

Experimental investigation of the dynamic hygrothermal performance of biobased wall assemblies under extremely cold conditions

Yuchen Chen^a , Pierre Blanchet^{a,*} , Louis Gosselin^c, João Vítor Felipe Silva^a , Xiaodong (Alice) Wang^b

^a Department of Wood and Forest Sciences, Faculty of Forestry, Geography and Geomatics, Université Laval, Quebec City, QC, G1V 0A6, Canada

^b Department of Mathematics, Computer Science and Engineering, University of Quebec in Rimouski, Rimouski, QC, G5L 3A1, Canada

^c Department of Mechanical and Industrial Engineering, Université Laval, Quebec City, QC, G1V 0A6, Canada

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ABSTRACT

Biobased materials play a crucial role in improving the hygrothermal performance and sustainability of building envelopes. While these materials offer significant benefits in thermal insulation and moisture regulation, comprehensive studies of their dynamic hygrothermal performance in extremely cold climates are limited. This study employed a climate chamber to reproduce severe cold conditions down to $-30\text{ }^{\circ}\text{C}$ and large diurnal temperature amplitudes to evaluate the hygrothermal performance of biobased wall assemblies under extreme winter climates. Full-scale split insulation assemblies with wood fiberboard and cork board as exterior insulation and hemp batt as interior insulation were tested under step change and sinusoidal temperature profiles. Long term mold growth risk was also examined through numerical simulations. The results demonstrate that the hygrothermal response of wall highlights a strong coupling between the temperature and the RH. Sinusoidal temperature variations provided a more realistic representation of the wall's thermal inertia compared with step change boundary conditions. Assemblies insulated with wood fiberboard and hemp batt exhibited superior moisture buffering capacity. In addition, five-year mold growth simulations indicated no mold risk for either biobased wall assembly under the selected climatic conditions.

1. Introduction

How can energy consumption and intrinsic carbon dioxide emissions in buildings be reduced simultaneously? One potential approach is to replace conventional insulation materials with biobased alternatives. Insulation materials play a crucial role in reducing energy consumption in buildings. In North America, conventionally used insulation materials include expanded polystyrene, extruded polystyrene (often used for exterior insulation), glass fiber, and mineral wool (typically used for interior insulation). However, several studies have highlighted that conventional insulation materials are characterized by high energy consumption and significant carbon emissions during their manufacturing processes [1–4]. In contrast, biobased insulation materials are characterized by low energy consumption during the processing, and can achieve carbon neutrality, or even carbon negativity. Consequently, they represent a key

* Corresponding author.

E-mail address: Pierre.Blanchet@sbfl.ulaval.ca (P. Blanchet).

pathway toward improving building energy efficiency and reducing greenhouse gas emissions [5–8].

Furthermore, due to the porous nature of biobased insulation materials, some, like hemp and wool, absorb water when exposed to high relative humidity (RH) and release it at lower RH. This property enables biobased insulation to act as a moisture buffer. Multiple studies have indicated that this property can passively regulate indoor RH balance [9–12]. Additionally, previous research has shown that, compared to traditional insulation materials, biobased insulations exhibit longer thermal inertia, contributing to energy savings in mitigating indoor temperature fluctuations [13–15]. Given these factors, biobased materials hold significant potential for applications in North American wood frame residential construction, both to reduce the environmental impact of buildings and to enhance occupants' living comfort.

Understanding the hygrothermal performance of building envelopes is critical for designing durable, safe and energy-saving buildings. Hygrothermal performance describes the coupled transfer of heat and moisture through envelope assemblies, which directly affects thermal comfort, mold growth risk, material degradation, and overall energy demand [3]. Common methods to evaluate the hygrothermal performance of biobased building envelope structures include theoretical models, laboratory-scale experiments, and full-scale testing [16]. Theoretical models are based on physical modeling and mathematical equations to predict hygrothermal insulation performance, while full-scale testing measures these properties in real full buildings. On the other hand, laboratory-scale testing provides more controllable boundary conditions.

Piggot-Navarrete et al. [17] conducted climate chamber experiments under steady-state boundary conditions to examine the effects of four common workmanship-induced defects on the airtightness and hygrothermal performance of wood frame wall assemblies. In the tests, the outdoor chamber was maintained at a constant -20°C and 50 % RH, while the indoor chamber was kept at 20°C and 40 % RH. The results indicate that any type of construction defect degrades the walls' hygrothermal performance, particularly by causing a pronounced increase in the RH at the OSB and wood structural interface, thereby increasing the risk of interstitial condensation and mold growth. Among all the defects, structural framing joints and vapor barrier punctured by staples exhibited the most detrimental impacts on wall durability. These defects substantially reduced airtightness, introduced pronounced thermal bridging effects, and increased the RH in wall by approximately 24 %. The study highlights the critical importance of construction quality control in wood frame buildings and suggests that prefabricated wall assemblies may effectively reduce the occurrence of workmanship defects at the source. However, the experiment focused on the effects of defects under steady-state conditions and did not address the wall's dynamic hygrothermal performance. Furthermore, the relatively short testing duration limited the ability to assess the long-term hygrothermal response and durability degradation associated with construction defects.

De Serres-Lafontaine et al. [18] conducted not only steady-state tests, but also performed step change outdoor conditions. In a climate chamber, four CLT walls insulated with biobased exterior insulation materials were tested. In the static test, the exterior boundary conditions were set at 10°C and 80 % RH to evaluate whether the different wall assemblies could reach a steady state hygrothermal distribution under constant environmental conditions. In the step change test, the exterior climate alternated between 10°C and 90 % RH and 30°C and 40 % RH every 12 h for 7 days to simulate the rapid temperature and RH fluctuations, characteristic of a spring day in a humid continental climate. The results indicated that wall assemblies insulated with wood fiber did not reach dynamic equilibrium during the 7 days static test, reflecting the material's pronounced hygroscopic behavior and thermal hysteresis. Under step change conditions, the wood fiber insulated walls exhibited a lower RH peak at the air barrier surface, demonstrated a better moisture regulation capacity compared with those insulated with stone wool.

Similarly, Palumbo et al. [15] conducted hygrothermal tests on External Thermal Insulation Composite Systems (ETICS) incorporating two biobased insulation materials, corn pith and wood. In these tests, the exterior temperature and RH varied progressively, following an approximately linear ramp. The hygrothermal performance of the biobased ETICS was then compared with an ETICS system using polystyrene foam. During the step change tests, the temperature gradually increased from 15°C to 30°C , while RH decreased from 80 % to 32 %. Each cycle lasted 24 h, with each test consisting of six identical cycles, designed to simulate typical spring weather under mild climatic conditions. The results indicated that the temperature and mass of the biobased walls changed more gradually over time compared to the EPS walls. Additionally, it took longer for the biobased walls to reach their stable temperature and mass. This behavior can be attributed to the higher thermal inertia and moisture absorption capacity of the biobased insulation boards.

The studies described above were hygrothermal tests conducted in a climate chamber under steady-state, step change, or progressively changed hygrothermal boundary conditions. Although those boundary conditions provide important information on the hygrothermal properties of materials, actual outdoor boundary conditions do not change abruptly but instead exhibit continuous, smooth, and diurnally periodic fluctuations. For example, long-term monitoring by Simonson et al. [19] indicates that the daily variation of outdoor temperature and RH more closely follows a sinusoidal pattern rather than a simple step input. From a theoretical standpoint, Peuhkuri and Rode [20] compared step, square-wave, and sinusoidal boundary conditions and concluded that sinusoidal inputs better represent the periodic characteristics of real climates. Therefore, sinusoidal boundary conditions are more suitable for investigating the realistic dynamic hygrothermal response of materials.

In a study by Rahim et al. [21], the authors not only evaluated the hygrothermal performance of a hemp lime concrete wall (HLC) and a straw rape concrete wall (SLC) under step change boundary conditions, but also conducted dynamic hygrothermal performance tests. In the step change experiments, the temperature was maintained at a constant 20°C while the RH varied between 50 % and 85 %. In the dynamic tests, the authors applied sinusoidal boundary conditions to the exterior surface, where both temperature and RH fluctuated following 24-h cycles. The imposed outdoor temperature varied between 5°C and 15°C in the winter scenario, and between 20°C and 30°C in the summer scenario, while the corresponding RH varied between 50–80 % and 45–70 %, respectively. The steady-state tests showed that both types of biobased walls exhibited significant moisture buffering capacity. The dynamic test results further revealed that both HLC and SLC displayed pronounced thermal inertia, and a strong heat and moisture coupling effect.

Giuffrida et al. [11] addressed the limited thermal performance of Compressed Earth Blocks (CEB) by adding two types of biobased insulation materials, lime hemp (LH) and sugarcane bagasse (SB), to the exterior side of CEB walls. Three walls (CEB, CEB + SB, CEB + LH) were tested by using a climatic chamber under steady-state and dynamic outdoor temperature modes. The steady-state results showed that the addition of biobased insulation significantly increased the thermal resistance of the walls. The thermal resistance of CEB + LH was approximately four times higher and nine times higher for CEB + SB compared to the uninsulated one (CEB). In the dynamic tests, the outdoor temperature followed a sinusoidal cycle between 5 and 10 °C with a 24-h period to simulate a mild Mediterranean winter climate. The thermal inertia results demonstrated that the walls with biobased layers exhibited significantly higher thermal inertia. The CEB + LH configuration showed the highest performance, with a time lag of 6.9 h, followed by CEB + SB at 4.8 h, while the CEB wall presented a time lag of only 3.78 h. However, the study focused solely on thermal behavior and did not investigate moisture content variation or moisture and heat coupling effects.

