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MOISTURE AND TEMPERATURE EFFECTS ON POROUS BUILDING INSULATIONS IN NZEB ENVELOPES: A REVIEW

BY

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Abstract. This paper is a literature review study comparing the thermal, hygrothermal and environmental performance of synthetic porous insulation materials (EPS, XPS) with a bio-based alternative, sheep wool, in the context of NZEB requirements. Although petrochemical materials are widely used due to their low initial thermal conductivity, data reported in literature show that moisture accumulation produces significant increases of their thermal conductivity, leading to errors in the assessment of thermal loads. Sheep wool shows a comparable thermal conductivity, 0.032 and 0.054 W/(m·K), depending on bulk density, fibre quality and binder, and its hygroscopic behaviour allows uptakes of 35–40% water by dry mass at 100% RH with a moderate rise in conductivity, due to water is rather bound within the keratin than filling the pores. Its high vapour permeability limits the risk of interstitial condensation. Reaction to fire, sound absorption and limitations of wool usage, are addressed in dedicated section.

Keywords: sheep wool, polystyrene, hygrothermal performance, moisture buffering capacity, bio-based insulation.

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1. Introduction

The building sector is responsible for a significant share of global energy consumption, which is why European regulations require the construction of nearly zero-energy buildings (NZEB). To meet these requirements, the performance of the thermal insulation systems in the building envelope becomes crucial. The insulation market has traditionally been dominated by synthetic, petroleum-based materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS), preferred for their low density and initially low thermal conductivity. However, classical evaluations often rely on idealised laboratory conditions (constant temperature of 24°C and completely dry panels), which do not reflect real operating conditions in buildings.

It has been shown that the insulating characteristics of porous materials degrade significantly when moisture accumulates within their structure, a phenomenon frequently observed in practice (Abdou and Budaiwi, 2013). In simple terms, a wet insulation layer drastically reduces its ability to limit heat transfer, similar to a winter coat that loses its thermal comfort when soaked. Experimental results have shown that polystyrene performance is affected not only by the presence of water but also by exposure to high temperatures; in roofs subjected to direct solar radiation, heat fluxes through polystyrene can substantially exceed the values anticipated from dry-state technical data sheets (Khoukhi *et al.*, 2016). Likewise, it has been observed that when moisture penetrates insulating materials, their thermal conductivity increases, leading to energy losses and serious errors in estimating heating demand (Jerman and Černý, 2012).

In view of these limitations, research has increasingly focused on bio-based natural materials. Laboratory studies on sheep wool insulation panels have shown that they can provide thermal conductivities comparable to conventional materials while maintaining stable performance under moist conditions (Zach *et al.*, 2012). Sheep wool has been described as an “intelligent” fibre, capable of absorbing up to 35% water relative to its dry weight without a significant degradation of its insulating properties (Corcadden *et al.*, 2014). Further investigations on natural fibres have confirmed that wool can capture and release moisture from indoor air like an “active sponge”, contributing to passive regulation of humidity in the indoor microclimate (Volf *et al.*, 2015).

A major difference between polystyrene and sheep wool lies in vapour permeability and the ability of the latter envelope to “breathe”. Experimental determinations have shown that wool allows water vapour to move relatively freely, reducing the risk of moisture accumulation and interstitial condensation (Hegyi *et al.*, 2020). In contrast, polystyrene acts as an almost closed hygrothermal barrier, which may favour condensation within the insulation layer and the development of mould in envelope systems.

This paper is a literature review study, and its objective is to bring together the experimental results published on polystyrene and on sheep wool used as building insulation materials, and to compare them under realistic temperature and humidity conditions. No new measurements are presented herein. Although there are numerous individual studies on these two material families, commonly these are reported with different specimen densities, moisture reference bases and test standards, so their results are rarely directly comparable. The gap this review addresses is therefore the absence of a single comparison in which the reported values are placed side by side together with the conditions under which they were obtained, so that the remaining differences can be attributed to the materials rather than to the test protocols.

2. Review methodology

The literature was collected between January and June 2026 from Web of Science Core Collection, Scopus, ScienceDirect and MDPI, supplemented by backward citation tracking of the reviews of Jelle (2011), Schiavoni *et al.* (2016), Asdrubali *et al.* (2015) and Hetimy *et al.* (2024). The search strings combined a material term (“sheep wool” OR “expanded polystyrene” OR “extruded polystyrene” OR “bio-based insulation”) with a property term (“thermal conductivity” OR “hygrothermal” OR “moisture buffer value” OR “water vapour diffusion resistance” OR “building envelope”)

Records were retained when they met all of the following criteria: (i) published between 1973 and 2026, the lower bound being the classical work of Bankvall on radiative transfer in fibrous media, with the great majority of the retained sources published after 2012; (ii) written in English; (iii) reporting measured thermophysical or hygrothermal data, or providing a validated model, for at least one of the three materials considered; (iv) stating the test method or the standard used. Records were excluded when they reported only manufacturer declared values without a stated measurement method, when the specimen density was not given for fibrous materials, or when they dealt with insulation systems outside the building envelope. Thirty-two sources met these criteria and form the evidence base of the present review.

This is a narrative, semi-systematic review and not a meta-analysis: no PRISMA flow diagram, no formal risk-of-bias appraisal and no statistical pooling were performed, because the retained studies use specimens of different density, thickness and binder and report moisture on different reference bases, which makes pooling unsound. All tables are compilations of literature values, and the measurement conditions attached to each value are given in the table notes.

3. Analysis of microstructure and fundamental heat transfer mechanisms

The thermal performance of porous insulation materials is primarily governed by their microstructural architecture and by the fraction of voids (porosity) they contain. From a building physics perspective, the macroscopic thermal behaviour cannot be attributed to a single transfer mechanism, but results from the superposition of all fundamental paths of heat transport.

3.1. Mathematical modelling of heat transfer

The effective thermal conductivity (λ_{eff}) of a porous insulating material is expressed as the sum of the contributions of its constituent phases. Fundamental building physics studies have proposed the following basic relationship in Eq. (1) (Jelle, 2011; He and Xie, 2015):

$$\lambda_{\text{eff}} = \lambda_{\text{solid}} + \lambda_{\text{gas}} + \lambda_{\text{rad}} + \lambda_{\text{conv}} + \lambda_{\text{coupling}} \quad (1)$$

where,

λ_{solid} - denotes conduction through the solid matrix.

λ_{gas} - conduction through the gaseous phase (air trapped in the pores).

λ_{rad} - radiative heat transfer.

λ_{conv} - gas convection within the pores.

$\lambda_{\text{coupling}}$ - secondary coupling effects between these mechanisms.

For most polymeric and fibrous insulating materials with micro- and millimeter-scale pores, the convective component λ_{conv} can be considered negligible in practice.

Recent research has shown that heat transport through the gaseous phase is strongly influenced by the Knudsen effect (Lian *et al.*, 2024). This mechanism has been experimentally validated for porous polymeric materials and nanocellular foams (Notario *et al.*, 2015). Reducing cell size decreases the frequency of molecular collisions with the pore walls, significantly diminishing the contribution of the gas phase to the overall conductivity.

