Systems Analysis

Comparative Performance Analysis of Mass Timber, Conventional, and SIPs Envelope Systems in Residential Buildings.

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The building envelope plays a crucial role in the construction industry, significantly influencing global energy consumption and greenhouse gas emissions —key contributors to climate change. Given that buildings account for a substantial portion of global energy use and emissions, improving the performance of building envelopes presents a major opportunity to reduce environmental impact and lower costs. In the U.S., residential housing accounts for about 21% of the total energy use, presenting a substantial opportunity for energy reduction through retrofitting solutions. This research focuses on evaluating the life cycle assessment (LCA), hygrothermal performance using WUFI® simulations, and thermal resilience of three distinct residential building envelope systems: Structural Insulated Panels (SIPs), a bio-based Cross-Laminated Timber (CLT) system, and a conventional stick-built system with continuous insulation. These systems were selected based on their common applicability to the climate conditions and the sustainability demand of the materials. Findings reveal that the bio-based CLT system exhibits superior moisture regulation and thermal resilience, while SIPs demonstrate high thermal performance. The conventional stick-built system shows moderate performance with notable moisture retention risks. These results underscore the potential for significant energy savings, reduced carbon emissions, and enhanced indoor environmental quality through the adoption of advanced building envelope systems. The study concludes with recommendations for the construction industry to implement sustainable and resilient envelope systems, thereby improving building performance and contributing to climate change mitigation.

Keywords: *Life-cycle Analysis (LCA), Building Envelope System, Energy efficiency, Thermal Resilience.*

Introduction

The building sector is a significant contributor to global energy consumption and greenhouse gas emissions, accounting for approximately 40% of the final energy demand and about 36% of emissions in the European Union [1]. This substantial energy demand is largely due to the poor thermal performance of existing building envelopes, particularly in structures built before current energy efficiency regulations were enacted. Enhancing the thermal efficiency of building envelopes is thus crucial for reducing energy consumption and mitigating environmental impacts. The building envelope is one of the most crucial elements influencing a building's energy efficiency, particularly in residential buildings, which account for approximately 21% of the total energy use in the United States [2]. Optimizing the building envelope has been shown to significantly improve thermal performance and reduce energy consumption. In cold and humid climates, this approach is essential for enhancing energy efficiency while maintaining occupant comfort. In these climates, building envelopes face unique challenges such as extreme low temperatures, heavy snowfall, and increased energy consumption. Advanced materials and technologies in climate-responsive building envelopes can enhance sustainability, reduce carbon footprints and operational costs, and improve thermal comfort under these environmental conditions [3].

One of these advanced materials is Cross-Laminated Timber (CLT), a key component of Mass Timber Construction (MTC). MTC has emerged as a sustainable alternative to conventional building methods, offering numerous benefits such as reduced carbon footprints, faster construction timelines, and improved building performance. CLT, as a primary MTC product, consists of multiple layers of wood panels bonded together at perpendicular angles, enhancing its structural strength and dimensional stability. Extensive research and industry applications have demonstrated that CLT provides superior thermal mass, which helps maintain stable indoor temperatures, excellent moisture management properties, and resilience to environmental stressors. While mass timber has been widely adopted in large-scale commercial construction, its application in residential buildings—particularly for retrofitting envelope systems—remains underexplored. Integrating CLT into residential envelope retrofits presents a promising opportunity for enhancing both energy efficiency and indoor comfort.

The present study examines CLT's potential in residential building envelopes, focusing on its sustainability, thermal performance, and resilience in comparison to conventional and Structural Insulated Panels (SIPs)-based systems. When

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evaluating different building envelope systems, it is essential to consider their hygrothermal performance, sustainability, and overall impact on energy efficiency. Various studies, as mentioned in the following literature reviews, have investigated these aspects to provide insights into the effectiveness of different materials and configurations.

Energy Efficiency of Residential Buildings

The energy efficiency of residential buildings is significantly influenced by the building envelope, particularly the facade. Retrofitting these facades can lead to substantial improvements in thermal performance and energy savings. This literature review explores various facade wall systems, focusing on their life-cycle analysis (LCA), thermal resiliency, and cost-effectiveness in cold and humid climates. For example, Mirzabeigi and Razkenari [4] explored the interconnected benefits of residential building envelopes for energy efficiency and thermal resilience. Their findings indicated that while some envelope wall strategies may not directly improve energy efficiency, they significantly enhance a building’s ability to withstand extreme heat events. The study emphasized the need for scalable envelope wall solutions that can be widely implemented to improve both energy efficiency and resilience. Similarly, Kneifel [5] focused on creating standard residential building designs to evaluate energy efficiency and sustainability, defining two prototype detached residential houses based on the 2009 International Energy Conservation Code (IECC). These prototypes served as baselines for analyzing homes built to older IECC codes, demonstrating significant energy savings and highlighting the benefits of adopting more stringent energy codes and implementing energy-efficient technologies in residential buildings.

Hygrothermal Performance

Hygrothermal management study is crucial in building envelope systems to prevent mold growth, improve durability, and maintain thermal performance. Cho et al. [6] evaluated the hygrothermal performance of cross-laminated timber (CLT) walls with different insulation systems, finding that CLT walls with external insulation exhibited lower total water content and consumed less energy compared to those with internal insulation. The study also indicated a minimal risk of mold growth across all CLT wall layers, with external insulation systems performing better in moisture management and thermal stability. In another similar study, Chang et al. [7] conducted a numerical analysis of the hygrothermal behavior of CLT wall assemblies in various environmental zones in Korea. Their simulations revealed that walls with external insulation were more effective in managing moisture and maintaining thermal stability, emphasizing the importance of selecting appropriate insulation materials and configurations to minimize mold growth risk and ensure energy efficiency.

System Design Considerations

In addressing the critical need for energy-efficient and sustainable building envelopes, studies have highlighted the importance of selecting and optimizing bio-based materials and configurations to enhance thermal performance, moisture management, and overall durability in residential buildings. For example, Kurzinski et al. [8] developed a zero-carbon bio-based wall panel to address energy inefficiencies in existing buildings, which are significant sources of carbon emissions due to poor insulation and air leakage. The study involved creating panels using cross-laminated timber (CLT) and bio-based insulation materials and testing them with hygrothermal modeling tools WUFI® [9] BIO and WUFI® Mould Index VTT across four U.S. climate zones. The results showed that these panels could reduce wall heat loss by up to 73% while maintaining acceptable mold growth risk, thus enhancing thermal performance and supporting sustainable building practices by reducing the carbon footprint and improving indoor environmental quality. In addition, Bourbia et al. [10] reviewed the state-of-the-art bio-based materials used in building construction, focusing on their hygrothermal characteristics and thermal performance. The materials discussed include hemp, wood, date palm wood, cork, alfa, and straw. Their review emphasized that bio-based materials offer significant advantages, such as being renewable, having low embodied energy, and being CO^2 neutral or negative. These materials are also excellent thermal regulators, which can improve in-use energy efficiency1. Their study highlighted the importance of optimizing these materials to enhance their performance in building envelopes, thereby supporting sustainable building practices by reducing the carbon footprint and improving indoor environmental quality.