The above studies focused on single climate chamber experiments of biobased wall assemblies. However, an increasing number of studies employ multi-scale hybrid methodologies that integrate laboratory experiments with numerical simulations to more comprehensively assess the biobased wall assemblies' long term hygrothermal performance and durability.

Benmahiddine et al. [12] conducted a multi-scale hygrothermal analysis of hemp concrete. Starting with material-scale experiments and extending through climate chamber to a building scale COMSOL-TRNSYS co-simulation. The study focused on quantifying the influence of the hysteresis occurring during the adsorption-desorption process on the hygrothermal behavior of the material and on the accuracy of building energy predictions. The results demonstrated that the impact of hysteresis on moisture transfer was consistent across the material, wall, and building scales. When hysteresis was considered, the deviation in predicted RH decreased from approximately 16 % to 6 %, while temperature variations remained almost unaffected. The study confirmed that incorporating the hysteresis mechanism into coupled heat and moisture models can significantly improve the reliability of predicting the hygrothermal

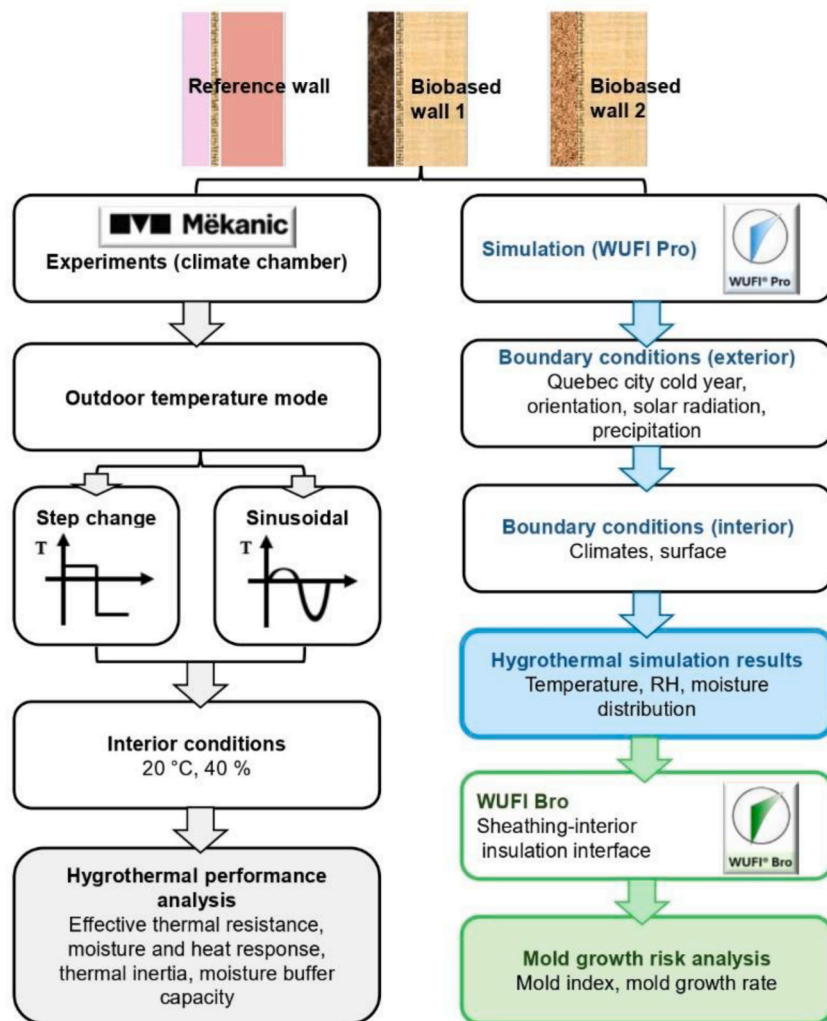


Fig. 1. Experimental and simulation workflow for hygrothermal analysis of biobased and reference walls.

performance of hygroscopic biobased envelopes and the accuracy of indoor energy assessments. However, the research did not address thermal inertia and thus did not include a comprehensive characterization of the coupled moisture-thermal inertia response of biobased wall systems.

Dams et al. [22] evaluated the hygrothermal performance of five innovative biobased external wall systems by combining Large Environmental Chamber (LEC) testing with 1-D simulation using WUFI Pro. These wall systems integrated different structural configurations (CLT, timber frame, and light-gauge steel frame), with biobased insulation materials (sheep's wool, wood fiber, mycelium, and cellulose). The experiments were conducted under steady-state temperature conditions (25 °C on the indoor chamber and 10 °C on the outdoor chamber) with uncontrolled RH to assess steady-state heat transfer and dynamic moisture transport responses. Results showed that the measured U-values of the five biobased wall systems ranged between 0.119 and 0.224 W/(m²·K), with four of the five walls achieving values below the UK Building Regulations benchmark of 0.18 W/(m²·K), indicating that their thermal performance is comparable to that of conventional wall systems. Simulation results indicate that all biobased wall assemblies reached moisture equilibrium within approximately one year, showing strong agreement with the LEC experimental data. Among the tested systems, the wood fiber and sheep wool walls exhibited pronounced moisture buffering capacity, effectively moderating external RH fluctuations. However, as with other large scale climate chamber experiments, this study had certain limitations in boundary conditions. The experiments applied a constant temperature difference, without considering diurnal temperature variations.

In summary, although existing studies have conducted either single or multi-scale hygrothermal analyses of various forms of biobased wall assemblies in climate chambers, challenges remain regarding their application in North America. First, research on the hygrothermal performance of typical North American wood frame walls is relatively limited, as most published studies focus on masonry or concrete wall systems in Europe. Second, there is a lack of hygrothermal experiments conducted under extremely cold or subzero conditions, resulting in insufficient empirical evidence regarding the suitability of biobased walls in severe cold climates. Finally, the coupled heat and moisture behavior of biobased materials within wood frame wall assemblies remains limited. Therefore, as shown in Fig. 1, this study carried out hygrothermal tests on two full-scale biobased wood frame wall assemblies compared with one conventional wall in a climate chamber under sinusoidal dynamic boundary conditions, while also comparing the results with step change conditions. The minimum experimental temperature was set to −30 °C to represent severe cold climates. Subsequently, long-term numerical simulations were performed for the highest RH surface within the walls to evaluate mold growth risks under realistic conditions. This study enriches the experimental dataset on the hygrothermal performance of biobased walls in extremely cold environments and provides new insights into the influence of different outdoor temperature variation modes on their thermal inertia, moisture buffering, and durability.

2. Methodology

2.1. Experimental wall assemblies

Three test walls were constructed using split insulation wall systems for cold climate applications. Split insulation wall assemblies typically refer to conventional 2 × 4 or 2 × 6 interior insulated wood frame walls that incorporate an additional continuous exterior insulation layer over the sheathing [23]. The continuous placement of exterior insulation can effectively increase the overall effective thermal resistance of the wall, together with the thermal resistance provided by the interior insulation within the wood frame, can offer effective thermal protection for above-grade wall assemblies. In cold climates, the addition of exterior insulation raises the temperatures of the sheathing and wood framing, thereby reducing the risk of interstitial condensation caused by vapor flow and air leakage [24]. The typical components for a split insulation wall, from exterior to interior, include siding, weather barrier, exterior insulation, sheathing, interior insulation, vapor barrier, and gypsum board [24]. To facilitate proper installation within the climate chamber, the siding and gypsum board layers were excluded from all walls tested in this study.

Table 1 shows the hygrothermal properties and the thickness of the wall components. Values were primarily sourced from manufacturers' material property sheet. The hygrothermal properties of wood siding and gypsum board were obtained from the WUFI Pro

Table 1

Hygrothermal properties and the thickness of wall components from material property sheet provided by the manufacturer and WUFI Pro.

Material	Density	Porosity	Special Heat capacity	Thermal conductivity	Diffusion resistance factor	Thickness
	(kg/m ³)	(m ³ /m ³)	(J/kg·K)	(W/(m·K))	(–)	(mm)
Composite wood siding	740	0.666	1880	0.094	53.1	10.5
Weather barrier	150	0.001	2300	2.4	55	1
XPS	28.6	0.95	1470	0.03	100	50
Cork board	143	0.22	1900	0.0417	28.3	50
Wood fiber board	320	0.97	1880	0.053	16.8	38
OSB	650	0.85	1880	0.13	812.5	15
Glass fiber	16.1	0.99	840	0.04	1.21	140
Hemp batt	35.25	0.78	1700	0.0391	2	140
Variable vapor diffusion membrane (W1)	105	0.001	2300	2.3	4359	1
Highly breathable membrane (W2 and W3)	112	0.001	2300	2.3	32.3	1
Gypsum board	625	0.73	850	0.2	8.33	13

database for numerical simulation. The insulation materials used in the reference wall assemblies, XPS and glass fiber, are commonly used insulation materials [25]. The selected biobased insulation materials, including cork board, wood fiber board, and hemp batt, are all readily obtainable within the current North American market.

The wall frame was built from spruce-pine-fir (SPF) and first assembled flat on the ground, as shown in Fig. 2 (a). The SPF were connected by nails, and each test wall measured 2.92 m in width and 2.676 m in height. Wood studs were spaced at 0.4 m intervals. Oriented strand board (OSB) panels were then installed on the upward-facing side and joined to the frame, as shown in Fig. 2 (b). After assembly, the wall was lifted into a vertical position using a crane. The insulation material was gently placed between the wood studs, as shown in Fig. 2 (c). Once the interior insulation was in place, the exterior insulation board was added to the exterior surface of the OSB. After placing the sensors and applying the interior and exterior membranes, the wall was lifted and moved between the two climate chambers, as shown in Fig. 2 (d). Sensor ends were connected to the monitoring system inside the chambers. The interior chamber was then moved to press the wall tightly between the two chambers. Finally, to ensure airtightness during the test, sealing tape was applied along the contact edges between the wall and the chambers, as shown in Fig. 2 (e).

