Resources, Conservation & Recycling 198 (2023) 107161

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Upcycling wheat and barley straws into sustainable thermal insulation: Assessment and treatment for durability

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ARTICLE INFO

Keywords:
Renewable alternatives
Barley straws
Wheat straw
Insulation material
Mould growth
Antifungal treatment

ABSTRACT

This study investigates the potential of wheat and barley straws as sustainable alternatives to conventional insulation materials. The focus is on evaluating the risk of mould growth in straw-filled wall assemblies across different climate types, while comparing the physical, thermal, hygroscopic, and durability properties of wheat and barley straws. Additionally, the effectiveness of boric acid as an antifungal treatment on straws is assessed. The findings reveal that both barley and wheat straws exhibit low thermal conductivity, ranging from 45 to 65 mW m^{-1} K^{-1} for bulk density of 60 to 100 kg m^{-3}. Notably, barley straws demonstrate lower sorption capacity, higher vapour diffusion, lower thermal conductivity, and reduced mould growth intensity, rendering them more suitable as insulation material. The application of boric acid treatment effectively enhances the mould resistance of straw without adversely affecting their hygric and thermal properties. Consequently, boric acid treatment is recommended for wheat straw under unfavourable climatic conditions.

1. Introduction

Straws, the leftover stalks of cereal plants, are a by-product of crop production. They have been upcycled as building materials, used as bedding for livestock, utilized as biomass for energy generation and animal feed, as well as burnt or ploughed back into soils (Yuan and Sun, 2010; Koh and Kraniotis, 2020). Of all crops grown in the world, wheat and barley are ranked third and twelfth by production volume; the annual production in 2019 is estimated at 764 and 159 million tonnes respectively (Food and Agriculture Organization of the United Nations, 2022). As a by-product, approximately 1.5 tonnes of straws can be obtained for every ton of cereal production (Yuan and Sun, 2010).

Straws are an abundant, sustainable, and cost-effective source of low-embodied carbon raw materials. Utilizing straws as a building material presents a viable low-carbon alternative to high embodied energy materials currently available in the market. By and large, straws are used for thermal insulation purposes (Koh and Kraniotis, 2020), and can be incorporated as a load-bearing strawbale wall or as infill in post-and-beam structures in buildings [(International Residential Code (IRC) 2015; Fachverband Strohballenbau Deutschland e.V. (FASBA) 2019; INTERREG V-A France-Wallonie-Vlaanderen 2021)]. To optimize their use as insulation material, it is essential to assess the hygrothermal and durability performance of various straw types in different climates and develop strategies to enhance their resource efficiency.

Wheat and barley are under the same *Poaceae* family but in different genera: *Triticum* for wheat and *Hordeum* for barley, hence physical differences between wheat (Yin et al., 2018; Bouasker et al., 2014) and barley straws [(Bouasker et al., 2014; Vejeliene et al., 2010),10]are presented. These physical variances could impact their thermal and hygric behaviours and influence their suitability as insulation material. For instance, different sorption isotherms have been measured between wheat (Yin et al., 2018; Bouasker et al., 2014; Lawrence et al., 2009; Carfrae et al., 2010) and barley straws (Bouasker et al., 2014; Laborel Préneron et al., 2017; Bui et al., 2017), where their microstructure could play a determinative role in this regard. On the other hand, no notable deviation of thermal conductivity between different types of straws is established, with measurements between 40 and 80 mW m^{-1} K^{-1} under bulk density between 60 and 120 kg m^{-3} reported in different studies (Koh and Kraniotis, 2020).

Straws, like other natural bio-based materials (Koh et al., 2022), are prone to mould growth when exposed to humid environments, leading to deterioration. The well-established negative health effects of indoor moulds (Koskinen et al., 1999; Portnoy et al., 2005; Curtis et al., 2004) necessitate the prevention of straw becoming a source of fungal proliferation. Freshly harvested wheat and barley straws are naturally contaminated with several fungi species such as *Aspergillus* and

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https://doi.org/10.1016/j.resconrec.2023.107161
Received 24 April 2023; Received in revised form 7 June 2023; Accepted 3 August 2023

Penicillium spp. from soil (Magan, 1988), and generally, straws are dried and applied directly, without treatment as building materials. A prior hygrothermal study on strawbale buildings reveals that there is a potential risk of mould growth on straws under unfavourable construction designs and local climates (Koh and Kraniotis, 2021). Conversely, mould growth on straws used for insulation is seldom reported (Koh and Kraniotis, 2020). A few observations however are described on fresh straw samples: mould is detected on a wheat straw sample (Thomson and Walker, 2014), at the inner cell wall of a barley straw sample (Bouasker et al., 2014), and on a rice straw sample (Marques et al., 2019). These findings highlight the need to address the mould growth risk on straws and emphasize the necessity of knowledge to ensure safe application. Several strategies can be employed, such as selecting a suitable straw type with higher mould resistance or applying a non-toxic antifungal treatment on straws to minimize the risk.

In terms of composition, wheat and barley straws are similar, but the average ratio of lignin to cellulose-hemicelluloses is lower in wheat straw than in barley straw, at 0.20 and 0.23, respectively (Sun and Tomkinson, 2000). The higher content of lignin in barley straw protects the cellulose and hemicellulose more effectively from glycoside hydrolases from fungi, thus delaying their degradation into simple sugars that could enhance mould growth (Niu et al., 2022). In addition, barley straw has a higher percentage of wax (Sun and Tomkinson, 2000), which provides a protective surface layer (Xu, 2010) and acts as the first barrier against any fungal attack. Both factors, i.e., higher ratios of lignin and wax against cellulose-hemicellulose, suggest that barley straw is more resistant to mould growth than wheat straw. However, limited information is available in the literature, and a comparative study between wheat and barley straws is necessary to determine which is more effective as an insulation material.