Moisture Monitoring

Ensuring the longevity and performance of building envelope systems hinges on a thorough understanding of their moisture dynamics. This involves not only recognizing how materials absorb and release moisture but also implementing effective strategies to manage these processes. Kordziel et al. [11] focused on the moisture performance and durability of CLT panels, utilizing laboratory and field measurements alongside modeling to simulate water uptake and drying processes. Their findings highlighted significant moisture absorption and drying characteristics of CLT panels made from spruce-pine-fir and Douglas-fir lumber, with vapor diffusion playing a crucial role in the moisture dynamics of these panels. In a follow-up study, Kordziel et al. [12] monitored and modeled moisture levels in mass timber buildings, employing sensors to track Moisture Content (MC) over time and advanced modeling techniques to simulate moisture dynamics. The research underscored the significant impact of environmental conditions on moisture levels, recommending proper detailing to prevent water ingress, the use of vapor barriers, and the selection of appropriate wood species for effective moisture management.

The present study evaluates and compares the environmental impact, energy efficiency, and moisture management of three residential building envelope systems. This evaluation includes an LCA, an assessment of thermal resilience against power failure, and hygrothermal performance. In the following sections, key terms are defined, and the rationale for the study is outlined, leading to the formulation of hypotheses. This comprehensive analysis aims to provide valuable insights into the performance of these systems, thereby guiding future research and development in sustainable building practices.

Methodology

2.1 Study Design

The research aims to compare three different envelope wall systems—Stick-built with continuous insulation, SIPs, and Bio-based CLT—to assess their thermal performance, environmental impact, and moisture resilience in a residential setting. The study employs a combination of simulation tools, including the Building Transparency© [13] Embodied Carbon in Construction Calculator (EC3), EnergyPlus, and WUFI®, to provide data-driven results. The objective is to evaluate and compare the environmental impact, energy efficiency, and moisture management of these residential building envelope systems. The systems compared include Stick-built with continuous insulation, SIPs, and Bio-based CLT. The tools used in the study are EC3 for LCA, EnergyPlus for thermal resilience analysis, and WUFI® for hygrothermal performance simulations. This comprehensive analysis aims to provide valuable insights into the performance of these envelope systems, guiding future research and development in sustainable building practices.

2.2 The Envelope Wall Systems

In this project, three different envelope wall systems were selected to showcase their differences and effectiveness in a residential setting. The first system, a conventional stick-built assembly with continuous insulation, is designed to provide continuous thermal insulation. This system typically includes layers such as exterior sheathing, a continuous insulation layer, and an interior finish, all working together to enhance the building's energy efficiency by minimizing thermal bridging and improving the overall thermal envelope.

The second system, SIPs, integrates an insulating foam core sandwiched between two structural facings, typically the Oriented Strand Board (OSB). SIPs are known for their high thermal performance and quick installation. This system includes the SIP panels, an exterior finish, and an interior finish, providing a robust and energy-efficient wall assembly. The third system, a bio-based CLT wall, incorporates CLT panels and wool insulation with a cement exterior board. CLT is a sustainable building material made from layers of solid wood boards glued together at right angles, providing structural strength and stability. The wool insulation, made from natural fibers, enhances the thermal performance of the wall while offering environmental benefits such as reduced carbon footprint and improved indoor air quality. This system includes layers such as the CLT panels, wool insulation, a cement exterior board, and an interior finish, creating a robust and sustainable wall assembly.

As shown in Figure 1, each system's unique composition and performance characteristics regarding sustainability, thermal performance, and moisture penetration were analyzed to determine their effectiveness in wall section envelope applications. By comparing these systems, valuable insights were gained into their potential benefits and limitations, providing a comprehensive understanding of their applicability in residential envelope wall projects.

2.3 EC3 Life-cycle Assessment (LCA)

LCA is a widely recognized method for evaluating the environmental impacts of buildings throughout their life cycle. The delineation of system boundaries significantly influences the results of the LCA, and a flexible definition of these boundaries is essential depending on the research objectives [17].

For the LCA of three envelope wall systems, the EC3 platform created by Building Transparency© was utilized. EC3 is a powerful tool designed to evaluate the environmental impact of building materials by analyzing their embodied carbon, which is the total greenhouse gas emissions associated with the production, transportation, installation, maintenance, and disposal of these materials. EC3 was selected in this study due to its ability to provide detailed insights into the Global Warming Potential (GWP) of different construction assemblies.

By using EC3, comparisons of the GWP of each envelope wall system across various life cycle stages were made, identifying the most carbon-intensive components and enabling informed decisions to minimize the overall environmental impact. The building life cycle stages encompass various phases from production to end-of-life. As Figure. 2 shows, stages A1-A3 cover the product stage, including raw material extraction (A1), transportation to manufacturing sites (A2), and the manufacturing process itself (A3). Stages A4-A5 involve the construction process, with the transportation of materials to the site (A4) and the actual construction and installation activities (A5).

Stage B represents the use phase, which includes maintenance, repair, and operational impacts throughout the building's life. Stage C addresses the end-of-life phase, involving

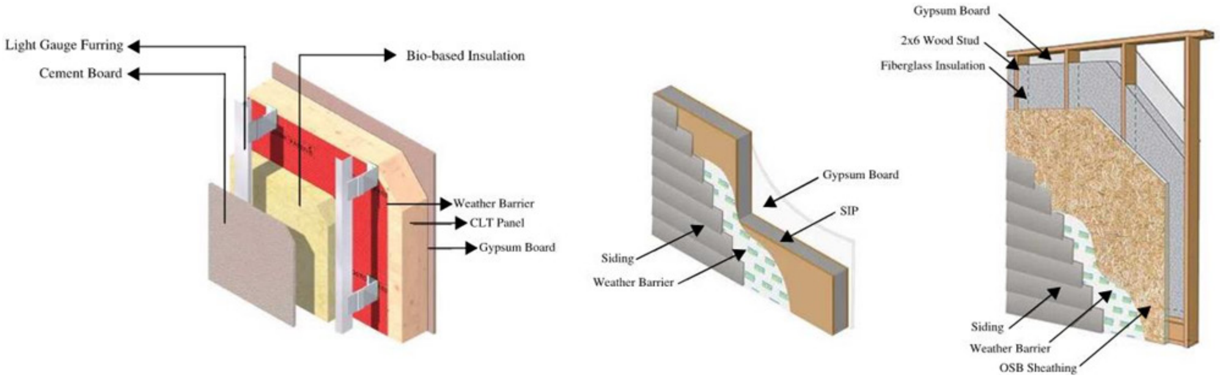

Figure 1. The Layers and Materials of Three Envelope System of CLT Bio-based, SIP, and Stick-built (Adopted with edits from [14], [15], and [16]).