The schematic configurations of three experimental walls are illustrated in Fig. 3(a)–(d), and (g), respectively. W1 served as the reference wall, incorporating extruded polystyrene (XPS) as the exterior insulation (Fig. 3 (b)) and glass fiber as the interior insulation (Fig. 3 (c)). W2 and W3 represented biobased walls, using cork board (Fig. 3 (e)) and wood fiber board (Fig. 3 (h)) for the exterior insulation, respectively. Both W2 and W3 utilized the hemp batt as interior insulation materials (Fig. 3 (f and i)). W1 and W2 have a thickness of 0.208 m, while W3 has a thickness of 0.196 m.

2.2. Climate chamber

The climate chamber tests were conducted at Université Laval in Quebec City (Canada), and the custom-built chamber was manufactured by Mekanik (Canada). As shown in Fig. 4 (a), the climate chamber comprises of an outdoor and an indoor chamber that can provide varied RH and temperature conditions to simulate outdoor and indoor boundary conditions. The exterior chamber's temperature can be adjusted between -30°C and 30°C , with a cooling rate of $0.3^{\circ}\text{C}/\text{min}$ and warming rate of $0.6^{\circ}\text{C}/\text{min}$, respectively. Its RH can be set between 20 % and 80 %. Meanwhile, the interior chamber can adjust its temperature between $+5^{\circ}\text{C}$ and $+50^{\circ}\text{C}$, with both a cooling and a warming rate of $0.3^{\circ}\text{C}/\text{min}$. Its RH range is also adjustable between 15 % and 90 %. Both chambers maintain a temperature stability of $\pm 1.7^{\circ}\text{C}$ and a humidity stability of $\pm 2.0\%$ RH. In Fig. 4 (b), the wall surfaces exposed to the climate chamber conditions are outlined with solid lines.

Before placing the wall inside the climatic chamber, RH sensors from Honeywell (HIH-4000-001) with a precision of $\pm 3.5\%$ at 25°C and temperature sensors from Omega RTD (NB-PTCO-006) with resistance tolerance $\pm 0.3\%$ were placed at different predefined positions of the wall. Fig. 4 (b) shows the location of the temperature and RH sensors placed at the center of the wall at three different heights. These sensors are positioned at the upper (blue area), middle (orange area), and lower (green area) of the wall, corresponding to T (Top), M (Middle), and B (Bottom) in Fig. 4 (c). In addition, temperature and RH sensors were installed on each wall surface at these three height levels. Fig. 4 (c) presents a cross-section view of the wall, illustrating the placement of the sensors at different surfaces. As the x-axis increases, the wall layers move closer to the interior, while the wall height increases along the y-axis. The sensor readings were collected by an acquisition system connected to the chambers. The red triangles represent RH sensors, while green squares indicate temperature sensors.

2.3. Experimental setup

Two outdoor boundary conditions were evaluated: by step changes and sinusoidal variations, as described by Fig. 5(a) and (b). Both profiles were tested on each test wall for five days. The five-day testing period was selected to capture the stabilization of thermal and hygric cycles within the wall assemblies under repeated forcing. Preliminary observations during system conditioning showed that the temperature and RH responses converged toward a stable periodic regime after approximately two to three full cycles. Extending the experiment to five days ensured that all three wall types experienced multiple repeated cycles, allowing assessment of peak values, phase behavior, and amplitude attenuation under steady dynamic conditions. Although long-term effects such as seasonal moisture accumulation cannot be observed experimentally in such a timeframe, the controlled five-day period is sufficient to characterize short-

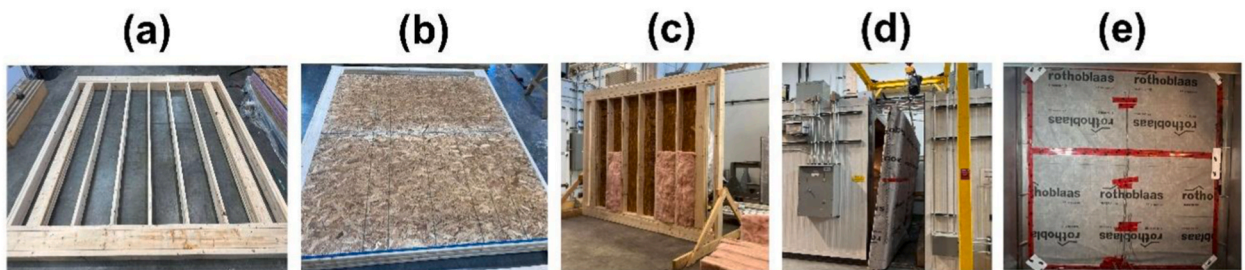


Fig. 2. Wall assembly process at laboratory. (a) wood frame layout; (b) OSB panels fastened to the wood frame; (c) installation of interior insulation; (d) wall positioned between climate chambers; (e) sealing with tapes.

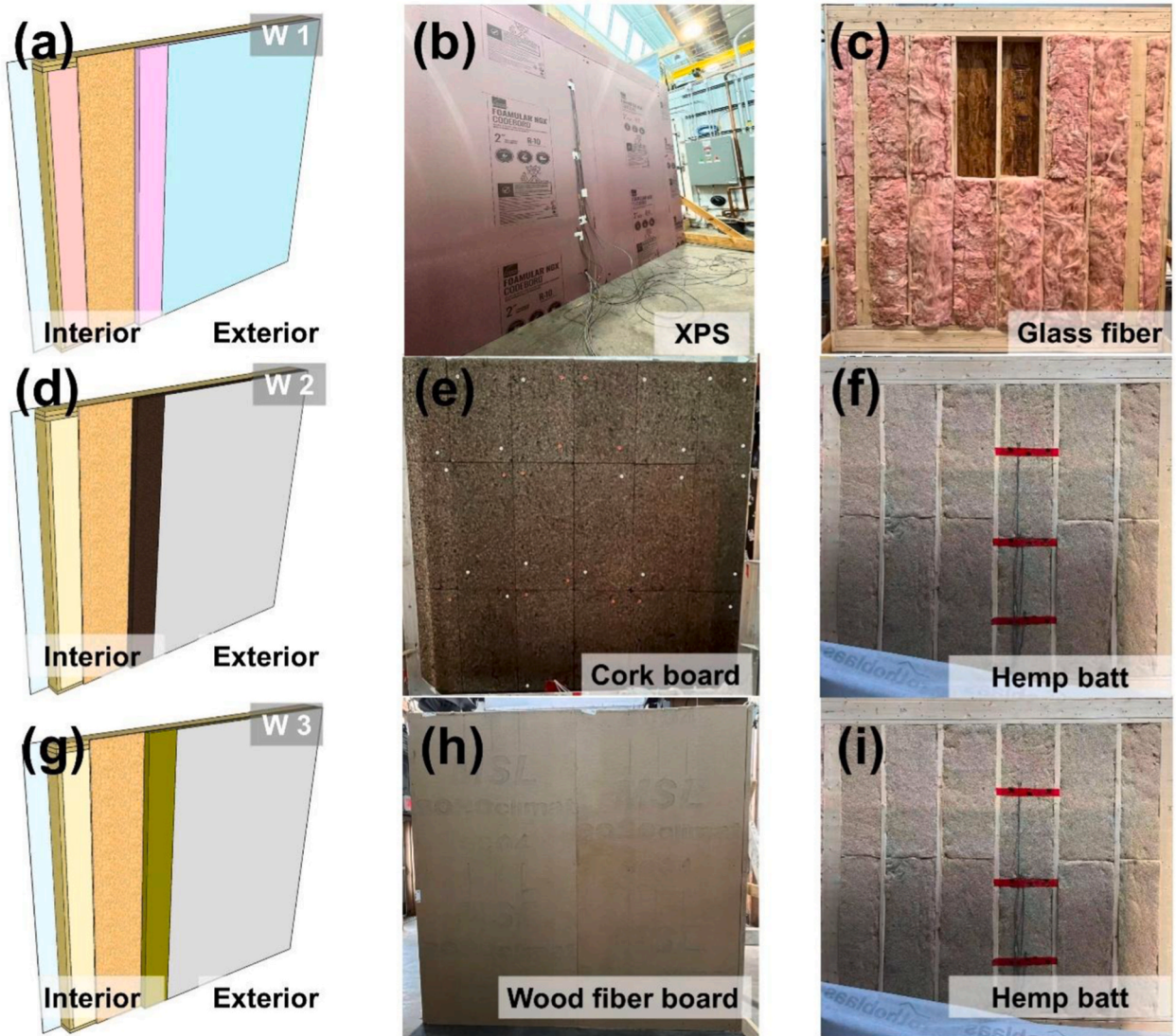


Fig. 3. Three wall specimens (a) W1, (d) W2 and (g) W3, with corresponding exterior insulations (b) XPS, (e) cork board and (h) wood fiber board; and interior insulations (c) glass fiber, (f) and (i) hemp batt.

term dynamic hygrothermal behavior, which was the primary objective of the laboratory campaign. Long-term risks were subsequently evaluated through numerical simulations, which complement the short-term measurements and extend the analysis over realistic time scales.