Irrespective of the straw type, antifungal treatment is a feasible approach to enhance the durability of straws. Boric acid and its sodium borate salts, which are relatively inexpensive and non-toxic, can be utilized to impede fungal growth by obstructing their reproductive process (25; Estevez-Fregoso et al., 2021). Wood preservation is a common application of boric acid against wood-decaying fungi (Baysal et al., 2007; Lesar and Humar, 2009), with higher effectiveness against brown rot fungi than white rot fungi (Lesar and Humar, 2009). Positive results have also been demonstrated using boric acid or borate compounds on other bio-based building materials, for example, on corn pith composites (Palumbo et al., 2017), wood composites (Fogel and Lloyd, 2002) and cellulose insulation (Omodon et al., 2007). However, the effectiveness of boric acid on wheat and barley straws against fungi is yet to be established.

This study aims to address research gaps concerning the use of two commonly available straw types, namely wheat and barley straws, as thermal insulation materials. The straw types are selected based on their status as the top two grain crops produced in the Netherlands and their frequent utilization as building materials compared to other crops. The study seeks to investigate their hygrothermal properties, mould growth resistance, mould growth risk in different climates, and the effectiveness of applying boric acid treatment to enhance their durability. The findings of this study will provide insights into the most suitable straw type for thermal insulation and assess the feasibility of using boric acid as an antifungal treatment to improve the durability of straws.

2. Material and methodology

The material properties and hygrothermal performance of wheat and barley straws are assessed following the methodology illustrated in Fig. 1. The mould growth risk of a wall assembly with straw infill under different climate types is modelled using computer simulation. In addition, laboratory experiments are conducted to evaluate material properties, anti-fungal treatment efficacy, and mould resistance.

2.1. Simulation setup

This study conducts Heat, Air, and Moisture Transport (HAM) simulations for a wall assembly that includes straws as insulation material and is exposed to twenty-two different exterior climates (Fig. 1a). The analysis focuses on the annual moisture content of the insulation material, with a special emphasis on the interfaced straw layers next to the exterior and interior sides. The interfaced layers are then simulated further for mould growth risk.

Non-steady heat and moisture transport processes are solved by coupled differential equations using the software WUFI Pro 6.6 (WUFI, 2022), i.e. heat transport and moisture transport by

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

and

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

respectively, where D_w ($m^2\ s^{-1}$) is the liquid transport coefficient, H (J m^{-3}) the enthalpy, h_v (J kg^{-1}) the evaporation enthalpy of water, p (Pa) the water vapour partial pressure, w ($m^3\ m^{-3}$) the water content, δ (kg $m^{-1}\ s^{-1}\ Pa^{-1}$) the water vapour diffusion coefficient in air, T (°C) the temperature, λ (W $m^{-1}\ K^{-1}$) the thermal conductivity, μ (dimensionless) the vapour diffusion resistance factor, ρ_w (kg m^{-3}) the density of water, and ϕ (dimensionless) the relative humidity RH.

The mould growth risk is examined using the software WUFI Bio 4.0, which employs the bio-hygrothermal model developed by Sedlbauer et al. (2003). By plotting the germination times in a temperature-humidity diagram and modelling the critical water content of mould spores, the germination and mould growth can be predicted if the water content in the model spore exceeds the critical water content.

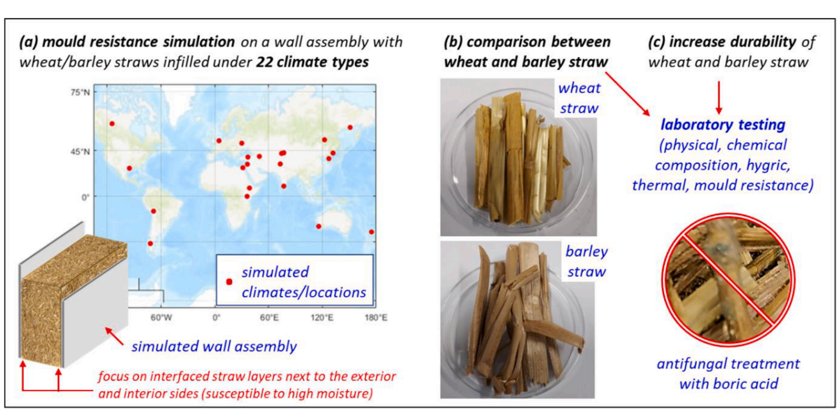

Fig. 1. Methodology.

The substrate class I, i.e. bio-utilizable substrates, is assumed for all samples in this research.

The assembly wall design [(International Residential Code (IRC) 2015; Fachverband Strohballenbau Deutschland e.V. (FASBA) 2019)] consists of a 50 cm thick straw layer that is covered with 3 cm lime plasters on both the exterior and interior sides (with material properties listed in Table 2). For the hygrothermal analysis, this study has carefully selected twenty-two locations that represent distinct climate zones based on the Köppen climate classification. These locations encompass a wide range of transient boundary conditions, effectively capturing the major climate variations. Furthermore, only cities situated in countries that locally produce wheat and barley crops have been included in the analysis. Table 1 summarizes the annual weather conditions (Dru Crawley; Linda Lawrie 2020) and the annual wheat and barley crop yield in their respective countries (Food and Agriculture Organization of the United Nations, 2022) for all twenty-two locations. The wall faces the main driving rain direction in all cases. The interior climate is set according to ISO 13788, with humidity class 3, which represents a building with unknown occupancy (ISO 2012), and a constant air temperature of 20 °C. The simulation runs for ten years or until hygrothermal equilibrium is achieved, and the results from the final year are extracted for further analysis.

2.2. *Experiment setup*

2.2.1. *Sample preparation*

The wheat and barley straws used in the study were obtained from local sources in the Netherlands, provided by Strobouwer, Haaren. To prepare the samples, the straws were chopped into smaller pieces measuring 6 ± 4 cm in length, as shown in Fig. 1b. While the barley straw consists solely of stalks, the wheat straw contains about 10% spikes and leaves. However, for comparative analysis, the leaves and spikes were removed from the wheat straw samples used in this study.

An aqueous solution of boric acid, $B(OH)_3$, at a concentration of 4% w/w (referred to as BA) is used as an antifungal agent, which is within the concentration limit of 5.5%w/w set by the European regulation (European Chemicals Agency (ECHA) 2010). For antifungal treatment, the outer surface of the straws is sprayed with the BA solution and manually mixed to create an almost uniform surface coating. The amount of BA present in each specimen is 9 ± 1% by weight of the dry straw.