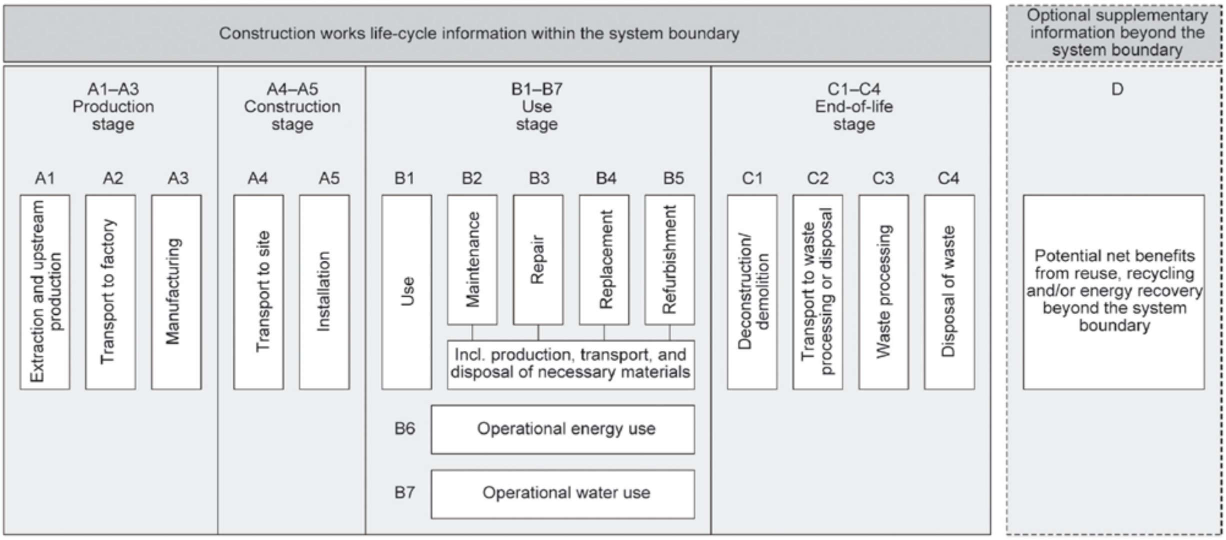

Figure 2. Building life-cycle stages. Adopted from [18]

deconstruction, waste transport, processing, and disposal. Stage D considers the benefits and impacts beyond the system boundary, such as recycling and reuse of materials. The focus of this study was placed on stages A1-A5 due to their critical role in determining the environmental footprint of the materials used in the envelope wall systems. Since the comparison was limited to three envelope wall systems for wall assemblies rather than a full building LCA, concentrating on the material life cycle in these initial stages provided the most relevant insights. The product and construction process stages are essential for understanding the embodied carbon and other environmental impacts associated with the materials and their installation, allowing for a detailed comparison of the environmental performance of the envelope wall systems. The results from EC3 included comprehensive GWP values for the A1-A3 and A4 phases of manufacturing and transportation for each wall system, allowing benchmarking against industry standards and optimization of material choices for sustainability.

2.4 Thermal Resilience Analysis

The purpose of thermal resilience analysis was to compare how three different envelope wall systems' thermal resilience capability under both extreme heat and power loss conditions. To this aim, the reference building model introduced by the U.S. Department of Energy [19] was used for the baseline building model development [20]. The geometry of building models replicates the residential single-family house. The building envelope characteristics were changed to create three different envelope wall systems, as described before. In the baseline model development, EnergyPlus was used to create and validate an energy model with available data or with assumptions. One single-floor zone represented the target zone model for the single-family house. There are various model inputs for the model including weather data, internal loads, and occupancy information [4].

Infiltration was set to 0.059 CFM per square foot of façade. For the transparent elements of the building envelope, the thermal transmittance value (U-value) of 0.60 BTU/(hr·ft²·°F).Solar Heat Gain Coefficient (SHGC) of 0.7, and visible transmittance (VT) of 0.8 have been considered. In addition, various internal load densities, including equipment (1.24 BTU/hr·ft²), lighting (1.11 W/ft²), and people (0.0028 people/ft², or 1 person per 35.8 ft²), were set according to the residential use. The occupancy, equipment, and lighting schedules were obtained accordingly from the default residential schedules of the Honeybee plug-in. The range of 68 - 75 F for the operative temperature was considered an acceptable level. The range of 75-82 F for the operative temperature was considered a habitable level, while an operative temperature that exceeds 82 F was considered an unhabitable level.

The impact of the disruption event was quantified using the metric of operative temperature [21]. The simulation framework is set up to account for the effect of direct solar radiation on thermal comfort, using the introduced framework in Grasshopper by Mirzabeigi et al. [21], with some modifications (to integrate the power loss with the proposed workflow). While different disruptive types of events can be considered in the simulation framework, this study considered a fixed duration of power loss and heat wave as disruptive events. In the post-processing phase, the operative temperature was calculated for the period of interest based on the environmental outputs from the simulation for each iteration (three simulations by changing the envelope configuration). This study conducted a case in Bristol, RI by simulating a four-day heat wave and blackout of July 16-19.

2.5 WUFI® Moisture Intrusion and Mold Growth

In this study, WUFI ® Pro 6 was employed to compare moisture intrusion and mold growth among the three envelope wall assembly systems. WUFI® is a simulation tool designed to predict mold growth based on hygrothermal conditions, providing insights into potential mold risks under varying environmental factors. WUFI® VTT and BIO, on the other hand, are adds-on to Pro used for analyzing the moisture performance of building components, allowing for a detailed assessment of how different materials and assemblies handle moisture over time. These tools were selected for their robust capabilities in simulating real-world conditions and providing comparative data on moisture dynamics and potential mold growth.

