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Lopez-Carreon, Itzel; Jahan, Esrat; Yari, Mohammad Hossein; Esmizadeh, Elnaz; Riahinezhad, Marzieh; Lacasse, Michael; Xiao, Zhe; Dragomirescu, Elena

Publisher’s version / Version de l'éditeur:

https://doi.org/10.3390/buildings15050762

Buildings, 15, 5, 2025-02-26

buildings

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Review

Moisture Ingress in Building Envelope Materials: (II) Transport Mechanisms and Practical Mitigation Approaches

Itzel Lopez-Carreon [1], Esrat Jahan [1], Mohammad Hossein Yari [1,2], Elnaz Esmizadeh [1,*], Marzieh Riahinezhad [1], Michael Lacasse [1], Zhe Xiao [1] and Elena Dragomirescu [2]

[1] Facade Systems and Products Group, Construction Research Centre, National Research Council Canada, 1200 Montreal Rd, Ottawa, ON K1A0R6, Canada; itzel.lopez-carreon@nrc-cnrc.gc.ca (I.L.-C.); esrat.jahan@nrc-cnrc.gc.ca (E.J.); mohammadhossein.yari@nrc-cnrc.gc.ca (M.H.Y.); marzieh.riahinezhad@nrc-cnrc.gc.ca (M.R.); michael.lacasse@nrc-cnrc.gc.ca (M.L.); zhe.xiao@nrc-cnrc.gc.ca (Z.X.)

[2] Civil Engineering Department, University of Ottawa, 161 Louis Pasteur, Ottawa, ON K1N 9K5, Canada; elndrag@uottawa.ca

* Correspondence: elnaz.esmizadeh@nrc-cnrc.gc.ca

Abstract: The primary goal of this review is to explore both the fundamental dynamics of moisture ingress and practical strategies for its mitigation. Moisture ingress remains a critical issue due to its impact on the structural integrity of buildings and the health and safety of occupants. This work adopts a systematic approach, focusing on key mechanisms of water transport—capillary action, vapour diffusion, and condensation—and how different parameters influence the process of moisture transport. Moisture ingress, whether through direct leakage, capillary action, air infiltration, or vapour diffusion, poses significant risks to the premature degradation of building envelope materials. In this study, emphasis has been placed on describing the methods for controlling liquid water movement, preventing condensation, and using moisture-resistant materials. Additionally in this study, the advanced design and hygrothermal performance simulation tools are examined; the use of such tools is considered essential for predicting and managing moisture-related issues in building envelopes. Finally, the significance of complying with moisture control standards and guidelines is highlighted, ensuring a comprehensive framework for effective moisture management in building design and maintenance. Beyond this review, key knowledge gaps in moisture control strategies have been identified, particularly in respect to material performance, the accuracy of predictive modeling, and the standardization of mitigation techniques. Addressing these gaps is essential for advancing building design, maintenance practices, and regulatory frameworks that together combine to enhance moisture resilience.

Keywords: moisture management; mitigation techniques; climate resilient; moisture ingress assessment; hygrothermal simulation; moisture control

Academic Editor: Antonio Caggiano

Received: 25 December 2024
Revised: 20 February 2025
Accepted: 23 February 2025
Published: 26 February 2025

Citation: Lopez-Carreon, I.; Jahan, E.; Yari, M.H.; Esmizadeh, E.; Riahinezhad, M.; Lacasse, M.; Xiao, Z.; Dragomirescu, E. Moisture Ingress in Building Envelope Materials: (II) Transport Mechanisms and Practical Mitigation Approaches. *Buildings* **2025**, *15*, 762. https://doi.org/10.3390/buildings15050762

1. Introduction

Moisture ingress is a pervasive and critical challenge to the building industry, having a profound impact on the durability, energy efficiency, and indoor environmental quality of buildings. The intrusion of moisture into building envelopes can lead to a range of problems, including mould growth, deterioration in the performance of thermal insulation, and ultimately structural degradation that may compromise the overall integrity of a building [1–4]. The risks associated with moisture ingress are exacerbated by climate change, which increases the intensity and frequency of environmental loads such as precipitation, humidity, temperature, solar radiation, and wind flow [5,6]. To effectively mitigate these risks, it is essential to understand the fundamental mechanisms of moisture transportation through building envelopes. Moisture can infiltrate a building from various sources including rainwater, groundwater, air leakage, vapour pressure gradients, and issues arising from defects in building facilities [7].