Samples with five different bulk densities, denoted by ρ_{bulk} (60, 70, 80, 90, 100 kg m^{-3}), are prepared for measuring thermal conductivity and vapour diffusion resistance. The bulk densities are controlled by adjusting the weight of the straws (±0.1 g) in fixed-volume containers.

2.2.2. *Physical properties and chemical composition*

For microstructure observation, the surface and cross-section of the straws are visually inspected with an optical microscope (ZEISS Axio Imager 2) and a scanning electron microscope SEM (Phenom ProX).

The particle density $\rho_{particle}$ (kg m^{-3}) of the straws is measured using a helium pycnometer (Micromeritics AccuPyc II 1340) with a 10 cm^3 cup. The porosity φ (%) of the specimen is calculated from their $\rho_{particle}$

Table 2
Main material properties for simulation.

	Barley straws	Wheat straws	Barley straws (treated)	Wheat straws (treated)	Lime plaster
Bulk density ρ_{bulk}, dried (kg m^{-3})	100	100	100	100	1600
Porosity (%)	0.89 *	0.90 *	0.88 *	0.90 *	0.4
Specific heat capacity C_p (J kg^{-1} K^{-1})	1645 *	1735 *	1692 *	1745 *	850
Thermal conductivity λ (W m^{-1} K^{-1})	0.052 *	0.061 *	0.054 *	0.059 *	0.7
Vapour diffusion resistance factor μ (dimensionless)	5 *	5 *	5 *	5 *	7
Moisture content at RH = 80% (%)	0.13 *	0.14 *	0.14 *	0.15 *	0.02

Note * *The values are obtained from the experiments in this study.*

Table 1
Simulated cases.

Climate type note 1	Represented location note 2	Mean temp (°C)	Mean RH (%)	Normal rain (mm/a)	Simulated orient note 3	Wheat yield (hg/ha) note 4	Barley yield (hg/ha) note 4
BSk	Baku, AZE	15.6	76.1	243.9	N	31,555	28,884
BSh	Coimbatore, IND	26.8	68.9	997.3	SW	35,334	28,372
BWk	Damascus, SYR	18.0	51.4	80.7	SW	22,927	20,617
BWh	Cairo, EGY	23.3	55.5	35.2	W	65,003	37,406
Cfa	Houston, USA	20.5	73.3	88.2	E	34,746	41,785
Cfb	Amsterdam, NLD	11.0	79.7	838.6	SW	93,781	72,588
Cfc	Auckland Islands, NZL	15.7	80.7	1280.3	N	88,522	69,180
Cwa	Islamabad, PAK	22.3	60.0	904.1	E	28,059	9682
Cwb	Addis Ababa, ETH	17.1	61.4	1633.5	S	29,705	25,012
Cwc	La Paz, BOL	7.8	59.7	975.8	E	11,993	8943
Csa	Perth, AUS	18.6	61.4	577.1	W	16,917	19,878
Csb	Nakuru, KEN	18.6	67.9	1427.9	N	26,287	35,721
Csc	Chile Chico, CHL	8.2	65.3	706.0	NW	62,860	73,725
Dfa	Almaty, KAZ	10.0	63.0	716.1	SW	10,137	12,866
Dfb	Kyiv, UKR	9.7	71.8	659.3	NW	41,566	34,174
Dfc	Yellowknife, CAN	-3.1	67.1	313.6	NE	33,834	38,066
Dwa	Pyongyang, PRK	9.4	73.7	1303.9	S	12,207	11,662
Dwb	Vladivostok, RUS	5.5	72.1	637.4	SE	27,016	24,001
Dwc	Mohe, CHN	-3.2	65.2	426.8	NE	56,298	39,354
Dsa	Bishkek, KGZ	12.3	55.0	921.8	W	25,093	22,717
Dsb	Sivas, TUR	9.7	62.3	410.8	SE	27,811	26,565
Dsc	Soldotna, USA	3.2	71.1	187.7	E	34,746	41,785

Note 1 Climate type is as per Köppen climate classification: *B*= dry, C= temperate, *D*= continental, *W*= arid desert, *S*= semi-Arid, *w*= dry winter, *f*= no dry season, *s*= dry summer, *a*= hot summer, *b*= warm summer, *c*= cold summer.
Note 2 *ISO 3166–1 alpha-3 codes (three-letter country codes) are used to represent the countries.*
Note 3 *Simulated wall orientation is facing the driving rain direction: N= north, S= south, W= west, E= east.*
Note 4 *Quantity is based on the annual wheat and barley yield (hectogram/hectare) in the whole country in the year 2019.*

and ρ_{bulk} (kg m^{-3}) as

$$\varphi = 1 - \frac{\rho_{bulk}}{\rho_{particle}} \quad (3)$$

The pycnometer has an accuracy of 0.03% in reading plus 0.03% of sample capacity.

The water contact angle (°) of the surface of the straws is measured using a contact angle system (Dataphysics OCA30) for its hydrophobicity. The apparatus has an accuracy of 0.1° reading.

Fourier transform-infrared FT-IR spectroscopy aligned with attenuated total reflection ATR attachment (PerkinElmer Frontier FT-IR) is utilized to analyse the chemical composition of the straws. The major components in both wheat and barley straws (Sun and Tomkinson, 2002; Sun and Sun, 2001) are polysaccharides (cellulose, hemicellulose, lignin) which cannot be easily distinguished using individual IR bands. It is, however, possible to use certain bands that can be assigned to specific components for identification and use the relative intensity of each band as an approximation proportion of those components in a sample (Garside and Wyeth, 2003). The selected components and bands are listed in Table 3.

2.2.3. Hygroscopic properties

The sorption isotherms of the straws are measured using the gravimetric sorption technique through dynamic vapour sorption (DVS) (Surface Measurement Systems DVS Resolution). The specimen is conditioned in the relative humidity RH environment between 0% and 95% RH. The weight of the specimen is measured at a 10% RH increment step for the sorption curve, and at a 10% decrement step for the desorption curve, all under a constant temperature of 20 °C. The specimen is considered to reach its constant mass once the rate of mass change dw/dt (%kg kg^{-1} min^{-1}) is equal to or less than 0.01. The DVS apparatus has a declared accuracy of 0.5% RH reading and a balance noise of less than 0.3 µg. Appendix C provides additional discussion on the DVS method.