3.2. Thermodynamics and morphology of polystyrene (EPS and XPS)

Polystyrene, as a synthetic petrochemical insulator, is commercially available in two distinct microstructural forms produced by different manufacturing technologies (Cai *et al.*, 2017). Expanded polystyrene (EPS) is obtained by expansion, generating a partially open interstitial cellular network. Experimental determinations have shown that EPS exhibits, in dry conditions, an

initial thermal conductivity in the range 0.031–0.043 W/(m·K), combined with limited water vapour diffusion (Jerman and Černý, 2012; Gnip *et al.*, 2012).

Extruded polystyrene (XPS) is produced by a continuous process of melting and injecting blowing agents under pressure, resulting in a compact network of fully closed cells with initial conductivities below 0.035 W/(m·K). However, the thermal performance of polystyrene does not remain constant over the service life. Its conductivity degrades significantly under high temperature fluctuations (in summer) and under moisture accumulation during operation (Khoukhi, 2018).

3.3. Anisotropic fibrous morphology of sheep wool and radiative effects

In contrast to artificial cellular structures, sheep wool is a renewable organic composite material capable of providing effective control of hygrothermal transfer. Detailed analyses of its hierarchical microstructure have shown that wool fibres consist of an outer epicuticle layer, a scaly cell layer, a cortex rich in keratin and a central medulla channel (Dénes *et al.*, 2019). The specific geometry and scales generate the natural crimp of wool fibres, forming a three-dimensional matrix that efficiently hinders convective air movement, as also indicated by comparative assessments of eco-materials (Schiavoni *et al.*, 2016).

Studies on wool batts have demonstrated that this material offers insulating properties fully comparable to those of synthetic polymers (Zach *et al.*, 2012). These performances are confirmed for wool-based biocomposites bonded with natural rubber latex and polyurethane resin, which achieve competitive thermal conductivities between 0.0324 and 0.0436 W/(m·K) (Dénes *et al.*, 2022). The apparent disagreement between the values quoted for wool in the literature is a density and binder effect rather than a contradiction: loose or low-density batts are reported up to about 0.054 W/(m·K), whereas compacted batts and resin-bonded biocomposites fall to about 0.032 W/(m·K) (Schiavoni *et al.*, 2016; Dénes *et al.*, 2022; Dikmen and Elias Ozkan, 2016). A single range of 0.032–0.054 W/(m·K) is therefore used consistently throughout this paper, and the narrower sub-ranges are quoted only together with the corresponding density.

For animal-origin fibres, the apparent density of the insulation panel is a critical parameter. Classical modelling of heat transfer in fibrous materials has shown that very low densities (maximum porosity) promote a strong increase in the radiative component λ_{rad} , because the amount of solid matrix is insufficient to extinguish infrared thermal radiation (Bankvall, 1973). Optimising the density of wool panels compensates for this effect and reduces the radiative contribution to the overall conductivity.

A synthesis of the fundamental thermophysical parameters, directly correlated with microstructural architecture and with specific mechanisms of heat transfer attenuation for each type of insulation material, is provided.

Table 1

Comparative fundamental thermophysical data (Values aggregated from Jerman and Černý (2012), Zach et al. (2012), Cai et al. (2017) and Dénes et al. (2022))

Analysed parameter / material	Expanded polystyrene (EPS)	Extruded polystyrene (XPS)	Sheep wool batt / biocomposite (20–40 kg/m ³)
Dominant microstructure	Cellular (partially fused, partly open beads)	Closed-cell structure (impermeable matrix)	Fibrous – anisotropic (keratinous cortex and medulla)
Thermal conductivity (λ_{dry}) [W/(m·K)]	0.031–0.043	0.025–0.035	0.032–0.054
Main heat transfer attenuation mechanism	Reduced gas mobility through cellular structure	Limited diffusion and Knudsen effect in closed cells	Air trapped in interstitial spaces by the crimped fibre network

Note: the values are literature data measured on different specimens and are not the result of a common test campaign. Polystyrene values refer to dry specimens at 10°C (EN 12667); wool values cover bulk densities from about 20 to 40 kg/m³. The width of each range reflects this spread in specimen density, fibre quality and binder, not measurement uncertainty, which is typically ± 2 –5% for guarded hot plate and heat flow meter methods.

4. Dynamics of water vapour diffusion and envelope “breathability”

The thermal analysis of a building envelope cannot be separated from the dynamics of moisture. Differences in temperature and partial vapour pressure between the indoor and outdoor environments generate a continuous mass transfer. The main mechanisms governing moisture transport in porous building materials are water vapour diffusion and liquid transport driven by capillary forces (Ducoulombier and Lafhaj, 2017). In the heating season, the vapour pressure gradient generally drives moisture from the interior towards the exterior, while sorption phenomena at pore surfaces significantly modify the thermophysical properties of the materials.

4.1. Mathematical modelling of vapour transport

The ability of an insulation material to allow or to block water vapour flow is quantified by the water vapour diffusion resistance factor (μ). This dimensionless parameter is determined experimentally using the cup method (dry/wet cup), as specified in EN 12086. According to fundamental hygrothermal studies (Jerman and Černý, 2012), the amount of diffused vapour (Δm) enables the calculation of the water vapour diffusion coefficient in the material (D), using the thermodynamic relationship Eq. (2):

$$D = \frac{\Delta m \cdot d \cdot R \cdot T}{S \cdot \tau \cdot M \cdot \Delta p_v} \quad (2)$$

where:

Δm – mass of water vapour diffused through the specimen during the exposure time (kg).

d – specimen thickness [m].

R – universal gas constant [J/(mol·K)].

T – absolute temperature [K].

S – exposed surface area [m²].

τ – exposure time for vapour transport [s].

M – molar mass of water [kg/mol].

Δp_v – difference in water vapour partial pressure on the two faces of the specimen [Pa].

Substituting these units gives D in [m²/s], as required.

Based on D , the water vapour diffusion resistance factor (μ) is defined as the ratio between the diffusion coefficient of water vapour in free air (D_a) and the diffusion coefficient in the material Eq. (3):

$$\mu = \frac{D_a}{D} \quad (3)$$

Alternatively, the water vapor diffusion resistance factor can be expressed by the following relationship in Eq. (4) (Ducoulombier and Lafhaj, 2017):

$$\mu = \frac{\delta_a \cdot S \cdot \Delta p_v}{G \cdot d} \quad (4)$$

where:

G – the mass flow rate of water vapour [kg/s].

δ_a – the water vapour permeability of air [kg/(m s Pa)].

S – exposed surface area [m²].

d – specimen thickness [m].

Δp_v – water vapour partial pressure difference across the specimen [Pa].

Eq. (4) follows from Fick's law written for the specimen, $G = \delta \cdot S \cdot \Delta p_v / d$ with $\delta = \delta_a / \mu$, and is consistent with Eq. (3): the two definitions of μ are equivalent.

4.2. Polystyrene (EPS and XPS) as a hygrothermal barrier

Porous synthetic polymers strongly reduce the “breathability” of the wall. Experimental studies have shown that expanded polystyrene (EPS) exhibits a high μ factor due to its architecture with partially closed pores (Ducoulombier and Lafhaj, 2017). From a hygrothermal point of view, Jerman and Černý (2012)

observed that EPS behaves similarly to cement mortar, acting as a very restrictive barrier to vapour transfer.