This review paper is the continuation of our first paper entitled "Moisture Ingress in Building Envelope Materials: (I) Scientometric Analysis and Experimental Fundamentals", which provided a detailed scientometric analysis of the scientific literature. The first paper successfully identified the key research trends and knowledge gaps in the field of moisture ingress as well as experiments, one of the most discussed categories under the topic of moisture ingress in building envelope materials (BEMs). Through a comprehensive statistical analysis of data sources in Scopus, the topics "moisture ingress" and "building envelope materials" were selected as the primary focus. Papers were then manually filtered, if necessary, to ensure relevance to the topic. This process identified 1758 papers, covering various aspects of moisture-related research. The topics discussed in these papers were categorized into ten different categories, where the category of experiments was one of those discussed in 55% of the database. The first paper also reviewed foundational methods such as capillary water absorption tests for liquid-phase moisture ingress [8], enhanced imaging techniques like X-ray computed tomography (CT) and gamma-ray transmission for detailed moisture distribution insights, and non-destructive methods such as single-sided nuclear magnetic resonance (SS-NMR) for analyzing both moisture content and distribution [9].

Building on the findings of the first paper, two additional aspects are reviewed in this paper including moisture dynamics and mitigation techniques. Regarding the dynamics of moisture, 38% of the database in the scientometric study from the first paper discussed the mechanism of moisture transport, while 72% focused on its sources, such as wind-driven rain (WDR), climate change, and relative humidity. Moreover, 17% of the database examined the effectiveness of the mitigation techniques in the prevention of moisture intrusion. In the review of this category, practical strategies and technologies are explored that are developed by the construction industry to manage moisture ingress and mitigate its detrimental effects. The use of moisture-resistant materials, the proper detailing of building assemblies, and the implementation of effective moisture control measures are key approaches to preventing water intrusion and controlling vapour diffusion [10]. Additionally, advanced hygrothermal modeling tools are discussed as useful approaches for predicting the moisture performance of building envelopes under diverse environmental conditions, thereby enabling more accurate assessments of risk to the formation of moisture issues and from which informed design decisions can be made that enhance the durability and resilience of buildings [11].

Finally, in this paper, the critical importance of adhering to established moisture control standards and guidelines is discussed to ensure the long-term performance and resilience of building envelope systems. Standards, such as ISO EN 13788 (2012) and CSA S478 [12,13], offer a comprehensive framework for assessing and managing moisture risks, guiding the design and construction processes to effectively address moisture-related challenges. As climate change continues to intensify, these standards and guidelines become increasingly vital in safeguarding building performance against the evolving environmental stressors emphasizing the undeniable need for ongoing research and development to enhance these guidelines.

2. Dynamics of Moisture Ingress in Building Envelope Components

Understanding the dynamic nature of moisture ingress is crucial for assessing its impact on building materials and structures. This requires examining two fundamental aspects: the sources of moisture and the mechanisms governing its transport. Identifying where moisture originates—whether from precipitation, condensation, or internal sources—is essential for predicting potential risks. Equally important is understanding how moisture moves through and across permeable materials, as this influences durability, energy efficiency, and structural integrity.

To build on this understanding, a comprehensive review of the existing research has been conducted to identify the key studies on moisture transport mechanisms in building envelope materials. This review follows a systematic approach to identify the relevant publications on moisture transport mechanisms in building envelope materials. The source of publications is from the first review paper where a literature search was conducted in Scopus, focusing on the past 30 years and considering only English-language sources across disciplines such as civil engineering, building science, physics, materials science, soil engineering, etc. Following the categorization in the scientometric study of the first review paper, this paper reviews the category of moisture transport and mitigation techniques. A total of 1758 publications related to "moisture ingress" and "building envelope materials" were identified. However, only the articles relevant to the category of transport mechanisms are presented in this section. Publications can cover multiple topics and may belong to more than one category. For instance, if a publication discusses vapour diffusion in a building envelope under high relative humidity, it can be classified under both the "mechanism of transport" category, as it addresses vapour diffusion, and the "source of moisture" category, as it involves humidity.

2.1. Source of Moisture Ingress

As indicated in Figure 1, the process of moisture penetration is dynamic and can occur at various stages of a material's lifecycle, starting from manufacturing and continuing through transport, storage, building construction, and during its in-service life. Each of these stages presents unique challenges and potential sources of moisture that can impact a wide range of materials, such as concrete, bricks, wood, and others [14]. The initial moisture content within a building material, which is introduced during the production process, can be a primary source of moisture ingress. For instance, the water-to-cement ratio in concrete manufacturing is critical; too much water can lead to a high initial moisture content that can affect permeability and strength [15]. Similarly, wood products may retain moisture from their natural state, requiring proper drying techniques to reach an acceptable moisture content level before use [16].