The analysis began by modeling each wall assembly with the exact layers previously used in the thermal and LCA analysis. This ensured consistency across all evaluations and allowed for a direct comparison of the assemblies' performance. The simulations were conducted considering the climate conditions of Bristol, RI, which is classified under ASHRAE Climate Zone 5A. This climate zone is characterized by cold winters and warm, humid summers, making it essential to evaluate the assemblies' ability to manage moisture and prevent mold growth effectively. Each assembly's total R-value, a measure of thermal resistance, was calculated to understand its insulation performance. The R-value is crucial as it indicates how well the assembly can resist heat flow, contributing to the overall energy efficiency of the building. Following this, the moisture penetration and mold growth rates over a specified period were analyzed for all three assemblies. The simulations provided detailed data on how each assembly performed in terms of moisture management and mold prevention in the given climate conditions.

The results of this analysis offered a comparative assessment of the three envelope wall systems, highlighting their effectiveness in preventing moisture intrusion and mold growth. This information is vital for determining which assembly is more suitable for use in residential buildings in Bristol, RI, ensuring better durability, indoor air quality, and overall performance in this specific climate zone.

The building details used in the modeling are based on a typical structure with a height of less than 33 feet, according to ASHRAE 160 standard [22]. Table 1 presents the properties of materials and products used in the selected wall assembly, sourced from the WUFI® built-in database. This includes specifications of major building products that have been experimentally tested and validated at the Fraunhofer Institute of Building Physics Laboratories in Munich, by relevant building codes and regulations. The wall section is assumed to be oriented west-east, with no sources of sinks or water leakage in any of its components.

3 Findings and Discussion

The present paper aims to evaluate and compare the

Table 1. Envelope Wall assemblies' description and material properties of the wall layers for WUFI® modeling

Envelope Typology	Layer Composition (Exterior to Interior)	Thickness (in)		Thermal Conductivity (Btu/hft°F)	Heat Capacity (Btu/lb°F)	Density (lb/ft³)	Permeability (perm.in)	Initial Water Content (lb/ft³)	Porosity (ft³/ft³)
Bio-based CLT **R=14**	Cement Board	5/16		0.0566	0.3105	25.6	0.2576	3	0.74
	Cavity with Light Gauge Furring	1/2		0.104	0.2388	0.0812	280	--	0.99
	Wool Insulation	2		0.0243	0.3344	9.6763	42.933	1.1861	0.981
	Weather Barrier	0		1.3	0.5493	8.12	0.258	--	0.001
	3-ply CLT	3 1/2		0.0693	0.3344	28.342	0.6345	4.5572	0.56
	Gypsum Board	1/2		0.1156	0.203	53.063	15.5181	0.3933	0.65
SIPs **R=19.8**	Siding	3/8		0.0543	0.449	46.196	2.4256	4.6821	0.666
	Weather Barrier	0		1.3	0.5493	8.12	0.258	--	0.001
	Structural Insulated Panel	OSB	3/4	0.05836	0.449	37.9	0.61	3.3	0.95
		Foam (EPS)	4 1/4	0.0208	0.3511	0.924	1.764	0.00375	0.99
		OSB	3/4	0.05836	0.449	37.9	0.61	3.3	0.95
	Gypsum Board	1/2		0.1156	0.203	53.063	15.5181	0.3933	0.65
Conventional **R=15.99 (cavity)** **R=5.1 (stud)**	Siding	3/8		0.0543	0.449	46.196	2.4256	4.6821	0.666
	Weather Barrier	0		1.3	0.5493	8.12	0.258	--	0.001
	OSB/Plywood Sheathing	1/2		0.05836	0.449	37.9	0.61	3.3	0.95
	Wood Studs (at stud)	5 1/2		0.0924	0.4777	37.5	0.9712	4.5	0.2
	Insulation (at Cavity)			0.02063	0.6076	3.4	64	0.41	0.93
	Gypsum Board	1/2		0.1156	0.203	53.063	15.5181	0.3933	0.65

environmental impact, energy efficiency, and moisture management of three residential building envelope systems: SIPs, a bio-based CLT system, and a conventional stick-built system with continuous insulation. In what follows, the section presents the data and results, focusing on the building's sustainability, moisture management, and thermal performance. The analysis is carefully organized to explain the methods used and the key outcomes. Advanced tools and life-cycle assessment techniques were used to evaluate hygrothermal performance, energy/thermal resiliency, and sustainability in each envelope wall system. The study found evidence in support of the effectiveness of bio-based CLT systems in reducing environmental impact and enhancing moisture management. SIPs demonstrated high thermal performance but had comparable environmental impacts to conventional systems. The conventional stick-built system showed moderate performance across all metrics but had higher moisture retention risks. These findings indicate that bio-based CLT systems offer significant advantages in sustainability and moisture management, while SIPs provide strong thermal insulation benefits. The findings are divided into three main areas: EC3 Life-cycle Assessment, WUFI® BIO and VTT Hygrothermal, and Thermal/Energy Resilience Analysis. Each part provides a detailed look at these aspects, highlighting important insights and their impact on improving building performance and sustainability.

3.1 EC3 Life-cycle Assessment

The analysis of the Global Warming Potential (GWP) for the envelope wall systems across stages A1-A3 (product stage) and stage A4 (transportation) reveals significant insights into the environmental impacts of different construction materials and systems. Figure 3 illustrates the conservative and achievable GWP for the three systems in stages A1-A3.

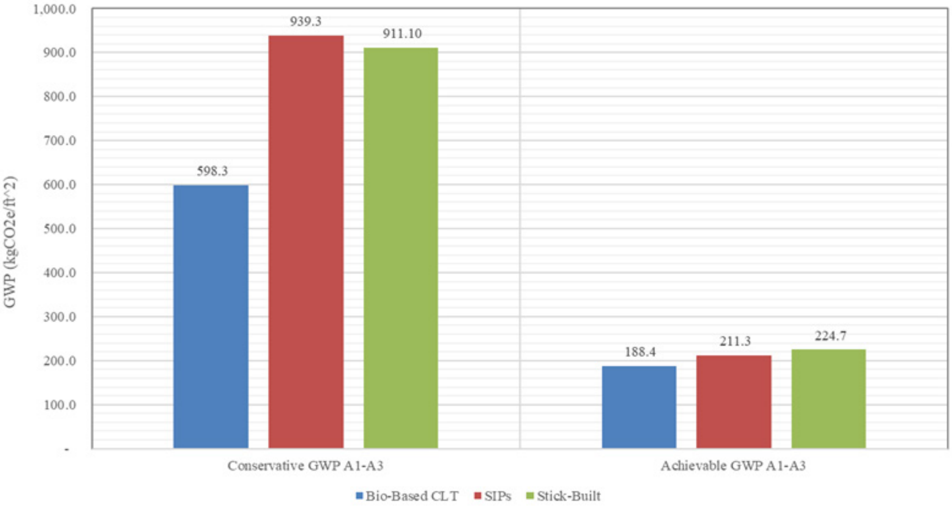

Figure 3. The Global Warming Potential (GWP) Impact of A1-A3 Stages Between Three Envelope Wall Systems