A major risk associated with EPS-based systems in service is that, although the material largely blocks vapour flow, it is not fully airtight. Water vapour can slowly penetrate microcavities, and if the temperature drops below the dew point, condensation occurs, and the resulting liquid water becomes very difficult to remove. The accumulation of water in a quasi-closed system increases thermal conductivity (liquid water has $\lambda \approx 0.6 \text{ W/(m}\cdot\text{K)}$, around 20 times higher than that of air), thereby accelerating the long-term energetic degradation of the envelope. For extruded polystyrene (XPS), the fully closed-cell structure further amplifies this blocking effect, with typical μ values ranging between 80 and 150 in practice.

4.3. Sheep wool: active hygroscopic management and “moisture buffering” effect

In sharp contrast to polymeric barriers, natural protein fibres act as open thermal membranes that facilitate vapour diffusion. Studies on sheep wool insulation biocomposites have reported significantly lower μ values, indicating much higher permeability: approximately 1.6 for panels bonded with latex and 2.9 for panels with polyurethane resin (Dénes, *et al.*, 2022). These results are consistent with previous investigations reporting ranges of 2.6-9.7 for various wool panel configurations (Hegyi *et al.*, 2020) and extremely low native values of 1.20-2.12 for untreated wool (Tuzcu, 2007).

The specificity of wool arises from its complex hygroscopic behaviour. Experimental work has shown that sheep wool can absorb between 13% and 18% moisture by dry mass at a relative humidity (RH) of 65%, reaching 35-40% at 100% RH, without flooding the macroscopic pore structure with liquid water (Parlato *et al.*, 2022; Hetimy *et al.*, 2024). Water molecules are retained at the molecular level by hydrogen bonds within the fibre cortex, and the process is characterised by an isothermal sorption-desorption hysteresis, as confirmed by thermogravimetric analyses.

The ability to regulate the indoor microclimate has been quantified by determining the Moisture Buffer Value (MBV). Tests carried out using a NORDTEST-derived protocol, based on cyclic exposure to 75% RH and 33% RH, have shown that materials based on wool and seagrass reach MBV values of about $1.81 \pm 0.24 \text{ g/(m}^2\cdot\%\text{RH)}$, placing them in the “Good-Excellent” performance class for moisture control (Ranefj rd *et al.*, 2024). By comparison, mineral wool exhibits MBV values of around $0.37 \text{ g/(m}^2\cdot\%\text{RH)}$, while polystyrene behaves practically as a hygroscopically inert wall.

The quantitative assessment of vapour permeability and hygroscopic storage capacity, highlighting the thermodynamic contrast between synthetic

cellular insulations and organic materials with active fibrous matrices, is summarised in Table 2.

Table 2

Comparison of diffusion and hygroscopic properties of insulation materials (Values synthesised from Ducoulombier and Lafhaj (2017), Dénes et al. (2022), Ranefjård et al. (2024) and Jerman and Černý (2012))

Thermal insulation material	Water vapour diffusion resistance factor (μ)	Maximum moisture uptake (mass-based)	MBV value [g/(m ² ·%RH)]	Hygrothermal classification
Expanded polystyrene (EPS)	35–70	< 2–3% (closed pores, marginal liquid permeability)	Insignificant (≈ 0)	Partial vapour barrier, hygroscopically inert
Wool-based biocomposite	1.20–2.9 (depending on treatment)	Up to 35–40% (at 100% RH)	1.81 ± 0.24	“Breathable”, active moisture buffer (Excellent)
Mineral wool	≈ 2.0	Low uptake in the fibre, water retained mainly between fibres	0.37 ± 0.07	Permeable, hygroscopically inert (Limited)

Note: μ values are cup-method results (EN 12086 or EN ISO 12572) obtained on different specimens; the dry-cup and wet-cup conditions are not identical across the sources, which is one reason for the width of the ranges. MBV values follow the NORDTEST protocol (8 h at 75% RH / 16 h at 33% RH, 23°C) and are quoted with the uncertainty reported by the original authors where available.

The thermodynamic interaction between wool and water molecules includes an enthalpic adsorption phase. The release and storage of latent heat of vaporisation within the wool fibre attenuate abrupt temperature fluctuations and further contribute to increasing the thermal inertia of insulation panels under variable operating conditions.

5. Direct impact of moisture accumulation on thermal conductivity

From a thermodynamic perspective, the performance of a thermal insulation material relies on the ability of its matrix to retain still air within the pore network. It has been shown that, under standard conditions, the thermal conductivity of air is approximately 0.026 W/(m·K) (Ducoulombier and Lafhaj, 2017). However, the presence of moisture in the porous structure triggers a severe penalty on thermal resistance, because the insulating air is gradually displaced by

liquid water. With an intrinsic thermal conductivity of about 0.6 W/(m·K), liquid water enables heat transfer rates more than 20 times higher than those of the trapped gas. Under such operating conditions, performance can no longer be assessed solely on dry-state declared values, and the use of the Thermal Conductivity Ratio (TCR), defined as Eq. (5):

$$TCR = \lambda_{wet}/\lambda_{dry} \quad (5)$$

5.1. Degradation of thermal performance in synthetic polymers (EPS and XPS)

Although expanded polystyrene (EPS) and extruded polystyrene (XPS) exhibit high structural hydrophobicity and excellent initial thermal conductivities, long-term moisture accumulation leads to significant increases in heat transfer. Owing to limited capillarity and high diffusion resistance, any water that penetrates the material - particularly as interstitial condensation - tends to remain trapped between polymer cells, forming liquid thermal bridges.

Experimental measurements have shown that, for XPS, an increase in moisture content from 0% to 10% by volume raises the thermal conductivity from 0.034 W/(m·K) to 0.044 W/(m·K) (Jelle, 2011). In the case of EPS, vulnerability is even more pronounced due to its partially open porosity. Studies conducted under conditions close to real operation have highlighted that, for a volumetric water content of 15%, the thermal conductivity of EPS rises from 0.036 W/(m·K) in the dry state to about 0.066 W/(m·K), representing a major performance penalty (Khoukhi, 2018).

Empirical correlations proposed for the TCR parameter indicate that once the water content exceeds approximately 10% by volume, the $\lambda_{wet}/\lambda_{dry}$ ratio increases rapidly, particularly in low-density materials, turning moisture accumulation into a critical energy-efficiency issue (Cai *et al.*, 2017).

A commonly used empirical relationship for predicting the conductivity of moisture-affected materials can be approximated by the model proposed by Künzel and further analysed by Apostolopoulou-Kalkavoura *et al.* (2020), in which the presence of liquid water directly increases the conductive component of the solid phase Eq. (6):

$$\lambda_{eff(w)} = \lambda_{dry} + f_w \cdot \Delta\lambda_{water} \quad (6)$$

where:

f_w - volumetric water fraction.

$\Delta\lambda_{water}$ - penalty factor associated with the higher thermal conductivity of water.

5.2. Hygrothermal response of sheep wool and preservation of insulation capacity

In sharp contrast to petrochemical synthetic materials, sheep wool exhibits a high chemical affinity for water molecules and manages moisture through a predominantly intracellular absorption mechanism, without flooding the interstitial voids within the batt structure. Recent studies have shown that natural wool-based insulations can absorb water vapour without significantly altering their macroscopic thermal characteristics (Hetimy *et al.*, 2024). This remarkable hygroscopic capacity allows wool to store up to 35-40% water by dry weight under saturation conditions (100% RH).

