-europe-cepi-2024-production-recycling-trade/
40. Ministry of the Environment, 2023. Rakennuslaki 751/2023 [Building Act No. 751/2023, Finland]. Finlex.
41. European Parliament and Council, 2024. Regulation (EU) 2024/3110 of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011, Official Journal of the European Union, L, 18 December 2024. Available at: https://eur-lex.europa.eu/eli/reg/2024/3110/oj/eng
42. European Union, 2024. Regulation (EU) 2024/3012 of the European Parliament and of the Council of 13 November 2024 establishing a Union certification framework for carbon removals. Official Journal of the European Union L, 6.12.2024. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R3012.

Publisher's Note