For the conservative GWP, the bio-based CLT system has a GWP of 598.3 kgCO2e, the SIPs system has a GWP of 939.3 kgCO2e, and the conventional stick-built assembly has a GWP of 911.1 kgCO2e. These values reflect the inherent environmental impacts of the materials and manufacturing processes used in each system, with the SIPs and conventional stick-built systems showing the greatest impact due to the use of traditional, energy-intensive materials. Interestingly, the GWP values for the SIPs and conventional stick-built systems are very close, both in their conservative and achievable scenarios. This proximity suggests that while SIPs offer advantages in terms of quick installation and high thermal performance, the environmental impact of their materials and manufacturing processes is comparable to that of the conventional stick-built system. This similarity in GWP values indicates that both systems have room for improvement in terms of reducing their carbon footprints.

When considering the achievable GWP, significant reductions are observed across all systems. The bio-based CLT system's achievable GWP in stages A1-A3 is reduced to 188.4 kgCO2e, highlighting the benefits of carbon sequestration and sustainable forestry practices. The SIPs system's achievable GWP is reduced to 211.3 kgCO2e, indicating improvements through innovative materials and advanced manufacturing technologies. The conventional stick-built assembly's achievable GWP is reduced to 224.7 kgCO2e, reflecting potential material sourcing and manufacturing improvements. Additionally, the GWP for stage A4 (transportation) is 249.4 kgCO2e for the bio-based CLT system, 117.8 kgCO2e for the SIPs system, and 129.1 kgCO2e for the conventional stick-built assembly, indicating the transportation impacts of each system.

In stage A4, which involves transportation, the bio-based CLT system has a GWP of 249.4 kgCO2e. Figure 4 highlights the transportation impacts, showing that the SIPs system has the lowest transportation-related GWP at 117.8 kgCO2e, reflecting the combined effect of material weight and transportation logistics. The conventional stick-built assembly follows with a GWP of 129.1 kgCO2e, attributed to the heavier weight and longer transportation distances of conventional materials. In contrast, the bio-based CLT system has a higher transportation GWP due to factors such as the logistics involved in sourcing and transporting timber. Between the layers that are composed in each system, each layer has a different impact on the total realized embodied carbon of the materials in the assembly. These differences are analyzed in Skankey diagrams shown in

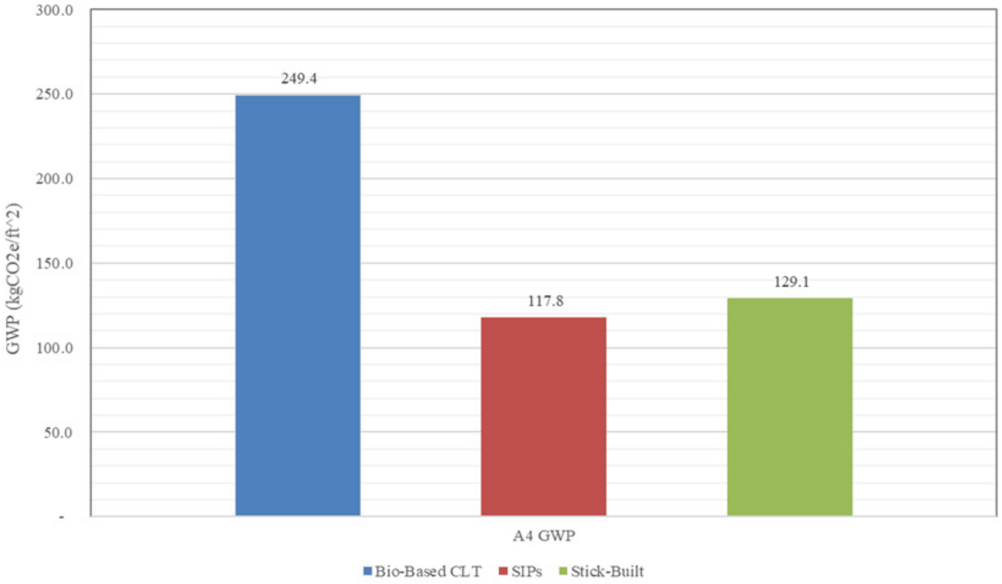

Figure 4. The Global Warming Potential (GWP) Impact of A4 Stages Between Three Envelope Wall Systems

Figures 5, 6, and 7 respectively for bio-based CLT system, SIPs assembly system, and conventional stick-built system.

These diagrams exclude the materials with negative GWP, such as CLT in bio-based systems, and OSB or Plywood sheathings in SIPs and stick-built systems but at the same time show how much each material is responsible for the total carbon emission of the whole individual system. The LCA results revealed that the bio-based CLT system had the lowest GWP compared to SIPs and the conventional stick-built system. This highlights the environmental benefits of using CLT, which not only reduces carbon emissions but also supports carbon sequestration. The scalability of CLT in residential retrofits further enhances its potential as a sustainable building material.