To quantify this behaviour, 80 mm thick sheep wool batts were subjected to detailed laboratory testing (Zach *et al.*, 2012). The results show that, up to a mass moisture content of about 20%, the increase in thermal conductivity is marginal: λ rises only from 0.036 W/(m K) in the dry state to approximately 0.041 W/(m K). Only at extreme saturation levels, above 30% mass moisture content, does water begin to influence this parameter more significantly, with values reaching around 0.047 W/(m K); even then, overall performance remains clearly superior to that of materials flooded with liquid water.

The physico-chemical explanation for this “paradox” - retaining a large amount of water without a severe loss of insulating capacity - lies in the fact that hydrogen bonds fix H₂O molecules within the keratin chains in the fibre cortex. The sorption process occurs mainly at the intracellular level, leaving the micro- and macropores free of liquid water; these pores remain filled with still air, which continues to act as an effective thermal insulator.

The moisture contents reported in the literature for wool are expressed on a mass basis, whereas those reported for polystyrene are volumetric, and the two are not interchangeable. They are related by $w_v = w_m \cdot \rho^b / \rho_{vo}$, where w_v is the volumetric water content (%), w_m the mass-based water content (%), ρ^b the bulk density of the dry material and $\rho_{vo} = 1000 \text{ kg/m}^3$. Because insulation materials have very low bulk densities, the conversion changes the picture substantially: for a wool batt of 30 kg/m³, a mass content of 20% corresponds to only about 0.6% by volume, while for an EPS board of 20 kg/m³ a volumetric content of 15% corresponds to roughly 750% by dry mass. Both bases are therefore reported in Table 3, and the comparison between materials must be read with this difference taken into account.

Table 3

*Impact of moisture content on effective thermal conductivity
(Data synthesised from experimental measurements by Zach et al. (2012) for wool and
by Jelle (2011), Khoukhi (2018) and Cai et al. (2017) for polystyrene)*

Insulation material	Material state	Moisture content mass basis / volumetric basis	Effective thermal conductivity λ [W/(m·K)]	Performance penalty (% increase in λ)
Sheep wool	Completely dry	0% (dry reference)	0.036	Reference (0%)
Sheep wool	Wet (intracellular sorption)	$\approx 20\%$ by mass $\approx 0.6\%$ by volume ($\rho^b = 30 \text{ kg/m}^3$)	0.041	+13.8%
Sheep wool	High saturation	$\approx 30\%$ by mass $\approx 0.9\%$ by volume ($\rho^b = 30 \text{ kg/m}^3$)	0.047	+30.5%
Extruded polystyrene (XPS)	Dry	0% (dry reference)	0.034	Reference (0%)
Extruded polystyrene (XPS)	Water-infiltrated	$\approx 286\%$ by mass 10% by volume ($\rho^b = 35 \text{ kg/m}^3$)	0.044	+29.4%
Expanded polystyrene (EPS)	Dry	0% (dry reference)	0.036	Reference (0%)
Expanded polystyrene (EPS)	Flooded (liquid water in pores)	$\approx 750\%$ by mass 15% by volume ($\rho^b = 20 \text{ kg/m}^3$)	0.066	+83.3%

Both the mass-based and the volumetric water content are given for every entry, converted with $w_v = w_m \cdot \rho^b / 1000$ using the bulk densities stated in the source (wool 30 kg/m³, EPS 20 kg/m³, XPS 35 kg/m³). The values come from separate test campaigns using different specimens and conditioning protocols, so the percentages in the last column compare each material with its own dry reference and not with one another at equal moisture content.

At equal volumetric water content, the two material families behave very differently: an ingress of about 15% by volume raises the conductivity of EPS by more than 80%, whereas the highest saturation state reported for wool corresponds to less than 1% by volume and costs about 30%. It must be stated plainly that these are not measurements at a common moisture level, and the comparison therefore does not show that wool tolerates the same quantity of water better. What the assembled data do support is a difference in mechanism and in what happens in service: in wool, water is bound within the keratin and the macropores stay air-filled, so the material reaches its practical moisture ceiling at a volumetric content that remains low; in EPS and XPS, water accumulates as liquid in the cellular structure and can reach volumetric contents an order of magnitude higher, with the corresponding loss of thermal resistance. Whether that difference is realised in a given wall depends on the vapour control layer and the drying capacity of the assembly, not on the insulation alone.

6. Hygroscopic behaviour and the “Moisture Buffering” effect

In building physics, the behaviour of porous insulation materials under the action of ambient water vapour is described by their hygroscopicity. The assessment of hygroscopic performance requires plotting sorption (adsorption and absorption) and desorption curves, which illustrate the relationship between the material's equilibrium moisture content and the relative humidity (RH) of the surrounding environment at constant temperature. Mathematically, the mass-based moisture content w is calculated as the ratio between the mass difference (wet vs. dry state) and the dry mass of the material, according to the relationship validated by Hung Anh and Pásztor (2021) in Eq. (7):

$$w = \frac{m_{wet} - m_{dry}}{m_{dry}} \cdot 100[\%] \quad (7)$$

6.1. Polystyrene: hygroscopic inertia and hydrophobicity

Cellular synthetic materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS) are structurally hydrophobic. Due to the nature of the polymer network and the predominantly closed-cell porosity, their ability to interact with atmospheric water vapour is practically negligible under normal humidity conditions. Experimental analyses have shown that, on isothermal sorption curves, the amount of vapour taken up by EPS from air is so small that it can effectively be considered zero, lying below the detection limit of high-precision gravimetric equipment (Jerman and Černý, 2012). Even under extreme saturation, mass or volumetric uptake of EPS remains at a very low level, below about 2–3% (Dénes *et al.*, 2019). Consequently, polystyrene behaves in the wall

as a hygroscopically inert material, unable to buffer excess moisture or improve indoor air quality.

6.2. Sheep wool: sorption, desorption and hysteresis

At the opposite end of the spectrum, sheep wool is a natural protein fibre with a remarkably complex structure, featuring a cell cortex rich in keratin and strongly hydrophilic chemical groups (such as amides). Recent research has demonstrated that wool exhibits a very high chemical affinity for water molecules (Hetimy *et al.*, 2024; Parlato *et al.*, 2022). It can absorb between 13% and 18% water vapour by dry mass under typical operating conditions (around 20°C and 50–65% RH), and reaches an impressive 35–40% at full atmospheric saturation (100% RH).

An isothermal hysteresis phenomenon governs the dynamic response of organic fibres to humidity variations. High-precision gravimetric DVS (Dynamic Vapour Sorption) measurements on bio-based insulators have revealed a clear asymmetry between the moisture uptake curve (sorption) and the desorption curve (Palumbo *et al.*, 2018), a hysteresis pattern similarly validated for sheep wool-based panels under standardized climatic chamber protocols (Dénes *et al.*, 2022). During desorption, the material retains a larger fraction of the stored moisture for a longer period before complete release; the gap between the two branches of the curve defines the material's ability to buffer vapour fluctuations.

6.3. “Moisture Buffering” effect and indoor comfort

Owing to hysteresis and high vapour diffusion permeability, porous wool insulation acts as an active moisture buffer. The ability of a material to moderate indoor humidity fluctuations is rigorously quantified by the Moisture Buffer Value (MBV). Determined according to the NORDTEST protocol, MBV evaluates the mass of vapour absorbed and released per unit area and per unit change in RH, when the material is subjected to typical daily humidity cycles (e.g. 8 h at 75% RH followed by 16 h at 33% RH).