Prior to the experiment, the test materials were placed in a controlled laboratory environment at 20 °C and 65 % RH for approximately one month to reach a steady state. The solid black line in Fig. 5 represents the temperature, and the dashed red line represents the RH. To simulate extremely cold winter conditions with significant temperature fluctuations, the outdoor temperature varied from −30 °C to 10 °C over a 24-h period. This approach enabled a clearer observation of the wall's thermal inertia behavior. Due to the control limitations of the chamber, once the temperature drops below −20 °C, RH can no longer be precisely regulated. Therefore, instead of implementing sinusoidal RH variations, the focus was on maintaining a stable RH of 50 %. Nevertheless, even when aiming for a stable RH of 50 %, adjustments were still necessary. When the temperature dropped below −20 °C, the RH had to be modified to 60 %.

When under the step change boundary conditions, the 24 h-period was divided into 12 h at 10 °C and 50 % RH and 12 h at −30 °C and 60 % RH, as shown in Fig. 5 (a). When under the sinusoidal boundary conditions, the temperatures were set to 10 °C, 6.2 °C, −3.8 °C, −16.2 °C, −26.2 °C, −30 °C, see Fig. 5 (b), each for 2.4 h. It is important to note that the temperature changes were set to be changed slowly when following sinusoidal variations in the chambers to better match sinusoidal curves. The data receiver of the climate chamber recorded the temperature and RH every 6 min. During the test, the indoor hygrothermal conditions were set to a steady state of 20 °C and 40 % RH.

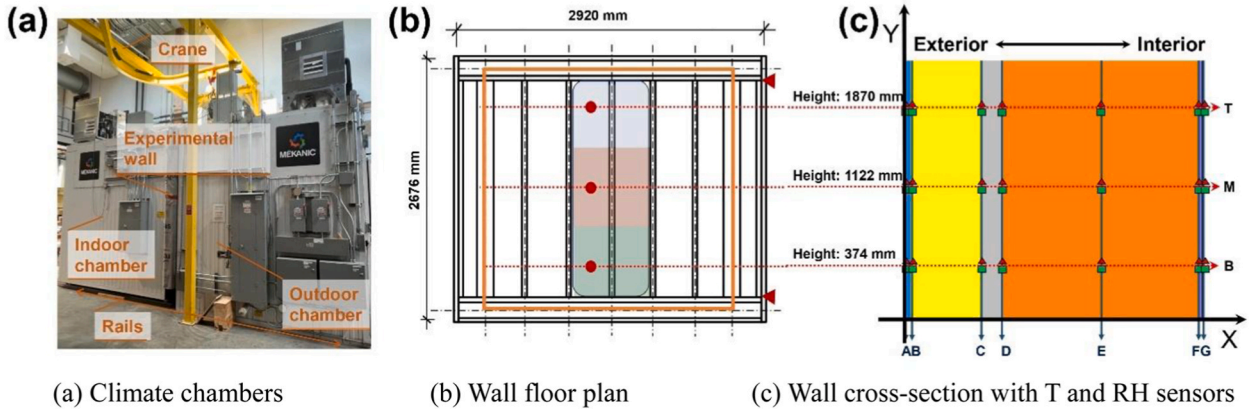


Fig. 4. (a) The climate chambers of Université Laval, (b) wall floor plan, and (c) temperature and RH sensors installation location on test walls.

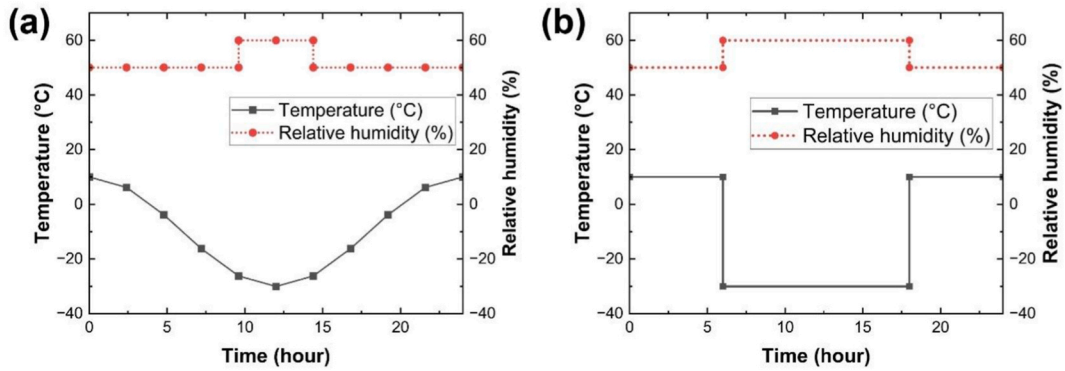


Fig. 5. The schema of the conditioning cycle performed. The solid line corresponds to temperature, and the dotted line to RH. The outdoor climate chamber step changes (a), and sinusoidal (b) temperature variations.

2.4. Simulation parameters setup

The hygrothermal properties of each wall component were first input into WUFI Pro. WUFI Pro is a validated dynamic simulation software capable of simultaneously calculating heat and moisture transfer within building envelope assemblies. The heat and moisture transport processes in building materials are described by the following equations (1) and (2):

$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + h_v \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial p}{\partial x} \right) \quad (1)$$

$$\rho_w \frac{\partial W}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x} \left(\rho_w D_w \frac{\partial W}{\partial \varphi} \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial p}{\partial x} \right) \quad (2)$$

where, H refers to enthalpy of moist (J/m^3), T refers to temperature ($^{\circ}\text{C}$), λ refers to thermal conductivity ($\text{W}/(\text{m}\cdot\text{K})$), h_v refers to evaporation enthalpy (J/kg), δ refers to vapor permeability ($\text{kg}/\text{m}\cdot\text{s}\cdot\text{Pa}$), μ is vapor diffusion resistance, p is saturation vapor pressure (Pa), ρ_w is water density (kg/m^3), W is water content (m^3/m^3), φ is humidity (%), and D_w is liquid transport coefficient.

Five-year hygrothermal simulations were conducted under the cold-year climatic conditions in Quebec City for the three test walls. The wall orientation was defined as facing northeast to account for the highest wind-driven rain exposure. The exterior surface heat transfer coefficient was set to $17 \text{ W}/(\text{m}^2\cdot\text{K})$, including a long-wave radiation of $6.5 \text{ W}/(\text{m}^2\cdot\text{K})$. The short-wave radiation absorption coefficient of the wood siding was set to 0.8, a value consistent with the material properties. The long-wave radiation emissivity to 0.9, which is typical for non-metallic building materials. The ground reflectivity for short wave radiation was assumed to be 0.2, which represents the typical reflectivity of soil and vegetated surfaces. The rain adhering factor was set to 0.7, in line with empirical studies and modeling practices of wind-driven rain exposure on vertical walls. The interior surface heat transfer coefficient was $8 \text{ W}/(\text{m}^2\cdot\text{K})$, consistent with commonly adopted steady-state indoor surface values. The initial hygrothermal conditions were set to 20°C and 65 % RH for the simulations. The indoor temperature and RH were maintained at constant values of 20°C and 40 %, respectively. The simulation time step was set to 1 h.

Subsequently, the temperature and RH results at the sheathing-interior insulation interface was then used as input for WUFI Bio to perform mold growth risks analysis, as this location often exists as the highest RH in the multilayer wall [13,26–28]. For the biobased walls, a more bio-utilizable substrate (Class II) was selected, while for the less bio-utilizable reference wall, a Class I substrate was chosen.

2.5. Evaluation criteria

2.5.1. Effective thermal resistance

The effective thermal resistance in the wood frame wall was calculated using the parallel path method, which accounts for the distinct heat flow paths through the wood frame and the insulated cavities [29]. In this study, a wood frame with framing elements occupying 11 % of the wood frame and 89 % of interior insulation. According to the Canadian National Building Code [30], the thermal resistance of the wood framing was taken as 1.19 (m² K)/W. The thermal conductivities and thicknesses of the interior and exterior insulation materials were previously provided in Table 1. Based on these parameters, the effective thermal resistance of the wall insulation layers was calculated as in equation (3):

$$R_{eff.} = R_{ext.} + \left(0.11 \cdot \frac{1}{R_{stud}} + 0.89 \cdot \frac{1}{R_{ins.}} \right)^{-1} \quad (3)$$

where $R_{eff.}$ represents the effective thermal resistance of the wall insulations, $R_{ext.}$ denotes the thermal resistance of the exterior insulation layer, R_{stud} denotes the thermal resistance of the wood frame, and $R_{ins.}$ represents the thermal resistance of the interior insulation.

2.5.2. Thermal inertia

The thermal inertia of the test walls was characterized by the time lag (ϕ) as equation (4):

$$\phi = T_{i_max} - T_{e_max} \quad (4)$$

where T_{i_max} represents the time at which the interior insulation temperature reaches its maximum during the last complete experimental cycle. In this study, the interior insulation temperature refers to the temperature measured at the middle height of surface E. Similarly, T_{e_max} refers to the time for the exterior surface temperature to reach its maximum during the same cycle. Previous studies have indicated that a longer time lag can help the wall mitigate summer overheating, as indoor temperatures continue to rise even as outdoor temperatures begin to decrease. This delay helps maintain indoor thermal stability and reduces the energy demand for air conditioning systems [14,17,21,31]. The temperature was recorded at 6 min intervals. Although several dynamic parameters, such as the decrement factor, periodic thermal transmittance, and thermal admittance, can be used to characterize thermal inertia, the time lag approach was selected because it can be directly measured from the multi-layer temperature profiles obtained in the climate-chamber experiment. Time lag is also defined as a standard metric in ISO 13786 [32], and the resulting phase shift provides a clear indication of how effectively the wall delays outdoor temperature fluctuations before they influence the indoor environment. Moreover, it offers a practical advantage for this study, since parameters like periodic thermal transmittance or thermal admittance require long-term, stable sinusoidal boundary conditions or extended frequency-domain analysis, which are less feasible within the experimental setup.