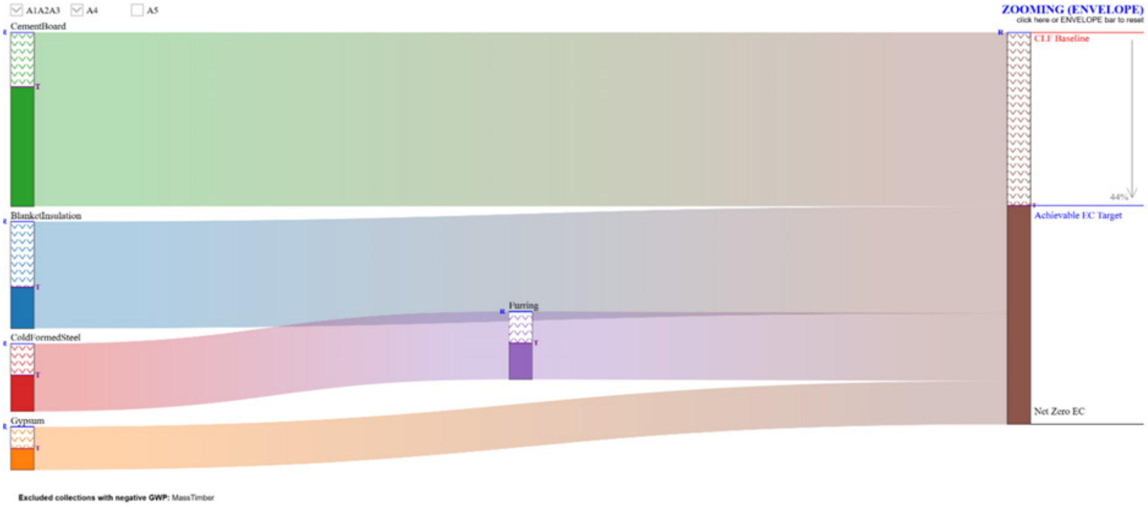

Figure 5. Bio-based CLT Skankey Diagram

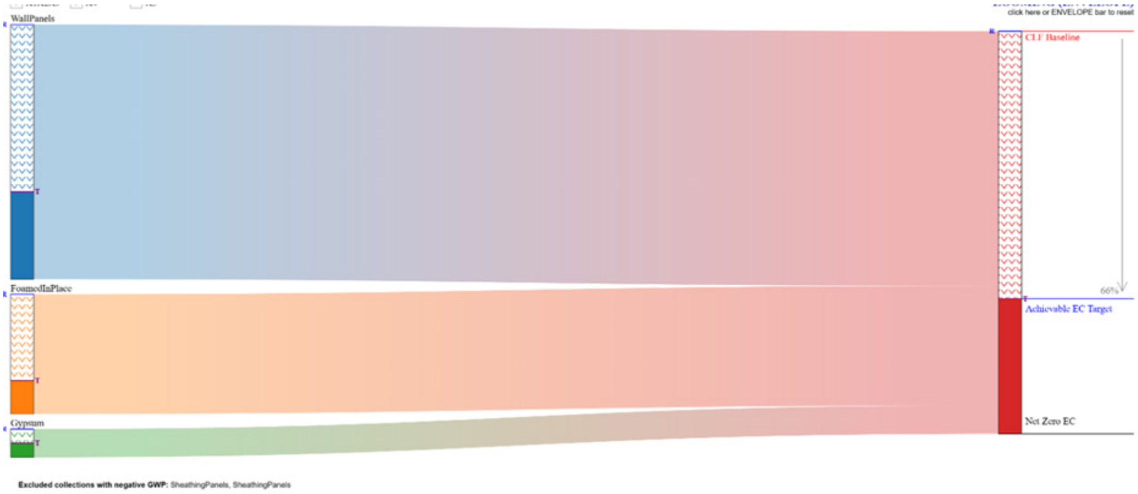

Figure 6. SIPs System Skankey Diagram

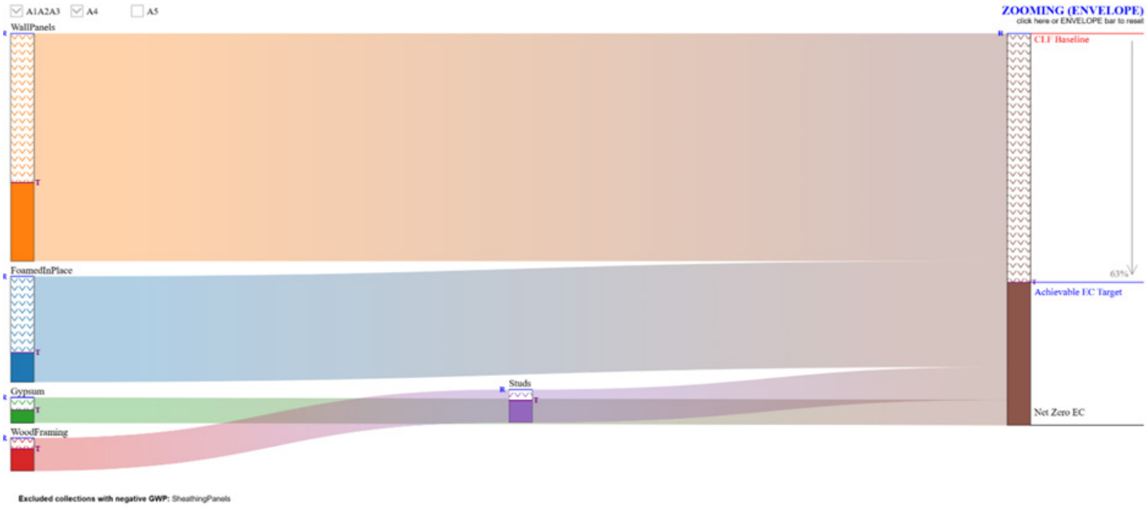

Figure 7. Stick-built Skankey Diagram

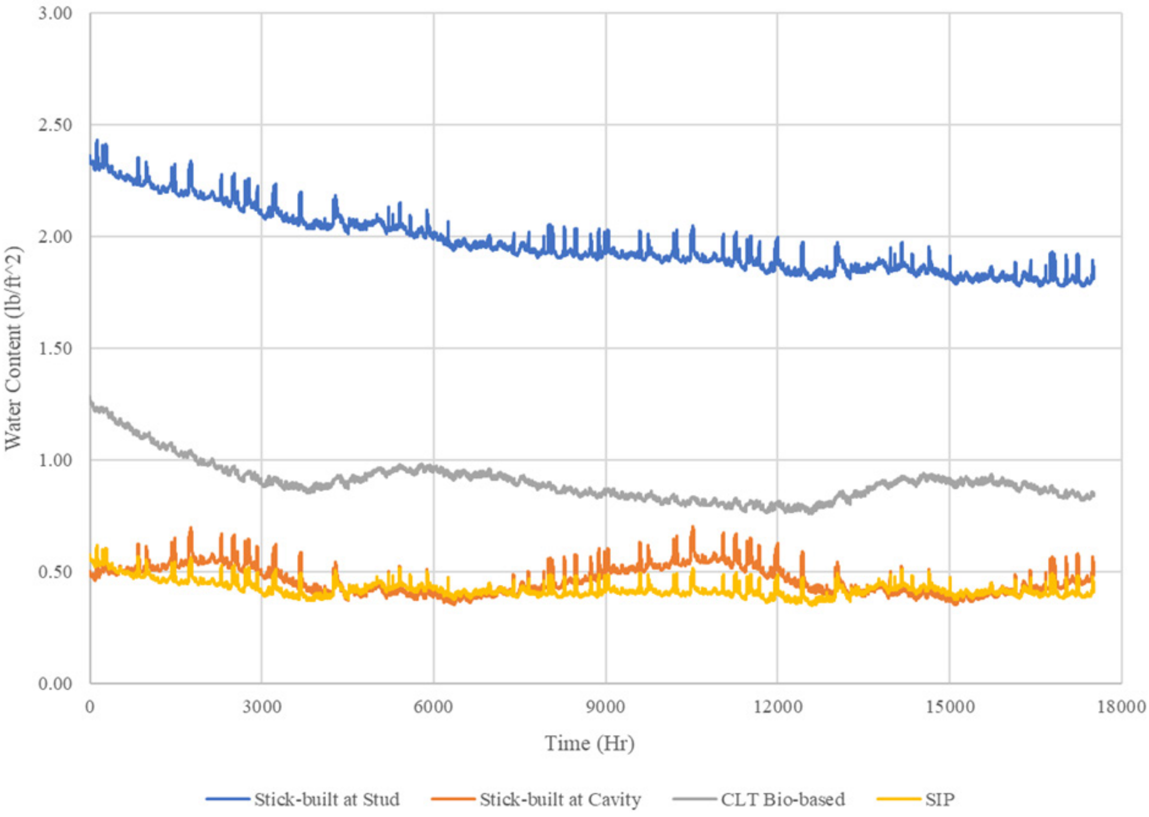

Figure 8. The Water Content Rate in Each Envelope System for the First Two Years of Service