Laboratory tests have shown that bio-based insulation materials reach exceptional MBV values, typically above 1.60–1.81 g/(m²·Δ%RH) and are classified in the “Good” to “Excellent” performance categories for moisture control (Ranefjärd *et al.*, 2024; Palumbo *et al.*, 2018). In contrast, synthetic materials such as EPS show virtually no buffering capacity, while conventional mineral wool exhibits much lower performance, with MBV values around 0.37 g/(m²·Δ%RH), and is classified as “Limited”.

In real building operation scenarios, this behaviour enables sheep wool to rapidly absorb excess vapour generated by occupants, household activities or outdoor weather variations when indoor air approaches saturation. This prevents reaching the dew point, thereby reducing the risk of surface condensation and

mould growth. When indoor air becomes too dry (as often occurs during the heating season), wool fibres slowly release the stored moisture, passively regulating the indoor microclimate and providing excellent respiratory comfort for occupants.

Thermodynamic analyses indicate that the interaction between water molecules and the polymeric keratin structure in wool is accompanied by the release and storage of significant amounts of sorption latent heat (enthalpy of mixing) (Palumbo *et al.*, 2018; Ranefjård *et al.*, 2024). This energy, dissipated within the porous matrix during vapour uptake, delays wall cooling and further enhances the overall thermal inertia of the building envelope.

The response of porous materials under atmospheric saturation and their ability to act as hygrometric buffers, quantified by MBV, are compared in Table 4.

Table 4

*Comparison of hygroscopic properties and indoor microclimate regulation capacity (Reference values aggregated from Jerman and Černý (2012), Palumbo *et al.* (2018), Dénes *et al.* (2022) and Ranefjård *et al.* (2024)) Note: values compiled from separate studies; EPS and mineral wool figures are dry-cup / NORDTEST results, wool figures are from resin-bonded biocomposite panels, so the entries are indicative of material class rather than directly comparable specimen by specimen*

Porous insulation material	Physical behaviour with respect to vapour	Maximum mass uptake at saturation (100% RH)	MBV value [g/(m ² ·Δ%RH)]	Ability to regulate RH (Moisture buffer)
Polystyrene (EPS/XPS)	Hydrophobic, high hygroscopic inertia	< 2–3%	≈ 0	Non-existent (acts as a blocking barrier)
Mineral wool	Limited interaction at fibre level	Low (water retained mainly by interstitial)	0.37 ± 0.07	Limited
Wool-based biocomposite	Strongly hydrophilic at intracellular level (keratin)	35–40%	1.60–1.81	Excellent (active sponge/moisture buffer with marked hysteresis)

7. Influence of temperature fluctuations under real operating conditions

From an engineering standpoint, treating thermal conductivity (λ) as a fixed, constant value represents a major vulnerability in building energy simulations. In practice, standards and technical data sheets declare thermal resistance at a reference temperature of 24°C (ASTM C518) or 10°C (European standards), under static laboratory conditions. In reality, envelope materials operate in a strongly transient thermodynamic regime, exposed to solar radiation and outdoor weather fluctuations, which substantially alters their insulating capacity.

7.1. Linear increase of thermal conductivity with temperature

Building physics principles show that conductive, convective and radiative heat transfer at the microstructural level intensifies as thermal energy increases. Consequently, material conductivity exhibits a critical dependence on operating temperature. Dedicated studies have confirmed that, for the vast majority of porous materials - both polymeric and fibrous - thermal performance degradation follows an approximately linear trend over the usual operating temperature range (Hung Anh and Pásztor, 2021; Wang *et al.*, 2023).

Mathematically, for porous insulation materials, the temperature dependence of thermal conductivity can be approximated by a simple linear equation Eq. (8) (Berardi and Naldi, 2017; Wang *et al.*, 2023):

$$\lambda(T) = \lambda_{ref} + \beta \cdot (T - T_{ref}) \quad (8)$$

where:

λ_{ref} - laboratory value at the reference temperature.

T - operating temperature.

β - specific thermal variation coefficient (typically between about 0.0001 and 0.0003 W/(m·K²) for most polymers).

This relationship clearly indicates that, as the material heats up, it progressively loses part of its insulating capacity.

7.2. Critical degradation of polystyrene (EPS) at high operating temperatures

The issue becomes particularly acute for polystyrene used in façades and, especially, in roof assemblies. To characterise the behaviour of EPS under realistic conditions, variations in conductivity were monitored at extreme summer temperatures (Khokhi *et al.*, 2016). The results showed that assessments based solely on λ measured at 24°C can severely underestimate cooling loads.

Under direct solar radiation, the mid-plane temperature of EPS layers installed in roofs can exceed 100°C, with peak values around 111.9°C at midday. At these temperatures, thermal resistance collapses: EPS transfers up to 20% more heat compared to the laboratory value at 24°C, with conductivity increasing from $\approx 0.039 \text{ W/(m}\cdot\text{K)}$ to $\approx 0.047 \text{ W/(m}\cdot\text{K)}$. For sun-exposed vertical walls, where temperatures reach about 65°C, the conductivity penalty for EPS can be as high as 9.4% (Khoukhi, 2018).

When this temperature-driven increase is combined with interstitial moisture, as discussed in previous sections, deviations become even more pronounced, leading to substantial under-sizing of HVAC systems and significantly higher-than-predicted cooling energy consumption.

7.3. Density-dependent thermal response of sheep wool

Bio-based insulation materials also exhibit a temperature dependence of λ , but the governing mechanism is strongly influenced by the density of the fibrous matrix. Experimental evaluation of sheep wool batts over the 10-40°C range has shown that low-density materials ($\approx 20 \text{ kg/m}^3$) can experience conductivity increases of up to 25% when heated (Zach *et al.*, 2012). This vulnerability is linked to the large air volumes within the structure, which promote internal convection and interstitial radiation as temperature rises.

The same study, however, demonstrated that this limitation can be mitigated by optimising density. By mechanically compacting the wool batts to a higher density of about 40 kg/m^3 , the interstitial porosity is reduced, thereby damping radiative and convective components. Under these conditions, the increase in λ with temperature is limited to a modest $\sim 16\%$: conductivity changes from $0.034 \text{ W/(m}\cdot\text{K)}$ at 10°C to roughly $0.039 \text{ W/(m}\cdot\text{K)}$ at 40°C. This behaviour maintains the overall energy performance of wool panels at a very good level even under summer overheating.

The dynamics of insulation performance degradation under direct summer overheating are summarised in Table 5, which highlights critical deviations in heat transfer relative to static laboratory reference values.

Table 5

Percentage variation of thermal conductivity (λ) driven by ambient temperature (Technological synthesis based on in-situ measurements by Khoukhi et al. (2016) and Zach et al. (2012)) Note: the reference temperatures differ between the two sources (24°C for the polystyrene measurements, 10°C for the wool measurements), so the percentage increases are relative to different baselines and the last column should not be read as a direct ranking

Insulation material and application	Ref. temp. (lab.)	Maximum operating temperature reached	λ at ref. [W/(m·K)]	λ at $T_{\max}$ operational [W/(m·K)]	λ increase
EPS polystyrene (insulated roof, warm climate)	24°C	111.9°C (peak under direct solar load)	≈ 0.039	0.0472	+19.9% $\approx 20\%$
EPS polystyrene (sun-exposed vertical façade)	24°C	65.4°C	≈ 0.039	0.043	+9.4%
Sheep wool (panel with optimised density)	10°C	40°C (thermotechnical test value)	0.034	0.039	+16%

Thermodynamic analyses clearly confirm that keeping thermal conductivity λ as a purely constant parameter hides a significant latent cooling load in NZEB design and calls for the use of dynamic, temperature- and moisture-dependent coefficients.