The vapour diffusion coefficient (cm^2 s^{-1}) of the straws is measured in parallel with the sorption measurement using the DVS apparatus.

The free water saturation w_{sat} is approximated by fully immersing the straws in water for 7 days, an approximation method based on ASTM C1498–01 note 3 (ISO 2020). The surface of the samples is then lightly blotted with a damp sponge to remove excess water and their weight is measured.

The water vapour diffusion resistance factor μ is measured using the wet cup and the dry cup methods according to standard ISO 12572 (ISO 2020). The cups are filled with anhydrous calcium chloride $CaCl_2$ for the dry cup method and water for the wet cup method. Specimen with a thickness d_μ (m) are attached to the cups with a specific exposed area A_μ (m^2) and the edges are sealed with aluminium tapes to block vapour passage at the edge of the specimen. The change of mass Δm (kg) at successive times Δt (s) is measured by weighing the cups to obtain the density of water vapour transmission rate g (kg m^{-2} s^{-1}) as

$$g = \frac{1}{A_\mu}\frac{\Delta m}{\Delta t} \quad (4)$$

The measurement is considered complete once five successive values of g only vary within ±5%. The value of μ (dimensionless) is then calculated using

$$\mu = \frac{\Delta p \cdot \delta_{air}}{g \cdot d_\mu} \quad (5)$$

where Δp (Pa) is the water vapour partial pressure difference and δ_{air} (kg m^{-1} s^{-1} Pa^{-1}) is the water vapour permeability of air.

Table 3
The selected ATR FT-IR bands for the chemical composition in straws.

To represent	With selected bands	Ref	Representative ratios
Cellulose	C-C ring breathing band at 1155 cm^{-1}	(Garside and Wyeth, 2003)	As denominator
	C—O—C glycosidic ether band at 1105 cm^{-1}		
Lignin	C = C in-plane aromatic vibrations at 1505 cm^{-1}	(Garside and Wyeth, 2003)	I_{1505}/I_{1155}, I_{1505}/I_{1105}
	C = C in-plane aromatic vibrations at 1595 cm^{-1}		I_{1595}/I_{1155}, I_{1595}/I_{1105}
Wax	C = O ester band at 1735 cm^{-1}	(Sun and Sun, 2001; Athukorala et al., 2009)	I_{1735}/I_{1155}, I_{1735}/I_{1105}
	CH_2 asymmetric stretching at 2918 cm^{-1}	(Wiśniewska et al., 2003; Jiang et al., 2009)	I_{2918}/I_{1155}, I_{2918}/I_{1105}

2.2.4. Thermal properties

The measurement of thermal conductivity λ W m^{-1} K^{-1}) is done using the transient line source method with a thermal needle probe (AP Isomet model 2104). The probe has a declared accuracy of 5% of the reading plus 0.001 W m^{-1} K^{-1}. Five different bulk densities (60, 70, 80, 90, and 100 kg m^{-3}) are prepared for measurements under dry conditions. To conduct measurements under dry conditions, the samples are first dried at 40 °C in an oven and then transferred to a desiccator filled with silica gel to reach a near 0% RH condition. For moisture-dependant thermal conductivity measurements, only samples with a bulk density of 80 kg m^{-3} are selected for analysis. The study includes five RH conditions, namely near 0%, 33%, 43%, 59%, and 85% RH. All measurements are taken at room temperature (20±2 °C). The sample is placed inside a fixed 500 ml container, with the straws randomly distributed to average the effect of fibre orientation. The weight of the straws is carefully adjusted (±0.1 g) to achieve the predetermined bulk densities.

2.2.5. Mould resistance

To determine the growth rate and presence of mould on the straws, a mould growth test was conducted following European Assessment Document EAD 040005–00–1201 Annex B (EOTA 2015). The test involved placing the straws in a desiccator filled with water for two months, during which time they were exposed to high relative humidity. At the end of each month, the specimens were visually examined for the presence of mould using both the naked eye and a microscope, following ISO 846 (ISO 1997).

3. Results and discussion

3.1. Simulated performance

In the selected wall type and climates, the areas with higher moisture content in the insulation layer are typically at the layers adjacent to the exterior lime plaster or behind the interior lime plaster. Fig. 2a presents the moisture content of these interfaced layers over a simulated year. The mould growth risk of these straw layers is then computed and shown in Fig. 2b, with a summary of the results in Fig. 2c. The results demonstrate no substantial distinction in mould growth risk between using wheat or barley straws as insulation material in the simulated wall assembly. Consequently, both types of straws are combined in the same figure.

Out of the twenty-two cases that represent different climate types, half of them have a significant risk of mould growth within the straw layers. amongst these cases, eight (BSk, BSh, Cfb, Cfc, Cwa, Cwb, Csa, Dwa, Dwb) have a higher mould growth risk at their exterior interfaced layer, while six cases (BSk, BSh, BWh, Cfa, Cwa, Dwa) have a higher risk at their interior interfaced layer. These findings suggest that it is essential to select a straw type with greater resistance to mould growth or apply an anti-fungal treatment on the straws when using them as