2.5.3. Moisture buffer capacity

Biobased materials typically exhibit porous structures, leading to greater moisture storage capacity than conventional insulations. Consequently, they possess a higher moisture buffer capacity, enabling them to moderate fluctuations in indoor RH. In this study, the moisture buffer capacity of the test walls was using the average RH of the interior insulation over the five days of testing and RH variation (Δh) on the interior surface, defined as equation (5):

$$\Delta h = h_{i_max} - h_{i_min} \quad (5)$$

where h_{i_max} is the maximum RH of the interior surface in the last complete experimental cycle, and h_{i_min} refers to the minimum RH of the interior surface during the same cycle. The calculation aims to compare the efficiency of each wall in regulating the indoor RH variations.

2.5.4. Mold growth risks

To perform the assessment, the hourly temperature and RH data at the sheathing-interior insulation interface, obtained from WUFI Pro hygrothermal simulations, were imported into WUFI Bio. This interface was selected as a critical location due to being often considered a mold-sensitive surface in multilayer walls. The WUFI Bio was then applied to evaluate mold growth risks in the three test walls. The model operates based on the VTT mold growth model developed by Viitanen et al. [33]. This empirical model predicts mold growth on building materials as a function of temperature, RH, exposure duration, and material sensitivity. The model assumes that mold spores absorb water based on their osmotic potential. At each time step, the spores' water content is compared with the temperature-dependent critical water content, determined using the lowest isopleth for the mold line of the specific substrate. Germination begins once the critical water content is reached, and mycelium growth stops when moisture falls below this threshold. The output was expressed in terms of mold growth rate and mold index. The mold growth rate represents the cumulative increase in the

radius of the mold blotch, while the mold index categorizes the affected surface into six levels, as detailed in Table 2. For the surface inside constructions without direct contact with indoor air, a mold index of 2 or less is required, and the mold growth rate should not exceed 176 mm per year [34]. Because the five-day climate chamber experiment does not allow measurable mold growth to occur, numerical predictions from WUFI Bio were used exclusively to assess long-term mold-growth risks under realistic cold-climate boundary conditions.

3. Results and discussion

3.1. Thermal performance of the walls

This section analyzes the steady thermal performance and dynamic thermal responses of the wall assemblies. In addition, the surface temperature distribution at surfaces C, D, E, and F was examined at the peak temperature during the last experimental cycle to assess the influence of the height.

The effective thermal resistance of the wood frame walls was calculated using the parallel path method as described in Section 2.5.1. As shown in Table 3, the effective thermal resistances of W1, W2, and W3 were 4.61 ($\text{m}^2 \text{K}/\text{W}$), 4.18 ($\text{m}^2 \text{K}/\text{W}$), and 3.63 ($\text{m}^2 \text{K}/\text{W}$), respectively. Due to the relatively small thickness of the wood fiber board (38 mm) and its comparatively higher thermal conductivity, the W3 wall exhibits the lowest effective thermal resistance among the three assemblies. It is worth noting that even without accounting for the interior and exterior surface resistances, siding, and sheathing, the effective thermal resistance of the insulation layers in all wall assemblies still exceeds the minimum requirement for above ground exterior walls in Quebec, which is 2.97 ($\text{m}^2 \text{K}/\text{W}$) [30]. This can be attributed to the continuous exterior insulation, which reduces thermal bridging, as well as the low thermal conductivity of the insulation materials, both of which contribute to the overall improvement in the wall's effective thermal resistance.

As shown in Fig. 6, the results indicate that the temperature response within the wall is strongly influenced by the pattern of external temperature variations. When the outdoor temperature follows a step change pattern, the temperatures at the surfaces closest to the exterior (surfaces A and B) also exhibit a clear step-like response. As the sensors move inward, the temperature curves progressively transform from an initial rectangular step shape into wave-like profiles with distinct peaks and eventually become attenuated and more stable at the interior surface. Similarly, when the outdoor temperature varies sinusoidally, the temperatures at the internal surfaces of the wall also exhibit corresponding periodic smooth fluctuations. Notably, regardless of the type of external temperature variation applied, the temperature at the interior surface consistently becomes more stable. This demonstrates the temperature regulation of the walls, which effectively buffers and attenuates the impact of outdoor temperature fluctuations on the indoor-side temperature (see Fig. 7).

A pronounced phase lag and amplitude attenuation can be observed in the temperature variation curves of each layer as the temperature sensors approached the interior surface of the wall. The temperature peaks at the inner and intermediate layers were significantly delayed compared to the outdoor temperature peaks, indicating a strong thermal inertia of the biobased insulations. In addition, the amplitude of temperature fluctuations was substantially attenuated as the heat transfers towards the interior surface. As the outdoor temperature changed by 40 °C, the amplitude at the sheathing-insulation interface was reduced to 15–20 °C and was further decreased at the interior surface. This is because the biobased materials exhibit low thermal conductivity and relatively high volumetric heat capacity, resulting in low thermal diffusivity. This slows down the propagation of the thermal wave through the wall, causing the interior layers to respond more gradually to outdoor temperature variations and thereby producing a pronounced time lag. In addition, the high porosity and moisture sorption capacity of these materials introduce latent heat effects associated with periodic evaporation and condensation. During the heating phase, a part of the heat is consumed by moisture evaporation within the pores, which reduces the rate of temperature increase. Conversely, during the cooling phase, water vapor condenses and releases latent heat, buffering the temperature drop. These opposing processes dampen the temperature amplitude and further delay the temperature response of the internal layers.

Fig. 7 (a) and (b) show the maximum temperature occurring at surfaces C, D, E, and F during the last complete experimental cycle at different heights when the outdoor temperature presents step change and sinusoidal patterns, respectively. The black solid line in the figure represents the top, the red solid line represents the middle, and the blue solid line represents the lower position in the wall. The results show that W3 exhibits the lowest overall temperature, followed by W2 and then W1, which corresponds to W3 has the lowest effective R values among the three assemblies. As the measurement position moves toward the interior surface, a clear temperature gradient showed, and the internal temperature gradually increases. However, at surface D (the sheathing-interior insulation interface), the temperature does not follow this increasing trend and instead drops locally. This occurs because the thermal conductivity of the

Table 2

The six levels of mold index describing the mold-infested fraction of a surface [34].

Mold index	Description
0	No growth
1	Some growth visible under a microscope
2	Moderate growth visible under a microscope, coverage above 10 %
3	Some growth detected visually, thin hyphae found under microscope
4	Visual coverage above 10 %
5	Coverage above 50 %
6	Tight coverage close to 100 %

Table 3
Thermal resistance of insulations obtained from product manual and effective thermal resistance calculated of wall insulation layers.

Wall assembly	Insulation materials	Thermal resistance (RSI) (m ² ·K)/W	Effective thermal resistance of the insulation layer (m ² ·K)/W
W1	XPS rigid insulation	1.76 (N/A)	4.61
	Glass fiber	3.52 (N/A)	
W2	Cork board	1.176 (24 °C)	4.18
	Hemp batt	3.598 (24 °C)	
W3	Wood fiber board	0.7 (N/A)	3.63
	Hemp batt	3.598 (24 °C)	

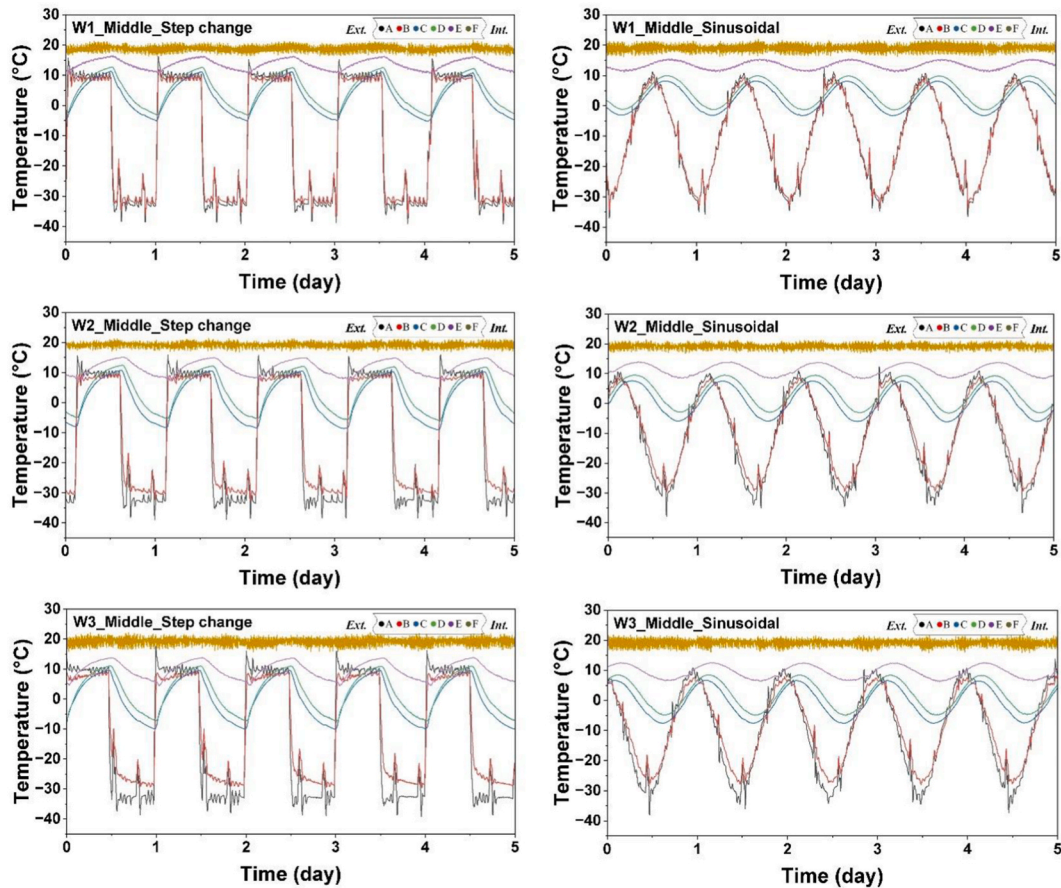


Fig. 6. Temperature variations over five days tests at middle height for three test walls under step change and sinusoidal outdoor temperature conditions.

sheathing is much higher than that of the insulation (approximately 3.3 times). To maintain continuous heat flux across the interface, the local temperature gradient must increase sharply, resulting in a significant temperature drop at this location. In addition, moisture evaporation may absorb latent heat, further reducing the interface temperature at the high RH interface.