8. Risks of interstitial condensation and material degradation

Assessing insulation performance only under dry, steady-state conditions neglects a fundamental issue of building physics: the real lifecycle of materials under temperature gradients and vapour diffusion. During the heating season, water vapour generated indoors migrates towards the exterior, crossing the wall layers. When the temperature inside the wall section drops below the dew point temperature ($T < T_{\text{dew}}$), the partial vapour pressure p_v reaches the saturation pressure p_{sat} , and interstitial condensation occurs.

The thermodynamic condition for condensation can be expressed as Eq. (9):

$$p_v(x, \tau) \geq p_{\text{sat}}(T(x, \tau)) \quad (9)$$

where:

x - the depth within the wall.

τ - time.

8.1. Vulnerability of polystyrene: the hygrothermal “trap” effect

Unlike fully impermeable materials (glass, metal), expanded and extruded polystyrene (EPS/XPS) act as partial vapour barriers. It has been shown that EPS exhibits a high vapour diffusion resistance factor ($\mu \approx 35-70$) due to its predominantly closed-cell porosity, yet it is not completely vapour-tight (Jerman and Černý, 2012). In winter conditions, water vapour can slowly penetrate, under pressure, into the micropores of the synthetic network.

The critical problem arises when this vapour condenses. As highlighted by Jerman and Černý (2012), liquid water accumulated in the partially closed cells of polystyrene has very limited pathways to re-evaporate. During summer, the driving forces (temperature and vapour pressure gradients) are often insufficient to expel capillary water back through the restrictive polymer structure. Recent investigations confirm that, once formed, liquid water gradually accumulates in the closed pores of EPS/XPS and in the microcracks between fused beads (Wang *et al.*, 2023).

This “trap effect” irreversibly damages the insulation layer. Liquid water ($\lambda \approx 0.6 \text{ W/(m} \cdot \text{K)}$) displaces air ($\lambda \approx 0.026 \text{ W/(m} \cdot \text{K)}$) from the pore space, causing a severe reduction in thermal resistance and a marked increase in heat losses.

8.2. Lifecycle degradation under real operating conditions

To assess long-term durability, experimental data from real building applications have been analysed for façades and roofs (Cai *et al.*, 2017). These studies show that, for XPS and EPS, moisture accumulation is not a reversible seasonal fluctuation but a cumulative process. After 10-15 years of service, the moisture content in extruded polystyrene can reach extreme levels, exceeding 60% by volume.

This degradation results from repeated interstitial condensation combined with mechanical damage to the cellular structure under freeze-thaw cycling. Consequently, the building's energy performance progressively deteriorates year by year, ultimately invalidating the energy-efficiency calculations used at the design stage. In addition, persistent water at the interface between the polystyrene insulation and the structural elements creates ideal conditions for microbial growth, mould development and deterioration of adjacent plasters.

8.3. Sheep wool: permeability and envelope safety

In sharp contrast to petrochemical insulations, sheep wool exhibits a structural behaviour that inherently limits harmful interstitial condensation. Studies have shown that wool-based panels have very low μ factors ($\approx 1.6-2.9$), indicating high vapour permeability (Dénes *et al.*, 2022). This “breathability”

allows vapour to travel relatively freely through the envelope, reducing the likelihood of reaching saturation pressure within the wall section and preventing moisture trapping. This advantage is conditional. It presupposes an assembly that can dry, a wool product whose binder does not raise μ appreciably, and protection against the biological risks discussed in Section 11; it is not an intrinsic guarantee of envelope safety.

Moreover, when extreme climatic conditions promote moisture accumulation, wool manages it predominantly at the molecular level. Instead of forming free water droplets that flood the pore structure (as in EPS), water molecules are chemically absorbed within the keratin fibre, while macroscopic voids remain filled with insulating air. As a result, wool batts do not build up significant amounts of stagnant liquid water, do not crack under freezing conditions and maintain both service life and thermal performance over the long term.

An analytical overview of the risks associated with interstitial condensation and of the impact of capillary blocking on the durability of envelope systems over the whole building lifecycle is presented in Table 6.

Table 6
Comparative analysis of interstitial condensation risk and lifecycle behaviour

Analysed characteristic	Expanded and extruded polystyrene (EPS/XPS)	Fibrous bio-based sheep wool
Diffusion behaviour (μ)	Partial, restrictive vapour barrier (≈ 20 – 150)	Permeable / “breathable” (≈ 1.0 – 3.0)
Response to temperature drop below dew point ($T < T_{\text{dew}}$)	Formation of liquid condensate in micropores and between fused beads	Active molecular uptake within the internal keratin fibre structure
Drying / evaporation capacity in warm season	Critically low: moisture becomes trapped (“trap effect”)	High: efficient desorption due to hygroscopic hysteresis
Lifecycle degradation (> 10 years)	Severe: progressive moisture build-up (> 10 – 60% vol.), loss of insulation efficiency	Stable: seasonal variations are buffered without cellular matrix degradation
Risk of interstitial freeze–thaw cycles	Major: accumulated water in cells expands on freezing and damages the polymer microstructure	Non-existent: moisture does not occur as free Non-existent: moisture does not occur as free macro-capillary water macro-capillary water

9. Interaction between diffusion, thermal properties and indoor environmental health

A comprehensive evaluation of thermal and acoustic insulation materials for Nearly Zero Energy Buildings (NZEB) must go beyond a simple assessment of thermal conductivity (λ) and incorporate their impact on indoor air quality (IAQ). From a building physics and chemistry perspective, the envelope acts as a dynamic transfer interface, where the diffusion properties of materials control not only the hygrothermal regime but also the degree of pollutant accumulation in occupied spaces.

9.1. Polystyrene: vapour barrier and impact on indoor air quality

Petrochemical polymeric materials such as expanded (EPS) and extruded polystyrene (XPS) provide excellent initial thermal performance but create a highly restrictive vapour barrier at envelope level. In-depth toxicity assessments of synthetic materials indicate that the predominantly closed-cell structure of polystyrene limits not only moisture transfer (high μ values) but also the natural exfiltration of volatile pollutants generated indoors (emissions from furniture, paints, cleaning products and human activity) (Zhao *et al.*, 2022).

In the absence of efficient mechanical ventilation systems with heat recovery, heavy reliance on polystyrene can transform a building into a nearly airtight enclosure. Over time, this favours the build-up of volatile organic compounds (VOCs) and carbon dioxide, contributing to the development of Sick Building Syndrome. Furthermore, the manufacturing process of polymer foams involves blowing agents, additives and flame retardants which may be slowly released during the service life (off-gassing), adding a source of toxicity to the indoor microclimate.

9.2. Sheep wool: active porosity and air purification by chemisorption

At the opposite end of the spectrum, the open porosity and chemical structure of bio-based fibres redefine the concept of an insulating wall, turning it into an active filter capable of regulating and improving air quality. Research on the integration of sheep wool in eco-friendly building components has demonstrated the ability of this material to significantly reduce concentrations of major pollutants such as formaldehyde (HCHO), nitrogen dioxide (NO₂) and sulphur-based compounds (SO₂) (Parlato and Porto, 2020; Hetimy *et al.*, 2024).