Once on the construction site, materials must be stored in a way that minimizes exposure to moisture. Poor storage conditions can lead to groundwater or surface water seepage, especially if materials are left on the ground without protective barriers. A high-humidity environment can also cause materials to absorb moisture from the atmosphere, which is a particular concern for hygroscopic materials such as wood [17]. During the in-service stage of a building's lifecycle, moisture ingress may significantly affect material integrity, exacerbated by its longer duration compared to other stages. Primary moisture sources include precipitation (rainwater and snow), groundwater, facility issues, air leakage, and vapour pressure gradient. Moisture can intrude in liquid form through construction defects, aged rain screen systems, diffusion, and capillary rise [18]. In the vapour phase, although the amount of moisture is lower, it can enter rapidly through air leakage and vapour pressure differentials due to small openings and material permeabilities that are impervious to liquid water [19].

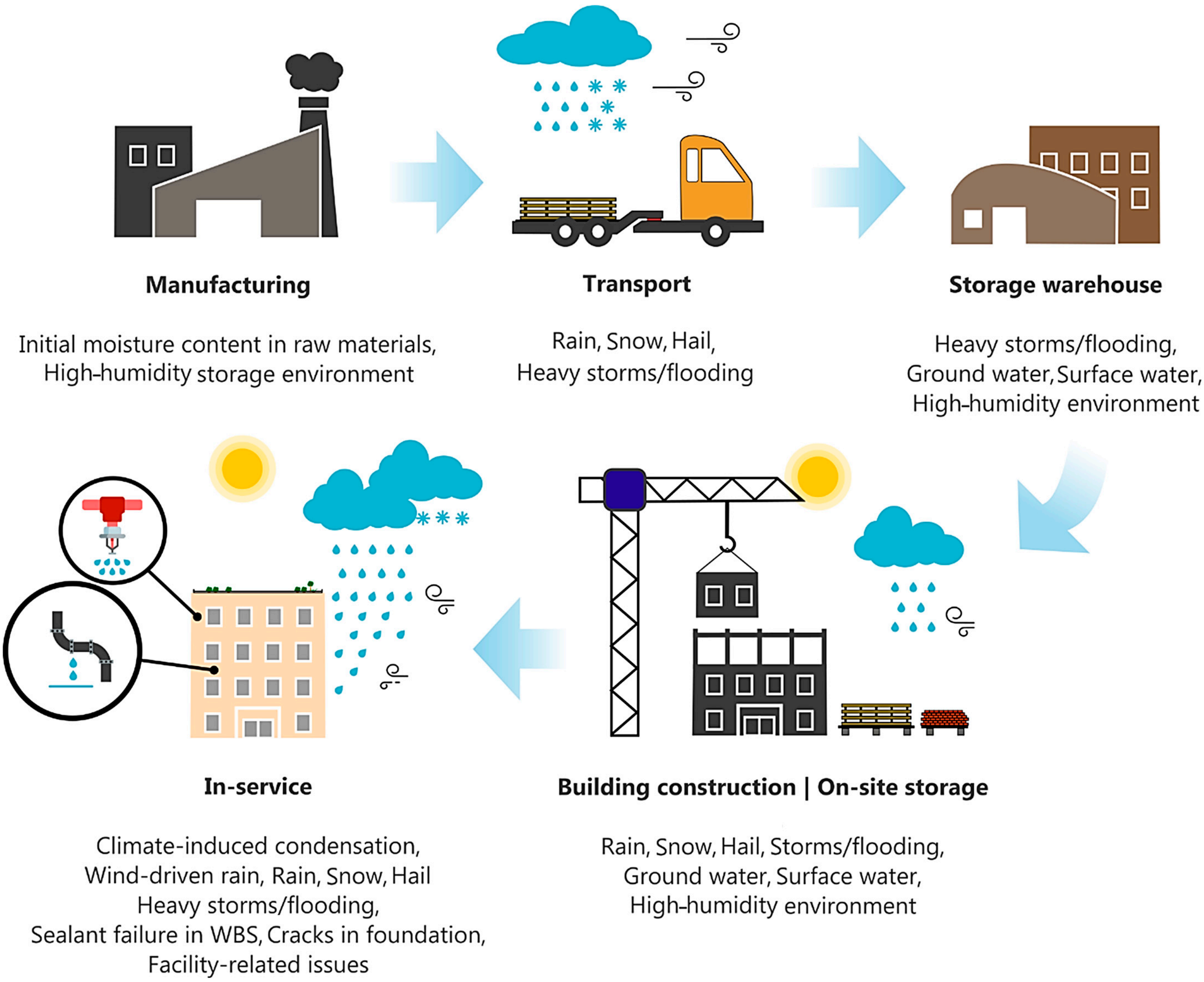

Figure 1. Sources of moisture ingress in building envelope materials throughout their lifecycle.

Within the investigation of topics related to the causes of moisture ingress, the eleven most frequently addressed subjects in the papers are presented in Figure 2. Among these eleven subjects, rain, climate, and humidity are the most widely addressed topics in the literature, whereas extreme weather is the least discussed.