In addition, it was observed that at the exterior side (C surface), the bottom part exhibits the highest temperature, whereas at the interior side (F surface), the top part shows the highest temperature. This can be explained by the different dominant convection mechanisms acting on each side of the wall. On the outdoor chamber, air movement was primarily governed by the forced airflow generated by the climate chamber's ventilation system. When the airflow hit the wall surface, the lower region was not only influenced by the airflow by the ventilation system but also by airflow rebounding upward from the floor. This enhances local convective heat transfer, causing the bottom region to warm up more rapidly. At the interior side (F surface), the opposite vertical temperature stratification compared to the exterior side was observed due to buoyancy driven air movement inside the wall. As heat penetrates the wall, the air trapped within the porous insulation materials tends to rise when heated, leading to a slight upward accumulation of heat. Therefore, the interior surface exhibits a maximum temperature at the upper part of the wall.

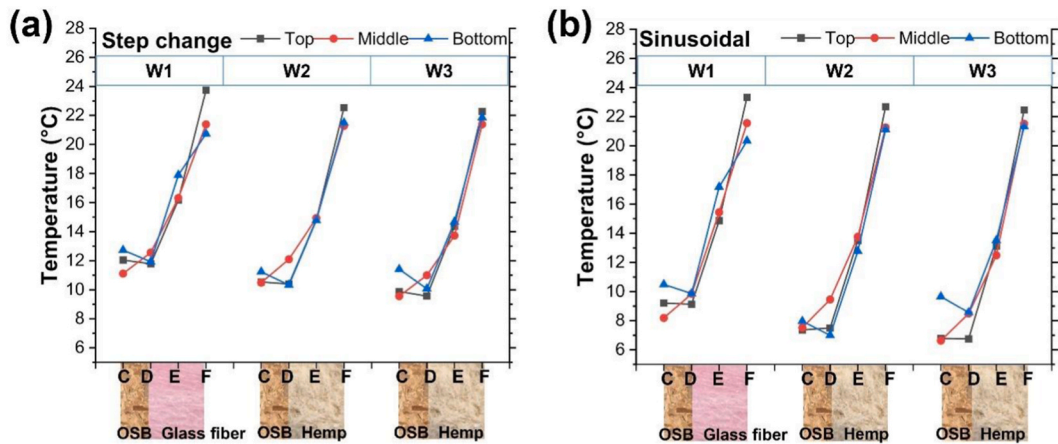


Fig. 7. The maximum temperature values during the last experimental cycle of the three test walls at top, middle and bottom heights (surfaces C, D, E and F) when outdoor temperature changes following the step change (a), and the sinusoidal (b) variations.

3.2. Sinusoidal and step change RH variations

This section analyzed the dynamic RH responses at various surfaces within the three test walls under sinusoidal and step change temperature boundary conditions at the upper section of the walls. The upper section was chosen because the data from the sensors located at layer D (sheathing-interior insulation interface) at the middle height of the wall was compromised due to a malfunction. To

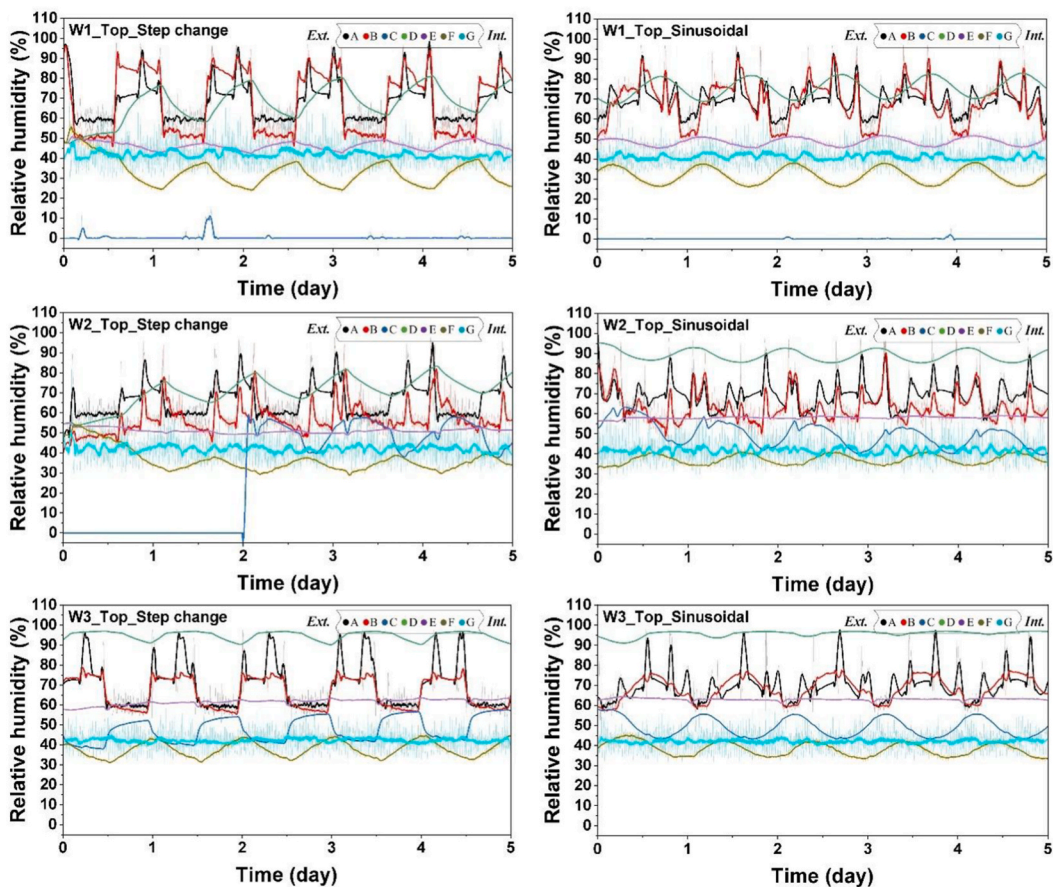


Fig. 8. Relative humidity variations over five days tests at top height for three test walls under step change and sinusoidal outdoor temperature conditions.

reduce the effect of sensor sensitivity, the RH variation curves at surfaces F and G were smoothed for analysis, while the original data were retained in the background as light-colored lines, see Fig. 8. Additionally, the maximum RH values of surfaces C, D, E, and F at different heights during the last experimental cycle were examined to assess the influence of wall height on RH distribution (see Fig. 9).

As shown in Fig. 8, RH variations were influenced by outdoor temperature variations. The corresponding RH variations showed sharp curves when the outdoor temperature underwent a step change. In contrast to the step change, sinusoidal variations in exterior temperature resulted in smoother fluctuations in RH within the wall. This moisture and heat coupled effect can be attributed to temperature fluctuations changing the saturated vapor pressure within porous materials. When the temperature increases, the saturated vapor pressure increases, thus making RH decrease. Moreover, RH hysteresis was observed at both the C surface and the F surface. This phenomenon arises because temperature changes occur almost instantaneously, whereas variations in the material's moisture evolve more slowly. As a result of this delayed moisture migration, the local vapor pressure and RH at these interfaces cannot respond synchronously to external changes, leading to significant delays and shifts in the RH at both the C and F surfaces. In contrast to W1, both biobased wall assemblies exhibited more stable RH fluctuations at the mid-depth of the interior insulation layer (E surface). This behavior reflects the better moisture buffering capacity of the biobased materials. At the D surface of both W2 and W3, a gradual increase in RH was observed, with the RH in W3 reaching a maximum of 97 %. In contrast, no comparable increase in RH was detected at the corresponding location in W1. Therefore, a more in-depth analysis of the long-term mold growth risk was conducted and presented in Section 3.4.

Fig. 9 (a) and (b) present the maximum RH observed during the last experimental cycle at surfaces C, D, E, and F at different heights, under step change and sinusoidal exterior temperature profiles, respectively. Among all measured surfaces, the D surface exhibited the highest RH. This can be attributed to the fact that indoor air migrates outward and encounters high moisture diffusion resistance and colder sheathing layer, causing vapor to accumulate at this surface and resulting in the highest RH within the wall assembly. Similar observations have also been reported in previous studies [13,26–28]. Additionally, the upper section of surface F exhibited the lowest RH, reflecting a typical moisture and heat coupling phenomenon. Because this location experienced the highest temperature (as explained in Section 3.1), the moisture holding capacity of air increased with temperature, leading to a corresponding decrease in RH.