Unlike simple physical adsorption - a mechanical and typically reversible process in which gas molecules are retained only in the voids of the material - purification by wool relies on chemisorption. Sheep wool contains keratin (about 60-97% of the fibre's protein mass), a complex natural polymer rich in amino acids (arginine, lysine, cysteine) with reactive side chains. In the case of

formaldehyde, amine (-NH₂) and thiol (-SH) groups within the keratin structure attract and chemically react with pollutant molecules, forming relatively stable covalent bonds.

The simplified biochemical scheme of formaldehyde chemisorption on keratin chains (via formation of methylol derivatives and Schiff bases) can be written as Eq. (10):



where: R- denotes the main keratin backbone.

Experimental studies indicate that this interaction allows wool-based insulation panels to continuously capture formaldehyde from indoor air, rapidly decreasing the concentration of this toxic gas. This process acts synergistically with the hygroscopic regulation of humidity, which limits mould growth associated with respiratory diseases (Mansour *et al.*, 2014, 2015). However, two remarks are necessary. First, chemisorption on keratin is finite. The reactive amine and thiol sites are consumed as the reaction takes place, so the capture capacity of a panel is limited, and reported capacities are expressed per unit mass of wool. Second, the same nucleophilic sites are the ones targeted by the borate and fire-retardant treatments described in Section 11.1, so that a treated commercial panel cannot be assumed to retain the formaldehyde uptake measured on untreated wool. Quantifying that reduction is an open question in literature.

9.3. Technical data in the context of NZEB standards and global sustainability

NZEB standards require a strict balance between embodied energy, operational insulation performance and the creation of a healthy indoor environment. Investigations on wool-based biocomposites have shown that competitive thermal conductivities ($\lambda \approx 0.032\text{-}0.043$ W/mK) can be achieved using natural binders such as natural latex, providing the desired thermo-energetic performance without the ecological burdens associated with plastics (Dénes *et al.*, 2022). For consistency with Section 3.3 and Table 1, the full range reported for wool products is 0.032-0.054 W/(m·K); the narrower interval quoted here refers specifically to the latex-bonded biocomposites of Dénes *et al.* (2022).

In contrast, extruded polystyrene relies on crude oil extraction and involves high manufacturing energy demands (often exceeding 100 MJ/kg), contributing significantly to global warming potential. Wool, on the other hand, exhibits a zero or even negative global warming potential, since it stores biogenic carbon during fibre growth and can be integrated into recycling or composting cycles at end of life.

A comparison of materials in terms of their ability to react with volatile pollutants (chemisorption), their direct impact on IAQ and their compliance with the stringent ecological requirements of NZEB standards is summarised in Table 7.

Table 7

*Comparative analysis of insulation materials' impact on indoor air quality (IAQ) and NZEB sustainability compliance
(Data aggregated from Zhao et al. (2022), Parlato and Porto (2020) and Hetimy et al. (2024))*

Parameter evaluated in NZEB context	Polystyrene (EPS/XPS)	Sheep wool (blanket/panel-type thermal insulation)
Source of raw materials	Petrochemical (non-renewable, high energy demand, positive GWP)	Biological–animal (annually renewable, carbon store, zero/negative GWP)
Hygrometric behaviour at wall level	Airtight barrier; favours condensation and mould growth without adequate mechanical ventilation	“Breathable”; acts as a hygric filter and active moisture buffer
Interaction with gases / pollutants	Chemically inert; risk of off-gassing residual synthetic compounds from production	Reactive (chemisorption); actively absorbs HCHO, NO ₂ , SO ₂ from the interstitial airflow
Overall influence on health (IAQ)	High risk of indoor air quality degradation (VOC build-up) if no forced ventilation	Excellent; filters and purifies the microclimate, supporting a healthy indoor habitat

Due to its high vapour permeability and chemisorption capacity of keratin, sheep wool is classified among the insulation materials that interact with the indoor environment rather than merely resisting heat flow. How much of that interaction survives the treatments required for commercial use, and over what service life, is examined in Section 11.

10. Reaction to fire and acoustic performance

10.1. Reaction to fire

Wool owes its relative favourable fire resistance behaviour to keratin chemistry. The fibre has a limiting oxygen index of about 25–26%, above the 21% oxygen content of air, an ignition temperature reported in the range 570–600°C, a high nitrogen and bound-water content, and forms an insulating char instead of melting or dripping (Hetimy *et al.*, 2024; Schiavoni *et al.*, 2016). Expanded and extruded polystyrene behave in the opposite way: they soften, melt

and drip well below 200°C and require brominated or polymeric flame retardants to be used as insulating envelope.

Nevertheless, this should not be read as non-combustibility. Untreated sheep wool batts are combustible and are commonly declared in Euroclass E under EN 13501-1, the same class as most other natural fibre insulations; higher classes are reached only after treatment, most often with borate salts which act simultaneously as fire retardant, fungicide and insecticide (Ruiu and Floris, 2019). The fire performance quoted for commercial wool products is therefore a property of the treated product, not of the fibre alone, and it is inseparable from the treatment questions discussed in Section 11.

10.2. Sound absorption

The crimped, randomly oriented fibre network that hinders convective air movement also dissipates acoustic energy by viscous friction, so wool products absorb sound in the same way as mineral wool and unlike closed-cell polystyrene, which is acoustically reflective. Measured performance is moderate rather than exceptional and depends strongly on thickness and packing density. Impedance tube measurements on felts and tufted fabrics produced from coarse mountain sheep wool gave noise reduction coefficients of about 0.4 for the thicker felt, comparable with commercial ceiling tiles. Thus, increasing the pile height of tufted fabrics from 12 to 16 mm raised the NRC from 0.40 to 0.42 (Kobiela-Mendrek *et al.*, 2022). Higher values reported elsewhere correspond to thicker batts installed as cavity insulation rather than as thin surface linings.

11. Limitations, treatments and practical constraints of sheep wool insulation

The preceding sections describe the hygrothermal behaviour of wool under favourable conditions. A balanced assessment requires the constraints that govern its use in practice, which the literature reports less prominently.

11.1. Biological durability and the treatments it requires

Keratin can be a food source. Larvae of the common clothes moth *Tineola bisselliella* digest it directly, and untreated wool is readily consumed; carpet beetles and, above roughly 75% relative humidity at the fibre surface, moulds present the same risk (Cox and Pinniger, 2007; Ruiu and Floris, 2019). Controlled assays quantify both the risk and the remedy: pure untreated wool suffered heavy larval feeding over 15 days, whereas a commercial panel incorporating borate salts limited the damage to the surface and significantly increased larval mortality, and disodium octaborate tetrahydrate incorporated in pure wool gave a concentration-dependent effect with good efficacy at application rates of 40–100

mg/mL (Ruiu and Floris, 2019). Pyrethroids, chiefly permethrin, are the conventional alternative applied during manufacture. The practical conclusion is that wool insulation is a treated product; the hygrothermal data reviewed above were in most cases obtained on treated or resin-bonded specimens, and untreated wool should not be specified in a concealed cavity.