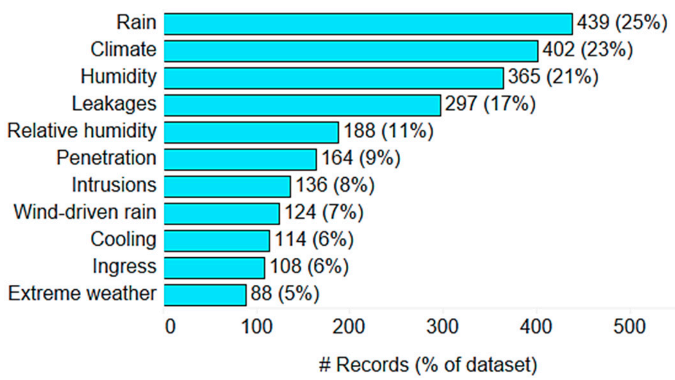

Figure 2. Distribution of research on the sources of moisture ingress in building envelopes.

2.2. Mechanism of Moisture Ingress in Building Envelope Components

The mechanisms of moisture ingress in building materials are influenced by various factors, including environmental exposure, material composition, and material porosity. Among these variables, pore size within the material plays a particularly influential role [20,21]. Pore size and pore-size distribution determine how moisture interacts with the material, i.e., which mechanism will govern moisture movement. In Table 1, the mechanisms for moisture ingress have been categorized as a function of pore size, ranging from macropores to nanopores, and as well, the predominant mechanisms have been highlighted, such as liquid water flow, capillary absorption, water vapour adsorption and diffusion, and capillary condensation. The size of the pores within a material not only determines the type of moisture movement but also the rate of movement through a porous material [22–24].

Table 1. Moisture transport mechanisms dependent on pore size within porous media [21].

Macropores	Micropores		Nanopores	
>1 mm	1 mm–10 µm	10 µm–0.1 µm	0.1 µm–10 nm	<10 nm
Liquid water flow				
	Capillary absorption			
		Water vapour adsorption and surface diffusion		
			Capillary condensation	
Water vapour diffusion				

In the liquid phase, moisture movement is primarily driven by capillary forces, which are dictated by Darcy's law. The liquid moisture flux J_l is proportional to the gradient of liquid pressure P_l, expressed as follows:

$$J_l = -K_l \nabla P_l \tag{1}$$

where K_l represents the liquid permeability of the material. Since moisture transport is often characterized in terms of moisture content w, an alternative formulation using liquid diffusivity D_l can be used as follows:

$$J_l = -D_l \nabla w \tag{2}$$

In the vapour phase, moisture moves due to differences in vapour pressure, following Fick's first law of diffusion:

$$J_v = -\delta_p \nabla P_v \tag{3}$$

where δ_p is the vapour permeability of the material. The total moisture flux can be described by a general moisture transport equation, incorporating both phases of liquid and vapour:

$$J = -D_l \nabla w - \delta_p \nabla P_v \tag{4}$$

Liquid diffusivity primarily corresponds to capillary absorption, while vapour diffusivity dominates in regions where condensation is below the critical moisture content. At the transition point, where moisture content reaches the critical level, capillary condensation occurs, combining both vapour- and liquid-phase movement within the porous structure [25].

In Figure 3, the number of publications discussing each mechanism of moisture transport in building materials is illustrated, highlighting the distribution of studies on moisture transport processes. Mechanisms involving moisture transport in the vapour phase are predominantly discussed in the literature, with condensation having the largest number of publications. Water flow and capillary absorption, both representing moisture transport in the liquid phase, are discussed less often. Although capillary absorption was the least mentioned mechanism in the literature of the eight reviewed categories and within the two liquid-phase categories, it is the dominant mechanism by which groundwater rises into the pore structure of building materials [26].

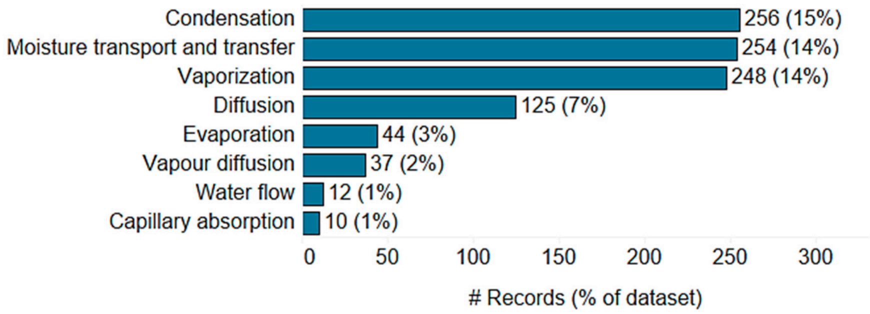

Figure 3. Distribution of research on the mechanisms of moisture transport in building materials.