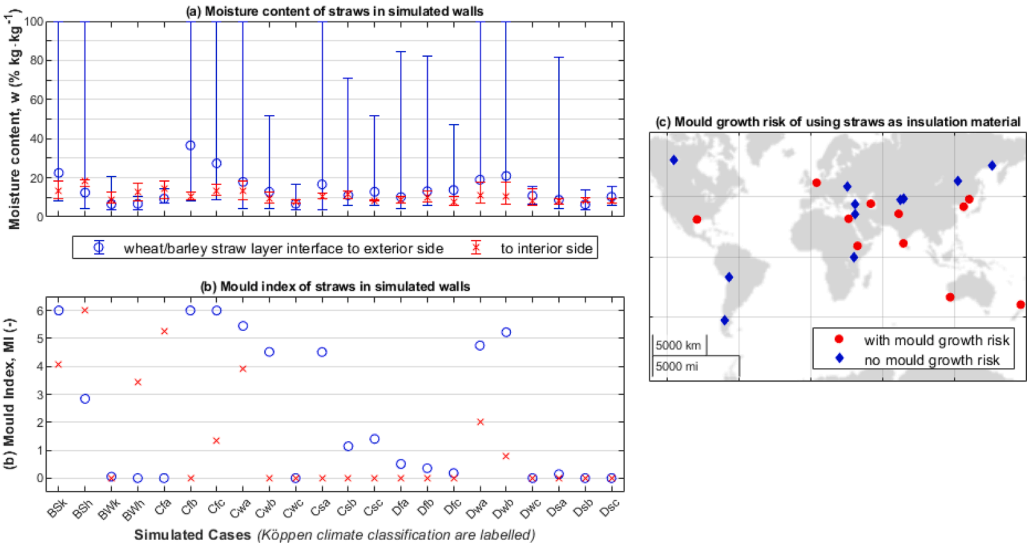

Fig. 2. Simulated results (a) moisture content of straws in simulated walls, (b) mould index of straws in simulated walls, (c) mould growth risk of using straws as insulation material.

insulation material in these unfavourable climates.

3.2. Physical properties and chemical composition

The straws used in this study have different stalk structures (Fig. 3). The stalk of the barley straw is wider and fuller on average than the wheat straw. It has a light-brown colour compared to the yellowish colour of the wheat straw. It contains a combination of macropores (~100–500 μm) and mesopores (~10–50 μm) and thicker stalk wall layers, while the wheat straw contains only mesopores. This gives barley straws a less dense structure compared to wheat straws. On average, the barley straw has a particle density of 872 kg m^{-3}, compared to 1013 kg m^{-3} for the wheat straw (Table 4). This lower particle density of barley straw makes them more vapour diffusible per individual stalk; with a diffusion coefficient of 3.4×10^{-7} cm^2 s^{-1} compared to the wheat straw at 0.8×10^{-7} cm^2 s^{-1}. In bulk, a material made of barley straws has a lower porosity compared to those made of wheat straws; a typical 80 kg m^{-3} bulk material made of barley straws has an open porosity of 91%,

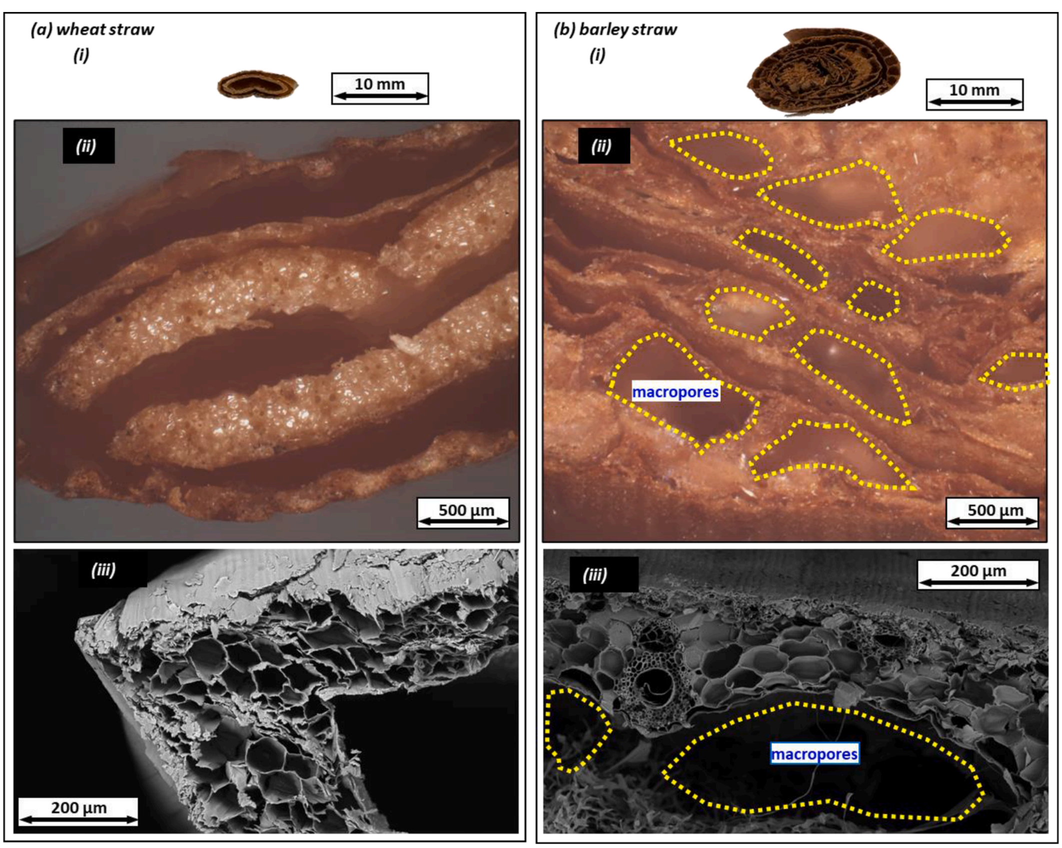

Fig. 3. Cross-section of (a) the wheat straw and (b) the barley straw; photos taken using an optical microscope (ii) and SEM (iii).

Table 4
Material properties and chemical composition of the wheat and barley straws (untreated and treated).