3.2 WUFI® Moisture Intrusion and Mold Growth

A time period of five years was selected for the mold growth test (VTT) and a two-year period for the water content analysis since the data for the RH and MC was found to have the same repetitive curve after the second year. Therefore, only the first two years are presented here for the analysis and comparison between the systems for the water content in each system.

For building envelope systems, the ideal performance involves losing moisture quickly to prevent initial issues and then stabilizing to maintain long-term integrity and efficiency. The analysis of the building envelope systems as presented in Figure 8 revealed significant differences in their moisture management performance.

The initial water content and the rate of moisture loss and retention were critical factors in determining the effectiveness of each system. The stick-built system at stud demonstrated a moderate water loss rate of 8.15%, indicating a relatively stable performance over two years. In contrast, the stick-built system at the cavity, which utilized fiberglass insulation, exhibited an unusual increase in MC, resulting in a negative water loss rate of -8.08%. This anomaly suggested potential issues with moisture ingress or inadequate drying. These varying results and occasional increases in MC are due to the material properties of fiberglass, potential moisture ingress, environmental conditions, installation quality, and airflow issues. Addressing these factors through proper installation, effective vapor barriers, and adequate ventilation could potentially help stabilize moisture levels and improve the performance of the insulation.

The CLT envelope system showed the highest rate of water loss at 23.24%, indicating significant drying over the two-year period. Similarly, the SIP envelope system exhibited a high water loss rate of 21.74%, reflecting substantial drying. These findings suggest that the CLT and SIP systems are more effective in managing moisture by losing it quickly and then stabilizing, which is beneficial for preventing mold growth, and material degradation, and maintaining thermal performance.

Among the three building envelope systems analyzed in WUFI® VTT for this study, only the stick-built system at the stud exhibited mold growth over the first five years of service (Figure 9). The analysis was conducted over a five-year period because, even for the stick-built system at the stud, no mold growth was observed after the fourth year, making it more efficient to present the data in this manner. Although there was a very small amount of mold growth, it remained below 1, which is the threshold for the risky mold index according to the ASHRAE 160 standard [21]. The stick-built system at the stud showed a gradual increase in the mold growth index, starting from 0 and reaching a peak of approximately 0.004 in the first year. This growth continued at a slow rate, with the index fluctuating slightly but never exceeding 0.005 over the subsequent years. By the end of the

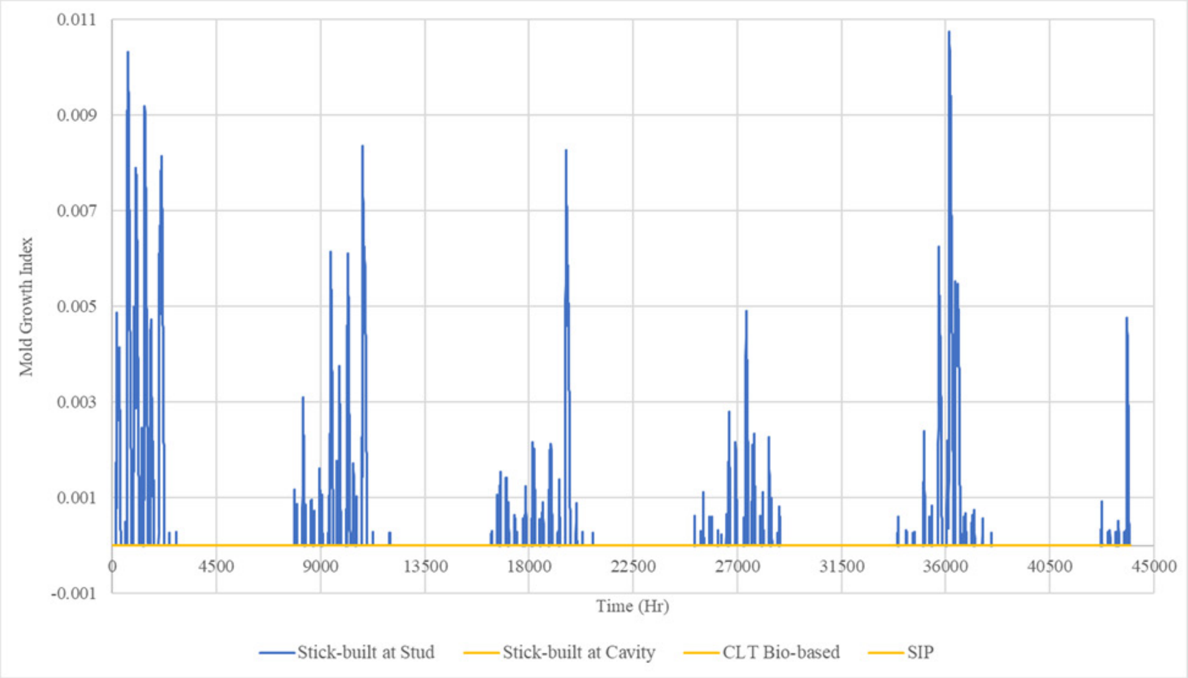

Figure 9. Mold Growth Index per WUFI® VTT for Three Envelope Systems over Five Years **of** Service