In the following section, the mechanisms of moisture transport in each phase—liquid and vapour—are reviewed and described separately.

2.2.1. Liquid Water Transport

In porous building materials, water transport can occur when liquid water moves through the interconnected pores by capillary action, initiated where the material first comes into contact with water. This movement involves two primary forms of water: free and bound. Free water freely fills the pores and moves relatively easily within the material, capable of being dried out at standard (normal) temperatures (i.e., 20 °C (293.15 K, 68 °F) and absolute pressure of 1 atm). In contrast, bound water is chemically or physically adhered to the structure of the material, thus requiring a higher degree of energy to cause it to dissipate from the pore structure given its strong attachment to the matrix of the material [27].

Liquid Water Flow

This refers to the movement of liquid water through the pores of a material. In macropores, which are larger than 1 mm, the flow of liquid water is primarily governed by gravity and can occur rapidly due to the large pore size. As pore sizes decrease to the micropore range (i.e., <2 nm), liquid water can still flow but the rate is significantly reduced [20,21].

Within porous building materials, the flow of liquid water governed by gravitational forces is typically negligible, as the pore sizes in these materials do not exceed 1 mm. This contrasts with some soils, such as gravels and sands, where the larger gaps allow gravity-driven water flow. Understanding this difference highlights why gravity is not a significant factor in moisture transport within BEMs. Gravity plays a significant role in the movement of liquid water on the surface of building materials, particularly building cladding, and is a key factor in water ingress into the building envelope.

Capillary Absorption

Capillary absorption occurs when liquid water moves through smaller pores due to capillary forces. This mechanism is active in micropores (1 mm–10 μm) and becomes more pronounced as the pore size decreases to the upper range of nanopores (10 μm–0.1 μm).

Capillary action occurs due to the adhesive forces between the water and pore walls as well as the cohesive forces within the water itself [20,21]. In Table 2, an overview is provided of the moisture transport mechanisms through the liquid water phase in a range of building envelope materials. From the database identified in the scientometric study, a selection of the most relevant papers on capillary transport mechanisms from the past 20 years has been compiled in Table 2. These studies were chosen to encompass various internal and external parameters (e.g., temperature, immersion depth, pore size and distribution within the material, composition, etc.) that affect the capillary absorption rate in building materials, ensuring comprehensive coverage of the topic.

2.2.2. Water Vapour Transport

The adsorption process in porous building materials can be classified as monolayer and multilayer adsorption where relative pressure plays a direct role in the mechanism of diffusion. At very low relative pressures, physical adsorption is minimal, except in microporous materials such as active carbon. A monolayer of adsorption is achieved around $P/P_{sat} \approx 0.1$, with multilayer adsorption occurring as pressure increases, leading to capillary condensation in pores at higher relative pressures. As the transition of the adsorption process from monolayer to multilayer in porous media varies with different transient relative pressures, dividing the literature based on this classification is challenging, since this transition is not recognizable in some materials. Many papers study the entire adsorption process from 0 to 1 relative pressure and define it as a sorption curve in porous materials. As indicated in Figure 4, there are five types of materials with respect to the adsorption process isotherm proposed by Brunauer [28]. In type I, adsorption occurs on a single surface layer, mainly describing surface diffusion. In type II, the vapour adsorption on the surface layer is distinguishable. However, with an increase in relative pressure, there is a transient point where surface adsorption completes, and multilayer adsorption begins. This process, known as vapour diffusion in the depth of a porous media, will be explained in subsequent sections. Type III adsorption isotherms describe adsorption that steadily increases with pressure, without distinct phases of monolayer or complete pore filling. This pattern suggests weak initial adsorption that becomes significantly stronger as additional layers form, implying a clustering effect rather than a uniform layering seen in types I, II, and IV. Types IV and V describe the materials with the potential for highly porous adsorption, and the flattening plateau shows the filling up of all pores at near-saturation pressure. Table 3 provides a review of the articles studying water vapour transport, including the level of surface (monolayer) adsorption, in-depth (multilayer) adsorption, and capillary condensation. In Table 3, the method of paper selection was the same as what was described for Table 2.

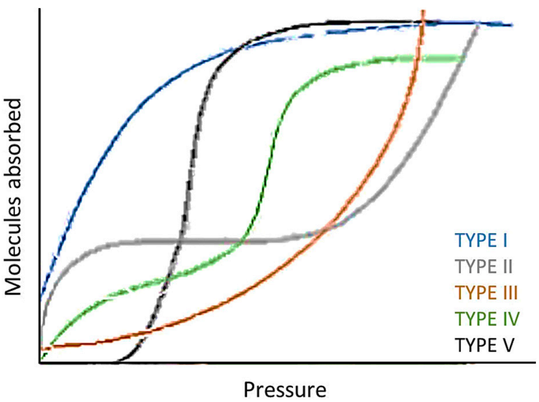

Figure 4. Five different types of adsorption isotherms proposed by Brunauer (adapted from [28]).