3.3. Dynamic hygrothermal performance

This section analyzed the dynamic hygrothermal performance of the three test walls. The thermal inertia was evaluated by comparing the time lags of the last complete experimental cycle for each wall. Meanwhile, the moisture buffering capacities were evaluated based on the five-day average RH of the interior insulations and the RH variations at the interior surfaces.

3.3.1. Thermal inertia

As shown in Fig. 10, when the exterior temperature underwent a step change, the time lag between the temperature peak at the middle of the interior insulation (surface E) and the temperature peak at the exterior surface (surface A) in W1 was 11.8 h. In W2, the time lag at interface E was 12.3 h. In W3, the time lag for interface E was 12.5 h. Under sinusoidal exterior temperature variations, the peak temperature at interface E occurred 4.3 h after the peak at surface A in Wall 1 (W1). In Wall 2 (W2), the time lag at surface E relative to the exterior surface was 5.1 h, while in Wall 3 (W3), the corresponding time lag was 5.8 h. It shows that the two biobased walls exhibit greater time lags than W1. This demonstrates that hemp interior insulation has more significant thermal inertia than glass fiber. Studies have shown that materials' thermal inertia helps regulate indoor temperature fluctuations, making indoor temperatures more stable and reducing air conditioning energy consumption [31,35].

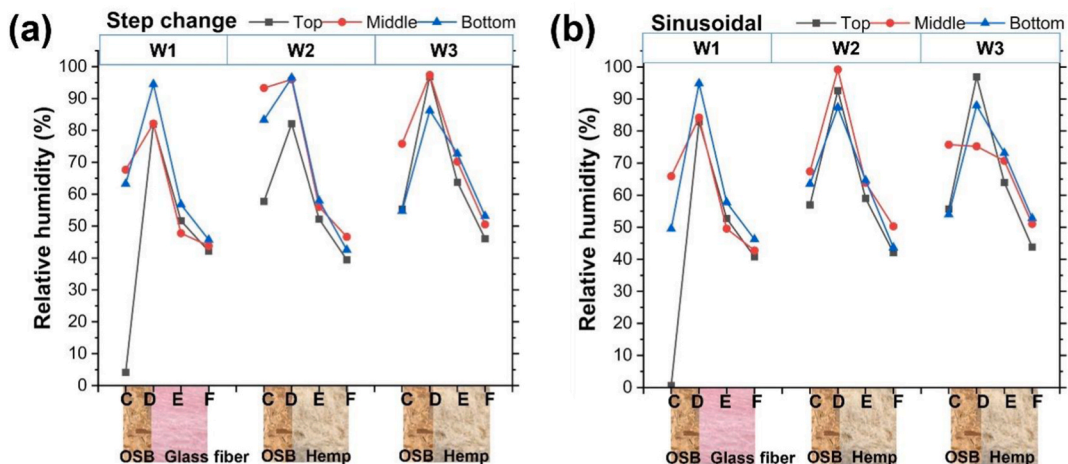


Fig. 9. The maximum RH values during the final experimental cycle of the three test walls at top, middle, and bottom heights (surfaces C, D, E, and F) under step change (a), and sinusoidal (b) outdoor temperature boundary conditions.

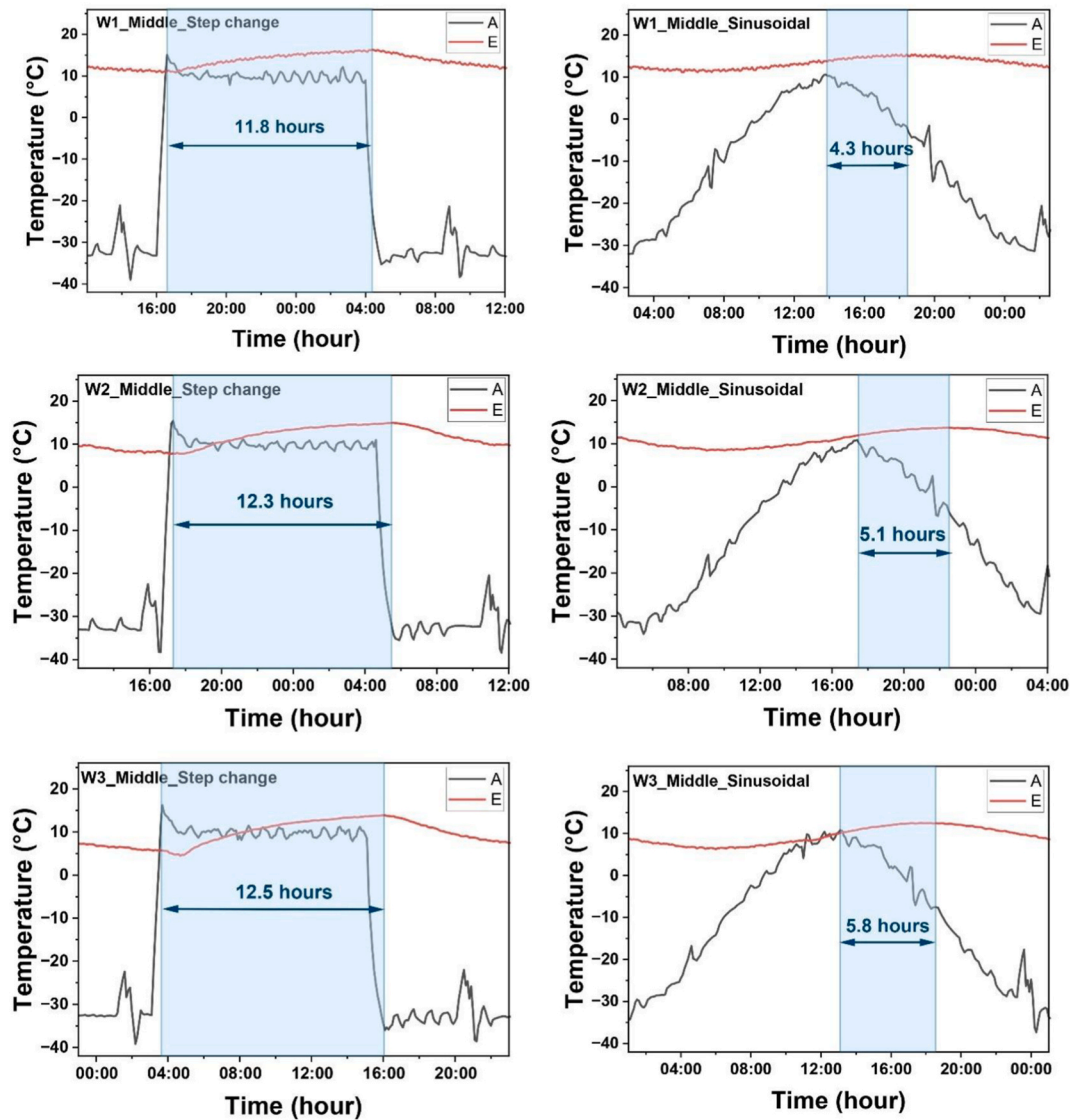


Fig. 10. The time lags of the three test walls under step change and sinusoidal outdoor temperature variations of the last complete experimental cycle.

It is important to note that, compared to walls subjected to step change temperature boundary conditions, walls under sinusoidal temperature variations exhibit considerably smaller time lags. Specifically, the time lag at the surface E in the biobased wall assemblies under step change outdoor temperature variation was approximately 2.5 times greater than that observed under sinusoidal temperature variation. In a field hygrothermal experiment, Douzane et al. [14] tested a 520 mm thickness straw wall in the Picardie region of France and reported a time lag of approximately 6 h. Similarly, in a laboratory study by Rahim et al. [21], a mixed straw rape concrete wall tested in a climate chamber exhibited a time lag of 5.7 h under a sinusoidal winter temperature profile and 6 h under a sinusoidal summer profile. These results indicating that continuous, smooth, and periodic sinusoidal boundary conditions better capture the realistic thermal inertia of wall assemblies. In contrast, step change boundary conditions resulted in larger time lag values. However, due to operational limitations of the climate chamber system, the actual time lags under a step change temperature pattern may be shorter. As mentioned in Section 2.1, the outdoor chamber's warming rate was 0.6 °C/min. In this study, the daily temperature difference was large (40 °C); as a result, the outdoor climate chamber takes approximately 1.1 h to transition from −10 °C to 30 °C. Consequently, the actual time lags under the step change pattern were about 1.1 h shorter than the calculated values.

3.3.2. Moisture buffer capacity

The moisture buffer capacity was assessed by analyzing the RH variations on interior surface of the last complete experimental cycle. As shown in Fig. 11, the results show that with the step change, RH amplitude of W1 was 15.0 %, W2 was 9.9 %, and W3 was

12.1 % at surface F. When a sinusoidal profile was used, values of 11.7 %, 7.0 %, and 8.7 % were found for surface F (see Fig. 12).

Between the two biobased wall assemblies, W2 exhibited smaller RH fluctuations at the interior surface, indicating a better moisture buffering capacity. Both biobased walls showed lower interior surface RH amplitudes, further demonstrating the enhanced moisture buffering capacity of biobased insulation materials. In addition, it was observed that when the outdoor temperature followed a sinusoidal profile, the interior surface RH amplitude was lower. This can be explained by the fact that step change temperature conditions impose abrupt thermal changes, and because RH is strongly influenced by temperature, such abrupt changes amplify RH fluctuations.