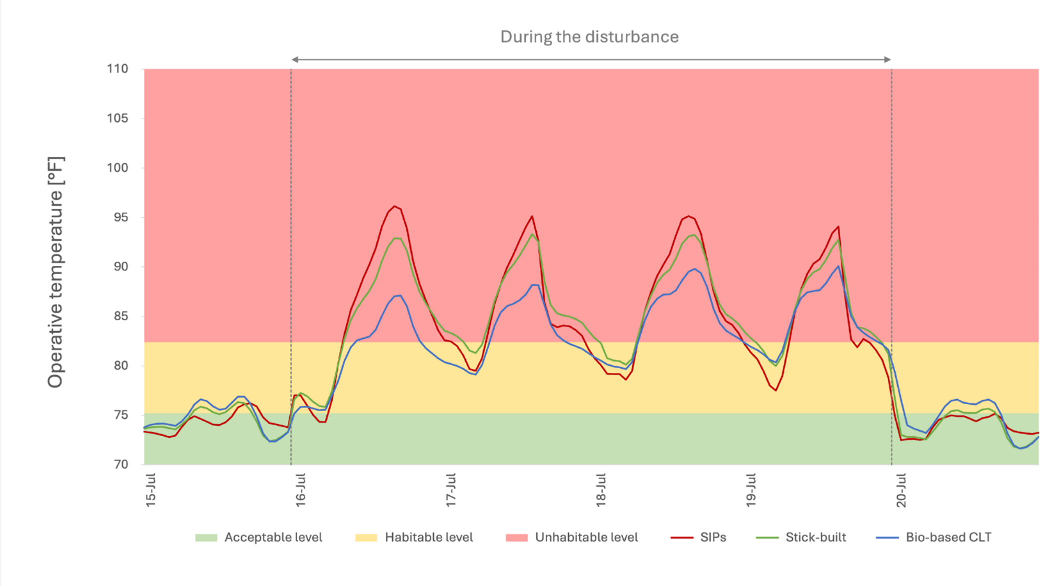

Figure 10. The Impact of Selected Envelope Systems on Thermal Resilience

fifth year, the mold growth index had stabilized and remained consistently below the critical value of 1, indicating that the risk of mold growth was minimal. This detailed analysis highlights the resilience of the selected systems in the service maintaining a no or low mold growth index over an extended period, even under varying environmental conditions. The findings underscore the importance of selecting appropriate building envelope systems to mitigate the risk of mold growth and ensure long-term durability and indoor air quality. The hygrothermal performance analysis in the present study demonstrated that the bio-based CLT system effectively managed moisture, reducing the risk of mold growth and moisture damage. This is crucial for maintaining the durability and indoor air quality of buildings. The study's findings on CLT's moisture buffering capacity emphasize its suitability for various climatic conditions, making it a reliable choice for mass timber construction.

3.3 Thermal Resilience Analysis

Understanding the thermal resilience of building envelopes is crucial for designing energy efficient and climate-resilient buildings, particularly in the face of extreme weather events and power outages. This section evaluates the ability of three envelope systems to maintain indoor thermal stability under a four-day power failure during a simulated heatwave. Figure 10 shows the time-dependent thermal resilience curve for three envelope systems in the living room zone.

The shape of the curves represents the actual performance of the building during the disturbance. Based on the simulation results, the thermal resilience of different envelope systems during a heatwave and power failure was analyzed. The post-processed time-series data (taking into consideration the solar radiation effect by simulation of the human manikin in the middle of the living room zone) illustrates how indoor operative temperatures evolve under a four-day power failure, emphasizing the impact of thermal mass and insulation. The SIP envelope system, despite its high insulation (R=19.8), exhibits rapid temperature spikes due to its low thermal mass, causing indoor conditions to quickly exceed habitable limits. In contrast, the bio-based CLT envelope system, benefiting from higher thermal inertia, demonstrates a delayed temperature rise and improved stability, staying within habitable levels for a longer duration (except during the peak solar radiation hours).

The conventional stick-built system shows moderate performance, heating up faster than CLT but performing slightly better than the SIP system. Overall, the bio-based CLT system provides the highest thermal resilience, maintaining lower indoor temperatures for a longer period during the blackout. This highlights the significance of incorporating thermal mass alongside insulation when designing buildings for extreme climate resilience. The findings support mass-timber construction as a viable passive design strategy to enhance occupant thermal comfort and reduce heat stress risks during power failures in hot conditions.

4 Limitations and Strengths

This study has several limitations that should be acknowledged. Firstly, the simulations and analyses were based on specific climatic conditions and may not fully represent the performance of the envelope systems in all geographic locations. Additionally, the study focused on three specific envelope systems, which may limit the generalizability of the findings to other types of building envelopes. The accuracy of the simulation tools (EC3, EnergyPlus, WUFI®) is dependent on the input data and assumptions made during the modeling process, which could introduce uncertainties in the results. Furthermore, the study did not account for long-term field validation, which is essential for understanding the real-world performance of these systems over extended periods. Despite these limitations, the study has several strengths that contribute to its value. The comprehensive approach to evaluating environmental impact, energy efficiency, and moisture management provides a holistic understanding of the performance of the envelope systems. The use of advanced simulation tools allows for detailed and data-driven analysis, offering insights that are beyond the scope of many other studies. The focus on bio-based materials and sustainable building practices addresses a critical area of research, contributing to the development of innovative solutions for reducing the carbon footprint of residential buildings. Additionally, the study explores the interconnected benefits of thermal resilience and energy efficiency, providing valuable guidance for future research and development in sustainable building practices.

5 Conclusions and Further Research

The present study evaluated the performance of bio-based CLT, SIPs, and conventional stick-built assemblies in terms of LCA, moisture management, and thermal resilience. The findings highlight the critical role of material selection in optimizing energy efficiency, durability, and climate resilience in residential buildings. The bio-based CLT system demonstrated the lowest GWP and superior moisture regulation, losing water quickly and preventing mold growth. Its high thermal mass contributed to enhanced thermal resilience, maintaining stable indoor temperatures for longer periods during heatwave-induced power failures. However, its transportation emissions were higher due to logistical challenges.

The SIPs system offered high insulation value but exhibited rapid temperature fluctuations due to its low thermal mass, while the conventional stick-built system showed the highest moisture retention risk and moderate thermal resilience, with some mold growth detected in the fiberglass-insulated cavity. These findings suggest that CLT is the most sustainable and resilient option among the selected envelope systems, though improvements in supply chain logistics could further reduce its environmental footprint. SIPs provide strong thermal insulation benefits, making them ideal for energy-efficient retrofits, while the conventional system remains viable but requires better insulation strategies to enhance long-term durability.

Future research should focus on long-term field validation of these envelope systems, hybrid wall designs that optimize both thermal mass and insulation, and cost-benefit analysis to assess large-scale adoption feasibility. Expanding resilience testing under various climate conditions will also provide deeper insights into year-round building envelope performance. This study reinforces the need for innovative, low-carbon building solutions to meet evolving sustainability and resilience demands. By integrating advanced envelope systems, the construction industry can significantly reduce energy consumption, improve occupant comfort, and extend building lifespans, contributing to a more sustainable and climate-resilient built environment.

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