Water Vapour Diffusion

Water vapour diffusion is the movement of water vapour through the material, driven by vapour pressure differences. This process primarily occurs in macropores and micropores, where gas-phase diffusion is dominant (see Table 1). As an example of this mechanism, in concrete or insulation, when liquid water transport is minimal, vapour diffusion allows moisture to move through the material, influencing drying rates and durability.

Water Vapour Adsorption and Surface Diffusion

As the pore size decreases further into the nanopore range (100 nm–10 nm), liquid water flow and capillary action become less dominant, and the adsorption of water vapour onto the surface of pores becomes more significant. In this range, water exists more commonly as vapour, and movement occurs through surface diffusion along the internal surfaces of the pores [20,21].

Capillary Condensation

In the capillary regime, the transfer of water vapour to the porous material involves a phase change from vapour to liquid. This transition typically occurs within the smallest pores of the material. This phenomenon occurs within nanopores, especially those smaller than 100 nm [20,21]. It involves the condensation of water vapour in pores due to the lower relative humidity required for condensation to occur, as compared to that required in bulk air. This is a result of the curvature of the liquid interface in the confined space of a pore [29].

Table 2. Selected studies on moisture transport in the liquid water phase within BEMs.

Type of Material(s)	Parameters Studied	Methodology	Highlights	Reference
Bricks Mortars	Temperature	Experimental	- Compared three European standards and recommendations for calculating the capillary water absorption coefficient of building materials - Found a linear relationship between temperature and the absorption coefficient	Karagiannis et al., 2016 [30]
Foam concrete (FC) Autoclave aerated concrete (AAC) Coral and sand concrete (SHS)	Temperature Water immersion depth Sample size	Experimental	- Investigating the effects of sample size, ambient temperature, and water immersion depth on the capillary water absorption coefficient - Found significant variations in absorption behavior across materials and conditions	Wang et al., 2021 [31]
FC AAC SHS	Ambient temperature Water immersion depth Sample size	Experimental	- Examined potential factors affecting capillary absorption tests - Compared data processing methods and proposed a new model for the capillary absorption coefficient and moisture content by conducting a thorough analysis of measurements on different materials	Feng & Janssen 2018 [32]
Tuff stone Andesite stone	Salt in liquid uptake Pore size Porosity Pore distribution	Experimental	- Analyzed the influence of pore size and shape on absorption - Investigated the effects of salty water - Found that salty water results in higher capillary absorption than pure water	Celik & Kacmaz 2015 [33]
Brick Plaster	Pore size Porosity	Experimental	- Proposed a first-order kinetic model for capillary absorption - Found that the capillary height time constant can be predicted if the average pore radius of the materials is known	Karoglou et al., 2004 [34]
Bricks Stones Mortars	Air temperature Relative air humidity Air velocity	Experimental and numerical	- Introduced a mathematical model to predict capillary water uptake in building materials - Applicable under various environmental conditions	Karagiannis et al., 2019 [35]
Lightweight aggregate concrete	Composition of aggregates Cement content Initial water content	Experimental	- Explored capillary absorption in lightweight aggregate concrete - Found that despite having higher absorption rates than normal-weight concrete, it shows similar or lower sorptivity - Sorptivity is influenced by the porosity of lightweight aggregates and composition adjustments	Bogas et al., 2015 [36]
Hardened cement paste	Pore structure	Experimental	- Capillary absorption in cement-based materials increases with water-binder ratios - Sensitivity of absorption to the dosage of mineral powders and a nearly linear relationship between absorption and porosity	Wang et al., 2022 [23]

Table 3. Selected studies on moisture transport in the water vapour phase within BEMs.