	Wheat straws		Barley straws	
	Untreated	Treated BA	Untreated	Treated BA
Stalk wall thickness (μm)	270 ± 80	–	540 ± 100	–
Particle density $\rho_{partocle}$ ($kg \cdot m^{-3}$)	1013 ± 18	961 ± 13	872 ± 24	830 ± 23
Open porosity φ (%) [note 1]	92.1 ± 1.8	91.7 ± 1.4	90.8 ± 2.8	90.4 ± 2.8
Vapour diffusion coefficient ($x\ 10^{-7}\ cm^2 \cdot s^{-1}$)	0.8 ± 0.2	1.1 ± 0.4	3.4 ± 0.7	4.0 ± 1.2
Water contact angle (°)	76.7 ± 2.6	100.4 ± 9.0	81.3 ± 2.1	99.2 ± 16.1
Ratio lignin to cellulose [note 2]				
I_{1595} / I_{1155}	0.87 ± 0.10	0.70 ± 0.14	0.94 ± 0.06	0.66 ± 0.06
I_{1595} / I_{1105}	0.78 ± 0.12	0.57 ± 0.15	0.86 ± 0.11	0.56 ± 0.11
I_{1505} / I_{1155}	0.85 ± 0.10	0.68 ± 0.14	0.87 ± 0.10	0.52 ± 0.05
I_{1505} / I_{1105}	0.77 ± 0.12	0.55 ± 0.15	0.79 ± 0.14	0.44 ± 0.10
Ratio wax to cellulose [note 2]				
I_{2918} / I_{1155}	0.95 ± 0.13	1.00 ± 0.21	1.07 ± 0.17	1.40 ± 0.45
I_{2918} / I_{1105}	0.86 ± 0.16	0.81 ± 0.22	0.97 ± 0.23	1.00 ± 0.49
I_{1734} / I_{1155}	0.86 ± 0.09	0.72 ± 0.15	0.90 ± 0.10	0.69 ± 0.33
I_{1734} / I_{1105}	0.78 ± 0.11	0.58 ± 0.16	0.82 ± 0.15	0.58 ± 0.37

Note [1] *for bulk density at 80 kg m^{-3}.*
note [2] *corresponding ATR FT-IR Spectroscopy is as per Fig. 4.*

compared to 92% for wheat straws.

After the antifungal surface treatment using BA, the particle density of the barley and wheat straws are decreasing by around 5%, which suggests that a more porous stalk structure is created. However, no significant cracks or wall collapse is observed under the microscope which can be directly attributed to the BA treatment. Nevertheless, the increasing vapour diffusion coefficient on both the treated straws likewise indicates that the straws are becoming more permeable due to the collapse in some of their wall structures.

The results obtained from ATR FT-IR spectroscopy (Fig. 4 and Table 4) are aligned with (Sun and Tomkinson, 2000); both wax and lignin contents in the barley straw are relatively higher than in the wheat straw. The higher relative wax content on the surface of the barley straw could indicate that the barley straw is less hydrophilic. This is further confirmed using the water contact angle measurement, where the barley straw exhibits a higher contact angle of 81° compared to the wheat straw at 77°

Both the wheat and barley straws show overall similar intensities in their FT-IR spectrum compared to their untreated counterparts, suggesting that there is no significant change in the chemical composition of the surface of the straw after being treated with BA. The relative ratios of lignin and wax to cellulose in the treated straws are largely lower than their corresponding untreated straws. The relative ratios also show both wax and lignin contents in the wheat straw are closer to the barley straw after treatment. This could imply that the impact of BA on the wheat straw is stronger than the barley straw, with more wax and lignin now exposed on the surface during the measurements.

On the other hand, the water contact angle measurement on the treated straws shows an increase in their hydrophobicity, implying that additional waxes or other nonpolar compounds may have been released onto the surface after the straws are treated with BA. The water contact angle of the wheat straw increased to 100° while the barley straw to 99°

3.3. Hygroscopic properties

The measured moisture content of the straws is plotted against the predetermined RH conditions, as shown in Fig. 5a. The average moisture that can be adsorbed by the wheat and barley straws is in the range of 12 to 13% at 80% RH, which is aligned with those found in other studies (Koh and Kraniotis, 2020). During the desorption process, their moisture contents are in the range of 14% to 17% at 80% RH.

The wheat straw has a higher sorption capacity and kinetics than the barley straw. The results are aligned with the microstructure observed in the straws, where the wheat straw has only mesopores compared to the barley straw with a combination of mesopores and macropores. The

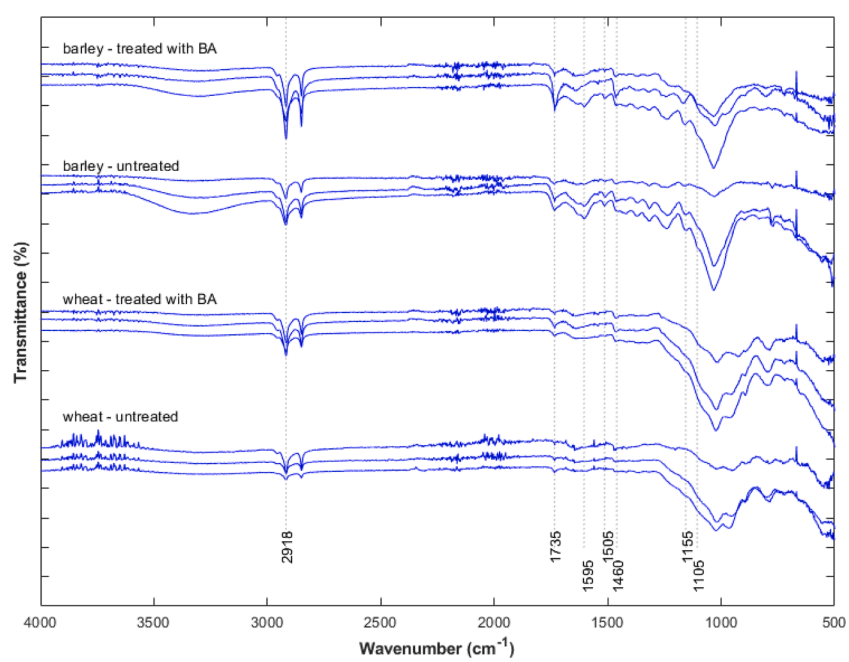

Fig. 4. ATR FT-IR Spectroscopy of the wheat and barley straws (treated and untreated); three samples per category are shown.