3.4. Mold growth risk simulation

Due to the limited duration of the climate chamber experiments, the five-day test period was insufficient to fully assess the mold growth risks in the test walls. Therefore, this study employed WUFI Bio to simulate mold growth risks over five years under outdoor boundary conditions for a cold year in Quebec City. Fig. 12 (a) illustrates the mold growth rate, and (b) the mold index of the three walls at the sheathing-interior insulation interface, where the highest RH was observed.

Regarding mold growth rate, the selected surface of W1 showed a value of 0 mm/year throughout the simulation, further confirming its resistance to mold growth. In comparison, the selected surfaces of W2 and W3 demonstrated varying degrees of mold growth risk. For W2, the mold growth rate increased during the first year and stabilized after approximately 1.5 simulation years, maintaining a growth radius of 11 mm until the end of the simulation, indicating that mold growth had stopped. In contrast, W3 exhibited a continuously increasing mold growth rate, with the mold growth radius expanding annually and reaching 104 mm by the end of the fifth simulation year. Despite W3's higher growth rate compared to W2's, both biobased walls exhibited annual mold growth rates well below the threshold of 176 mm/year [33].

Regarding the mold index, W1 maintained a value of 0 at the sheathing-interior insulation interface throughout the entire simulation, indicating no risk of mold growth on this surface. For the two biobased wall assemblies, the mold index for W2 gradually decreased to 0 over the simulation period, indicating that mold growth ceased after the initial phase. In contrast, the mold index for W3 increased rapidly during the first simulation year, then peaked and declined in the second year. However, it gradually rose again from the third to the fifth year. Nevertheless, the mold index for both biobased walls remained below the accepted threshold value of 2 for mold risk [34].

In summary, during the five-year simulations, both biobased wall assemblies exhibited some degree of mold growth at the sheathing-interior insulation interface, but the levels remained below the critical mold risk thresholds. Among the two, the wall with cork board as exterior insulation (W2) demonstrated a lower mold growth risk than the wall insulated with wood fiber board (W3).

4. Conclusion

This study analyzed the dynamic hygrothermal responses of biobased walls under extremely cold conditions using climate chamber experiments, considering two exterior temperature patterns: step changes and sinusoidal fluctuations. In addition, the experimental findings were contextualized with existing research on hygrothermal behavior and thermal inertia of biobased materials, which has reported similar trends in time lag, amplitude attenuation, and moisture-heat coupling. Mold growth risks were also assessed through five years of numerical simulations under a Quebec City cold-year boundary conditions. While the five-day chamber experiment was designed to capture short-term dynamic hygrothermal responses under stabilized cyclic conditions, the subsequent five-year simulation addressed long-term moisture accumulation and mold growth, ensuring that both immediate and extended behaviors were fully assessed.

The results show that the effective thermal resistance of all wall assemblies meets the minimum requirement for above ground walls specified by the local regulations. Due to the low thermal diffusivity of the insulation materials and the latent heat effects, the temperature variation curves exhibit pronounced attenuation and phase lag as the temperature sensors approach the interior surface of the wall. Moreover, opposite thermal stratification was detected on the exterior and interior surfaces of the wall, driven respectively by airflow on the exterior side and buoyancy driven air movement on the interior side.

These thermal behaviors align with previous studies on lime-hemp, wood-fiber, and straw-based walls, which consistently report higher thermal inertia and delayed heat transfer compared to mineral-based insulations, thereby reinforcing the relevance of biobased materials for attenuating dynamic temperature loads.

The hygrothermal response of wall highlights a strong coupling between the temperature and the RH. The interface between the sheathing and the interior insulation exhibited the highest RH. The biobased walls exhibited greater moisture buffering capacity and thermal inertia, confirming their ability to maintain the hygrothermal equilibrium of the indoor environment. This enhanced moisture regulation is consistent with the high moisture buffer values reported for hemp- and wood-fiber-based materials in previous experimental studies, which identify these insulations as excellent hygric regulators. Furthermore, under sinusoidal temperature conditions, the walls' thermal inertia more closely reflected the dynamic responses observed in real world climates. Simulation results from a five-year mold growth risk assessment indicated that the mold growth risks for all biobased wall assemblies remained below the critical threshold, meaning an acceptable level of mold risk. This finding is also consistent with prior WUFI-Bio based evaluations, which show that bio-based envelopes, when properly detailed, can remain within acceptable mold-index limits despite their higher hygroscopicity. Overall, the results provide essential hygrothermal and long-term mold growth evidence for evaluating the suitability of biobased wall assemblies under extreme cold conditions, while situating these findings within the broader body of literature demonstrating the strong thermal inertia, moisture buffering, and durability potential of biobased building materials.

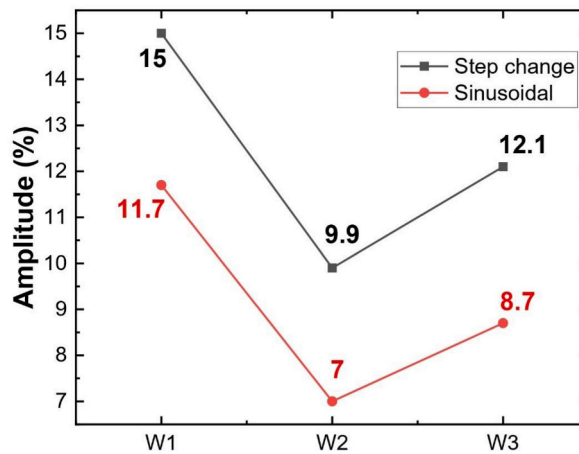


Fig. 11. The last complete experimental cycle RH amplitude at surface F.

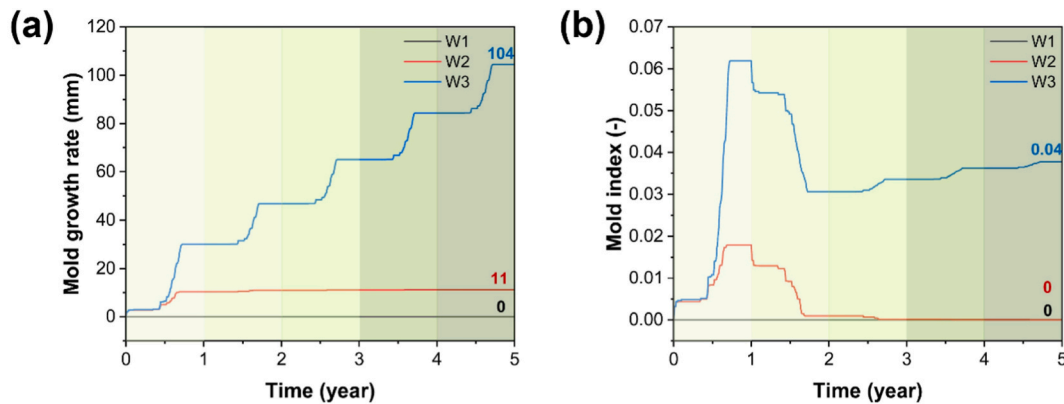


Fig. 12. WUFI Bio simulations of mold growth rate (a) and mold index (b) for three wall assemblies over five years.

CRedit authorship contribution statement

Yuchen Chen: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Pierre Blanchet:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Louis Gosselin:** Writing – review & editing, Validation, Supervision. **João Vítor Felipe Silva:** Writing – review & editing, Validation, Formal analysis. **Xiaodong (Alice) Wang:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Funding acquisition, Conceptualization.

Paper's contributions

This paper offers a clear contribution to the understanding of biobased wall assemblies used in extreme cold climates by combining controlled climate chamber experiments with long-term numerical simulations. It provides an integrated analysis of thermal and moisture behavior under both abrupt and cyclic temperature conditions, showing how biobased insulations influence thermal inertia, moisture buffering, relative humidity responsiveness, and overall heat-moisture interactions. The study also introduces new insight into height-related stratification inside the wall and identifies the sheathing and interior insulation interface as the most sensitive location for moisture accumulation. By extending the investigation to a five-year mold growth simulation based on a cold-year climate profile for Quebec City, the work delivers durability evidence and demonstrates that hemp- and wood-fiber-based assemblies can remain within acceptable mold risk levels.

Limitations and future work

Although this study provides detailed insight into the dynamic hygrothermal behavior of biobased wall assemblies under extreme cold climate conditions, several limitations should be acknowledged. First, the five-day climate chamber experiments were designed to evaluate short-term thermal and moisture responses under controlled cyclic boundary conditions and therefore do not capture the

seasonal or multi-week moisture accumulation processes that may occur in real buildings. To address this limitation, a five-year numerical simulation was performed; however, laboratory testing over longer periods or under varying outdoor climates could further strengthen the validation of long-term predictions.

Second, the climate chamber airflow patterns, despite being well controlled, cannot perfectly replicate all outdoor natural convection behaviors such as wind-driven pressure variations, solar radiation effects, or transient precipitation exposure. Future work could incorporate full-scale outdoor test huts or rotatable test cells to evaluate the same wall assemblies under natural weathering.

Third, the study focused on three specific biobased configurations with fixed material properties and thicknesses. Variations such as alternative insulation densities, different vapor control strategies, or modified sheathing and cladding systems were beyond the scope of this experiment but could influence thermal inertia, moisture transport, and mold risk. Future investigations could systematically explore parameter sensitivity across a wider range of wall designs.

Finally, mold growth assessment relied on numerical modeling, because measurable biological growth cannot occur within the short experimental duration. Although WUFI Bio is widely used for risk-based evaluation, future work may benefit from long-term biological exposure tests to directly observe early-stage mold germination on biobased insulation interfaces under cold-climate cycling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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