Type of Material(s)	Parameters Studied	Methodology	Highlights	Reference
AAC; Lightened ceramic brick; Lime plaster; Ceramic brick; Paraffin wax	Adsorption isotherm model	Experimental and theoretical	- Developed semi-empirical formula combining BSB and FHH isotherms - Provided accurate approximations of moisture adsorption across all humidity levels	Pavlik et al., 2012 [37]
Porous clay minerals including sepiolite, allophane, diatomite, selectively leached	Pore size Relative humidity	Experimental	- Identified optimal pore diameters for humidity self-control in living spaces - Suggested optimum pore diameter materials as potential candidates for managing indoor humidity levels	Tomura et al., 1997 [38]
Gypsum; Some types of brick and sandstone; AAC	Different diffusion coefficients of liquid and vapour moisture Ambient temperature and pressure conditions	Experimental and theoretical	- Developed a mathematical model distinguishing liquid water and vapour diffusion - Calculated diffusion coefficients for various materials	Litavcova et al., 2014 [39]
Low-density fiberboard	Sample thickness microscopic diffusivity Environmental conditions such as air velocity, temperature, and relative humidity	Experimental and numerical	- Multiscale simulation revealed limitations of traditional Fickian diffusion laws for low-density fiberboard's moisture dynamics - Dual-scale model provided a closer match to experimental observations - Indicated scale effects become insignificant for thicker fiberboards	Perré et al., 2022 [40]
AAC	Sample length, sensor size, and porosity's impact on the water vapour diffusion coefficient	Experimental	- Highlighted the significance of selecting an appropriate sample length for the accurate transient measurement of water vapour diffusion coefficients	Tian et al., 2019 [41]
AAC Wood fiber insulation Hempcrete	Temperature Hygrometric coefficient Sorption isotherm modeling	Experimental and numerical	- Analyzed temperature dependence of sorption isotherms in various hygroscopic building materials - Demonstrated that temperature influences relative humidity changes, supported by both experimental and modeling approaches	T. Colinart and P. Glouannec 2017 [42]
Expanded polystyrene concrete	Sorption hysteresis	Experimental and numerical	- Demonstrated that excluding sorption hysteresis can lead to significant inaccuracies in hygrothermal behavior predictions, with errors of up to 28%	Maaroufi et al., 2021 [43]
Mesoporous materials	Hysteresis in adsorption and desorption isotherms, pore size and shape	Experimental and numerical	- Emphasized the complexity and variability of hysteresis in capillary condensation within mesoporous materials - Temperature increases lead to smaller hysteresis loops and higher condensation and evaporation pressure	Horikawa et al., 2011 [44]
Recyclable insulation material	Water vapour permeability, diffusion resistance	Experimental	- Provided experimental validation and analytical modeling of vapour transport characteristics - Findings contribute to sustainable building practices by promoting recyclable materials	Bozena Orlik-Kozdon, Tomasz Steidl 2018 [45]

3. Mitigation Techniques to Minimize Moisture Ingress

3.1. Moisture Control Principles

Moisture sources in the form of water vapour and liquid water can be classified into two categories: internal and external. Internal moisture sources refer to moisture that originates from within the building and that which is intentionally brought into the building for cleaning, bathing, and cooking; some is subsequently drained as wastewater. On the other hand, the external sources of moisture refer to the moisture that comes from outside the building, including rain, snow, and groundwater. Additionally, certain building materials, such as AAC and CS brick, contain a significant amount of moisture upon delivery due to their wicking properties [46]. Water damage is often associated with visible forms of liquid water, such as rain, plumbing leaks, or floods, which readily come to mind for most individuals. Detecting these leaks is relatively straightforward. However, numerous water-related issues are less visible and challenging to identify or diagnose. For instance, the inadequate curing of flooring adhesive on a concrete slab due to dampness can lead to loose flooring and microbial proliferation within the adhesive. Likewise, the condensation of humid indoor air on the cooler backside of vinyl wallpaper covering an exterior wall can create an optimal environment for mould growth. These subtler issues, unlike obvious leaks, occur without visible water flowing across the floor, with the actual damage concealed beneath flooring or behind walls [47]. Figure 5 illustrates the moisture sources affecting building envelope components.