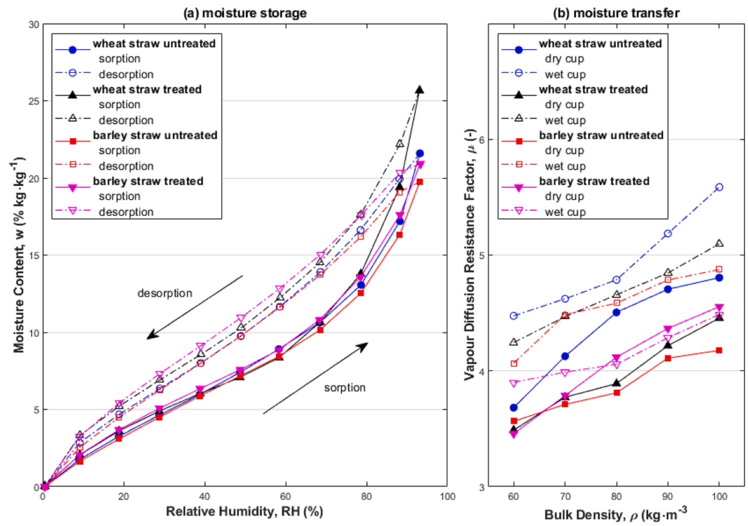

Fig. 5. (a) Sorption isotherms and (b) vapour diffusion resistance factor for the wheat and barley straws (treated and untreated).

smaller pores (mesopores) are quicker to be filled with water vapour and reach a saturated state, while the larger pores (macropores) take a longer time to be filled under the same pore volume. In addition, the capillary rise is inversely proportional to the radius of the pore, i.e. the smaller the pore is, the greater the rise or fall of the moisture in the pore (Çengel and Cimbala, 2006), and the higher the sorption kinetics.

The second observation is that the treated straws have a higher sorption capacity than the untreated straws. The higher sorption capacity suggests that additional microcracks are introduced in the straw structure that allows more vapour to be filled. This explanation is parallel to the vapour diffusion coefficient of a treated straw, where it becomes more permeable due to the collapse of some of its wall structures.

From the full immersion test, the free water saturation w_{sat} for the wheat straw is around 600% of their dry weight, and 500% for the barley straw. These results are higher than the 400% estimation typically used in the sorption models for straws (Hedlin, 1967; Lawrence et al., 2009; Yin et al., 2018). No significant difference in w_{sat} is found between the treated and untreated straws. The higher w_{sat} of the wheat straw is mainly contributed by their higher open porosity in bulk compared to the barley straw, which can be filled with more water under full immersion.

The vapour diffusion resistance factor μ is used to describe the vapour permeability of bulk material (Fig. 5b). The barley straw shows a slightly lower factor than the wheat straw, however, both are in the range of 4 and 5 under the investigated bulk densities, similar to those reported in (Marques et al., 2019; Munch-Andersen and Andersen, 2004; Deutsches Institut für Bautechnik DIBt 2017; Reif et al., 2016). No substantial change is found between the treated and the untreated straws. There is a slight increment of the factor with increasing density, aligned to the finding in (Lebed and Augaitis, 2017).

3.4. Thermal properties

The effective thermal conductivity λ of both treated and untreated wheat and barley straws are plotted against their bulk densities in Fig. 6a. The thermal conductivities fall within the range of 45 and 65 mW m^{-1} K^{-1} for bulk density ranging from 60 to 100 kg m^{-3}, which aligns with values reported in previous studies (Koh and Kraniotis, 2020). In general, a lower bulk density or higher porosity results in a lower thermal conductivity of the straws. This is because the air in the pores has a lower thermal conductivity than the solid part of the straws, which is consistent with the findings of other studies (Costes et al., 2017; Shea et al., 2012). The treated straws have a lower porosity compared to the untreated straw at the same bulk density, resulting in higher thermal conductivities.

The thermal conductivity of barley straw is only slightly lower than that of wheat straw. At a bulk density of 80 kg·m^{-3}, the mean dry thermal conductivity (λ_{dry}) of barley straw is 51 mW m^{-1} K^{-1}, while that of wheat straw is 53 mW m^{-1} K^{-1}. As the bulk density increases from 60 to 100 kg m^{-3}, the mean thermal conductivity of barley straw increases

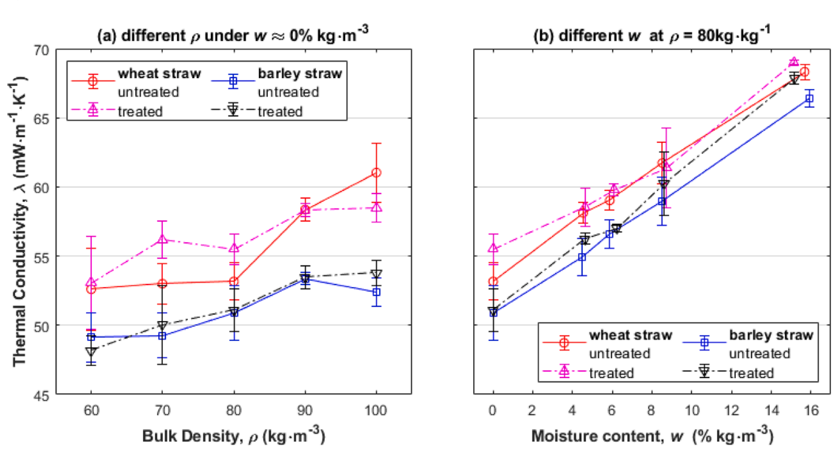

Fig. 6. Thermal conductivity plotted against (a) different bulk density and (b) different moisture content of the wheat and barley straws (treated and untreated).

from 49 to 53 mW m^{-1} K^{-1}, while that of wheat straw increases from 53 to 61 mW m^{-1} K^{-1}. The wheat and barley straws have different microstructures, with barley straw having larger pores and thicker wall structures, which could affect their effective thermal conductivity.

There is no noticeable difference in thermal conductivity between the treated and untreated straws. The use of an antifungal treatment with boric acid (BA) has no significant impact on the thermal conductivity of the straws.

Straw samples with a bulk density of 80 kg m^{-3} are selected for additional moisture-dependant λ analysis. Fig. 6b illustrates the linear relationship between the thermal conductivity and moisture content of both treated and untreated wheat and barley straws. The thermal conductivity of the straws increases with increasing moisture content in the pores because water has a higher thermal conductivity than air within a pore (598 mW m^{-1} K^{-1} as opposed to 25 mW m^{-1} K^{-1}). Both straws demonstrate a comparable incremental trend in thermal conductivity with increasing moisture content, emphasizing the prominent role of moisture in determining the overall insulation performance. No significant difference in thermal conductivity between the treated and untreated straws is observed under different moisture contents.