11.2. Consequences of the treatments: emissions, regulation and end of life

The available treatment methods carry their own burdens, and this is where the environmental advantage of wool is most often overstated. Borates are added at high loadings relative to the fibre mass, and boric acid and several borate salts are classified in the EU as toxic for reproduction and are on the REACH candidate list of substances of very high concern, which constrains formulation and worker exposure even though boron is of low acute toxicity and its predicted no-effect concentration in surface water is of the order of 1 mg/L (Ruiu and Floris, 2019). Three consequences follow for the assessment made in Section 9. Treated panels are no longer emission-neutral, and the volatile organic compound profile of a finished wool product depends on the binder, the fire retardant and any residual scouring agents rather than on the fibre. Published VOC data for treated commercial panels are scarce. The borate loading is water soluble and can leach, which raises questions about persistence of the protection over decades and about the leachate at demolition. And the composting or return-to-soil end-of-life route usually invoked for wool is valid only for untreated or biodegradable bonded products; a borate-treated, resin-bonded panel is not compostable, so the zero or negative global warming potential quoted in Section 9.3 should be understood as applying to the fibre, with the treatment and binder counted separately in any life cycle assessment.

11.3. Cost, ageing and industrial availability

Sheep wool insulation is consistently more expensive per unit of thermal resistance than mineral wool or EPS, and thickness-optimisation studies that include material cost place it among the least favourable options on a purely economic criterion (Braulio-Gonzalo and Bovea, 2017). Supply is the second constraint: production is rather small in scale and regionally concentrated, fibre quality varies with breed, husbandry and the season of shearing, and the coarse wool most suitable for insulation is a by-product whose availability follows the meat and dairy markets rather than construction demand (Pennacchio *et al.*, 2017; Parlato and Porto, 2020). This variability is itself a source of the spread in the reported λ and μ values discussed in Section 3.3. Long-term ageing is the least documented aspect of all: settlement of unbonded batts, gradual loss of borate protection, and the durability of the sorption behaviour after repeated wetting and drying cycles have not been followed in situ over periods comparable with the

10–15 year datasets available for polystyrene, so the lifecycle comparison in Table 6 rests on a much thinner evidence base for wool than for EPS and XPS.

11.4. Position among other bio-based insulation materials

Sheep wool is one of the several bio-based options. Cellulose, hemp, flax and expanded cork occupy the same thermal conductivity band, and the choice between them usually turns on cost, availability and the specific hygric requirement rather than on λ . Wool is distinguished mainly by its sorption capacity at high relative humidity and by the chemisorption behaviour described in Section 9.2. It is penalised by cost and by its vulnerability to keratinophagous insects, a risk the plant-based fibres do not share, although those in turn require borate or ammonium-salt treatment against fire and fungal attack. Indicative ranges compiled from the reviews of Asdrubali *et al.* (2015) and Schiavoni *et al.* (2016) are given in Table 8.

Table 8

*Indicative comparison of sheep wool with other bio-based insulation materials (ranges compiled from the reviews of Asdrubali *et al.* (2015) and Schiavoni *et al.* (2016); values are literature compilations obtained on different specimens and are indicative of material class only)*

Material	Thermal conductivity λ [W/(m·K)]	Typical bulk density [kg/m ³]	Main advantage relative to the others	Main limitation
Sheep wool	0.032–0.054	20–40	Highest moisture sorption and buffering capacity; chemisorption of formaldehyde	Attacked by keratinophagous insects; highest cost; small-scale, variable supply
Cellulose (recycled paper)	0.037–0.042	30–80	Lowest cost of the bio-based options; well-established blown-in application	Settlement in vertical cavities; requires borate or ammonium-salt treatment
Hemp fibre	0.038–0.060	20–100	Fast-growing crop; good availability in Europe	Higher λ at low density; needs fire treatment

Flax fibre	0.033–0.045	20–80	Low λ comparable with mineral wool	Moisture sensitivity; requires fungicidal treatment
Expanded cork (ICB)	0.037–0.050	90–140	Binder-free, rot-resistant, dimensionally stable	Limited supply; high embodied cost per unit R

12. Conclusions

This review has assembled published data showing that the in-service performance of polystyrene is more vulnerable to moisture ingress and temperature fluctuations than static dry-state catalogue values suggest. In the reviewed studies, the combined effects of interstitial condensation and summer overheating increase the effective thermal conductivity of EPS and XPS by 20–80% relative to the declared value, and cumulative moisture uptake over 10–15 years of service has been reported to reach volumetric contents above 60%.

Sheep wool manages moisture by a different mechanism. Its permeable fibrous structure and the affinity of keratin for water allow large amounts of vapour to be bound intracellularly without flooding the macropores, so the increase in thermal conductivity stays moderate even at high mass-based moisture contents. When the reported moisture contents are converted to a common volumetric basis, however, wool and polystyrene are not compared at equal water content, and the advantage should be stated as a difference in the mechanism and in the moisture ceiling reached in service rather than as a superior tolerance to the same amount of water.

Beyond heat transfer, the open porosity and reactive keratin matrix contribute to indoor environmental quality through chemisorption of formaldehyde and passive humidity regulation, although the capture capacity is finite and its retention after chemical treatment has not been quantified, yet. These benefits come with constraints that are decisive in practice: untreated wool is attacked by keratinophagous insects and mould, the borate and fire-retardant treatments that prevent this are themselves regulated and remove the composting end-of-life route; cost per unit of thermal resistance is the highest among the bio-based options; supply is small in scale and variable, and long-term field data are far scarcer than for polystyrene. On the evidence reviewed here, sheep wool is best described as a credible alternative or complement to petrochemical foams in assemblies where vapour permeability and moisture buffering are the governing requirements, rather than as a generally superior material.

The gaps identified in this review define the priorities for further work: coupled hygrothermal simulation and long-term field monitoring of mixed EPS

and wool assemblies; measurement of VOC emissions, borate leaching and residual formaldehyde chemisorption on treated commercial panels rather than on laboratory wool; life cycle assessment that accounts separately for the fibre, the binder and the treatment, including end-of-life scenarios; and design guidelines that incorporate dynamic $\lambda(T, w)$ coefficients and moisture buffering into NZEB envelope calculation methods.

Disclaimer. We mention that for the bulk processing of literature sources and partially language editing artificial intelligence has been used.

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EFECTELE UMIDITĂȚII ȘI TEMPERATURII ASUPRA IZOLAȚIILOR POROASE ALE CLĂDIRILOR NZEB: STUDIU DE LITERATURĂ

(Rezumat)

Lucrarea este un studiu de tip review asupra performanțelor termice, higrotermice și de mediu ale unor materiale izolatoare poroase sintetice (EPS, XPS). De asemenea, este considerată și o alternativă de biomaterial, utilizarea lânii de oaie, în contextul cerințelor NZEB. Deși materialele petrochimice sunt utilizate pe scară largă datorită conductivității termice inițiale reduse, datele din literatură evidențiază că acumularea de umiditate în structura acestora determină creșteri semnificative ale conductivității termice, conducând la erori în evaluarea sarcinilor termice. Lâna de oaie prezintă o conductivitate comparabilă, care se situează între 0,032 și 0,054 W/(m·K), în funcție de densitatea aparentă, calitatea fibrei și liant, și poate absorbi 35–40% apă raportat la masa uscată la o umiditate relativă de 100%, cu o creștere moderată a conductivității, deoarece apa este legată în keratină și nu umple porii. Permeabilitatea ridicată la vapori limitează riscul condensului interstițial. Comportarea la foc, fonoabsorbția, precum și limitările utilizării lânii sunt tratate în secțiuni distincte.