3.5. Mould resistance

The test specimen is subjected to high humidity conditions in a desiccator filled with water for two months. At the end of the first and second months, the specimen is visually examined with the naked eye and a microscope to detect the presence of mould. The specimens before humidity conditioning and after the first and second months under high humidity conditioning are shown in Fig. 7. The intensity of fungal growth on the test specimen is evaluated according to the scales of mould growth specified in ISO 846 (ISO 1997).

By the end of the first month, significant mould growth covering

Fig. 7. Mould resistance tests on the wheat and barley straws (treated and untreated). Photos are taken on Day 1, Day 28 and Day 56, with the intensity of mould growth (IG) included.

more than half of the test surface is observed on the untreated wheat straw, while only minor mould growth is present on the barley straw as observed with the naked eye. After an additional month of humidity conditioning, heavy mould growth is visible on the entire surface of the wheat straw, but no significant increase in mould growth is observed on the barley straw. These results support the hypothesis that the lower ratio of lignin to cellulose-hemicellulose and a lower percentage of wax in barley straw contribute to its higher resistance to mould growth compared to wheat straw. In addition, wheat straws have higher moisture content and are less permeable, i.e. with higher sorption isotherms compared to barley straws and a higher vapour resistance factor, which signifies more free water in wheat straws to sustain any mould growth.

The use of BA as an antifungal treatment on both wheat and barley straws resulted in a significant improvement in retarding mould growth under the same humidity conditioning. Although visible mould growth covering up to 25% of the surface of the treated wheat straw can still be observed, no mould growth is visible on the treated barley straw to the naked eye or under the microscope by the end of the first month. By the end of the second month, significant mould growth covering up to 50% of the wheat straw is observed, while minor, visible mould growth started to show up on the barley straw. The effectiveness of BA as a fungicide on the straws is noticeable, with improved mould resistance on the treated straws.

Additionally, whitish spots observed on the treated wheat straw (Fig. 7b, Day 56) match the account of white rot fungi (Langer et al., 2021). This aligns with the literature where BA has a higher efficacy against brown rot fungi compared to white rot fungi (Lesar and Humar, 2009). It should be noted that severe testing conditions were applied, i.e. continuous exposure under a high-humidity environment for a long period. Therefore, the results are conservative and show higher mould growth potential than what is expected in actual applications.

4. Conclusions

This research aims to explore the possibility of using renewable alternatives, namely wheat and barley straws, as substitutes for conventional insulation materials, leveraging their widespread availability as by-products of global crop production. The study investigates the risk of mould growth in wall assemblies with straw infill across twenty-two distinct climate types, while also comparing the physical, thermal, hygroscopic, and durability properties of wheat and barley straws. Furthermore, the study evaluates the effectiveness of using boric acid as an antifungal surface treatment on straws and assesses its impacts on straw properties.

In general, half of the twenty-two simulated cases, representing different climate types, demonstrate a considerable probability of mould growth within the straw layers. This finding highlights the importance of selecting straw types with higher resistance to mould growth or applying antifungal treatments when using straws as insulation material in such unfavourable climates.

When applied as thermal insulation material, barley straws exhibit better hygrothermal characteristics compared to wheat straws. Specifically, barley straws demonstrate a lower sorption capacity, lower moisture content at the same relative humidity level compared to wheat straws, and a lower thermal conductivity, albeit insignificant, at 51±2 mW m^{-1} K^{-1} compared to 53±1 mW m^{-1} K^{-1} under the dry condition and bulk density at 80 kg m^{-3}. In terms of durability, barley straws exhibit a lower intensity of mould growth compared to wheat straws, which can be attributed to the higher wax and lignin contents, lower sorption isotherms, and higher vapour diffusion due to the existence of macropores within stalk structures. Collectively, these factors suggest that barley straws are more suitable as thermal insulation material than wheat straws.

Boric acid, recognized for its low toxicity and affordability, has been utilized as a fungicide. The straightforward application of boric acid as an antifungal treatment involves simple spraying onto the surface of straws. This treatment can be applied to straw bales, loose-fill, or other bulk materials composed of straws. In the case of straw bales, boric acid can be sprayed onto the bale surface, considering that higher moisture content in the insulation layer is typically concentrated at the layers adjacent to the next layer, where mould growth is prone to occur. Straw bales can be pre-treated and air-dried in the field prior to transportation to the construction site, minimizing the cost impact of pre-treatment. Similarly, for loose straws infill, the straws can be treated during the shredding process. As only surface treatment is necessary, excess moisture from pre-treatment can be eliminated through ambient air-drying or low-temperature accelerated drying.

The application of antifungal surface treatment using boric acid on both wheat and barley straws substantially improves their resistance to mould growth. Treated straws demonstrate a lower intensity of mould growth under identical testing conditions. Although the treated straws exhibit slightly higher sorption capacity compared to the untreated ones, no significant effect is observed on their thermal conductivity.

To conclude, both barley and wheat straws demonstrate significant potential as thermal insulation materials, characterized by low thermal conductivities and no risk of mould growth in favourable climate conditions. The research findings further indicate that barley straws are more suitable than wheat straws for thermal insulation, based on their thermal, hygric, and durability characteristics. Moreover, it is recommended to utilize boric acid as an antifungal treatment for straws in building materials, particularly for wheat straws in unfavourable climatic conditions. This treatment effectively enhances the mould resistance of both wheat and barley straws while having minimal adverse effects on their hygric and thermal properties. Further investigations are warranted to evaluate the suitability of other straw types as insulation material and the efficacy of boric acid on other straw types.

Spotlights

1 Provide insight into the suitability and durability of wheat and barley straws as sustainable insulation materials
2 Suggested using barley straws and boric acid treatment in unfavourable climates when applied as insulation materials
3 Boric acid as an antifungal treatment to improve mould resistance without significant impact on hygrothermal properties
4 Straw type selection and treatment for an affordable and effective solution for sustainable building practices
5 Guideline of selecting and durability treatment on a wider range of bio-based materials as a building material

CRediT authorship contribution statement

C.H. Koh: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **F. Gauvin:** Writing – review & editing, Supervision. **K. Schollbach:** Writing – review & editing, Supervision. **H. J.H. Brouwers:** Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

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