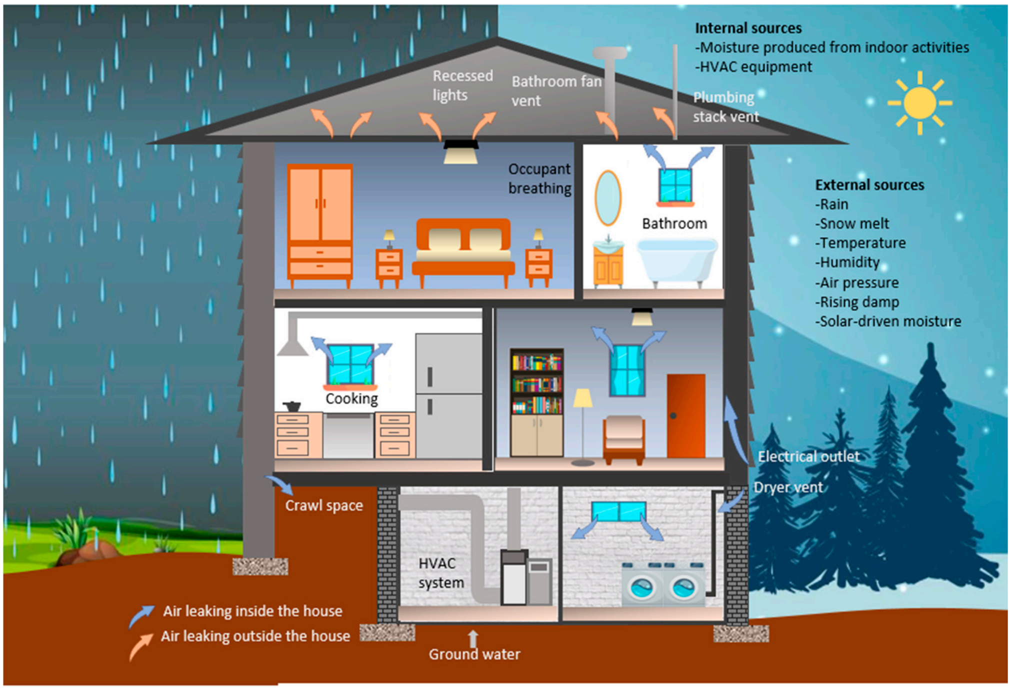

Figure 5. Moisture sources acting on building envelope components.

3.1.1. Control of Liquid Water Movement

It is essential to control the liquid water intrusion in the building by draining rainwater and snowmelt away from the building. Exterior cladding, drainage cavity, roofing, and stormwater management systems are designed to intercept the majority of rainfall and divert it away from the building. If rainwater penetrates into the exterior cladding of an exposed wall and is retained by the wall for a prolonged time period, it may cause severe damage. When raindrops hit the exterior surface of a wall assembly, they can take different paths, as illustrated in Figure 6. These include spreading out over the surface (1a), splashing open and fragmenting into smaller drops (1b), or rebounding off the exterior surface (1c). After impacting the surface, the water drops may be absorbed by the exterior surface (2a) and evaporate (2b). Alternatively, if the droplets are not immediately absorbed, they may run off along the exterior surface due to gravity (3a) or adhere to the surface (3b), or infiltrate through the cladding (4) [48]. Porous cladding materials like bricks have the capability to absorb, retain, and gradually release rainwater through evaporation. Through capillary action, water can penetrate the outer surface of the cladding and then migrate deeper into the material through its pores. Water can penetrate the cladding through intentional or unintentional openings, whether it is a non-absorptive cladding or one that is fully saturated. Intentional openings, such as open joints between panel cladding, allow for water infiltration. Unintentional openings, like cracks in the cladding surface or deficiencies at the interface between various building components due to aging effects, also facilitate water ingress. There are studies that quantify moisture in specific wall assemblies through experimental testing. However, these data are not sufficient to provide reliable, generalized quantitative information about water ingress in different types of walls. Thus, ASHRAE Standard 160, titled "Criteria for Moisture-Control Design Analysis in Buildings" [49], suggests using a default penetration rate of 1% of the rain hitting the cladding as a moisture load for hygrothermal simulations.

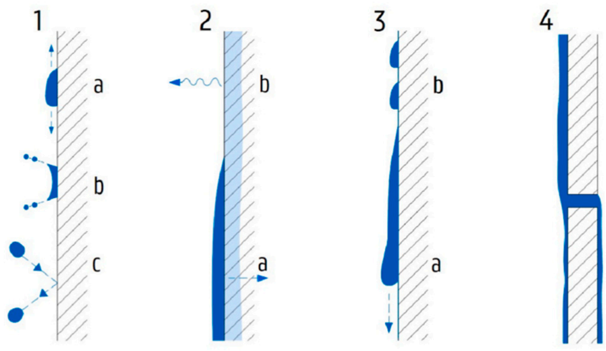

Figure 6. Occurring phenomena after raindrops impact the exterior cladding of a wall assembly: (**1** a) spreading, (**1** b) splashing, (**1** c) rebounding off the exterior surface, (**2** a) absorption, (**2** b) evaporation, (**3** a) run off, (**3** b) adherence to the surface, and (**4**) infiltration through the cladding (reprinted with permission from [48]).

According to the guidance developed by the U.S. Environmental Protection Agency, Indoor Environment Division, it is advisable to position plumbing lines and components in areas that are easily accessible for inspection and repair, ensuring their separation from porous cavity insulation materials [47]. Irrespective of climatic conditions, it is advisable to avoid installing plumbing lines, valves, and drain lines within exterior walls and ceilings that contain porous insulation. This precaution is essential because, in the event of a plumbing leak, it will ensure that insulation within those walls or ceilings does not become saturated. Porous insulation materials exhibit prolonged drying times or may remain perpetually damp, fostering conditions conducive to mould proliferation, corrosion of structural fasteners, and unnecessary energy expenditure caused by reducing the thermal resistance of the insulations. Moreover, in regions experiencing cold winters, plumbing situated within exterior walls or above ceiling insulation faces heightened vulnerability to freezing and subsequent rupture. Therefore, careful consideration of plumbing placement is crucial to mitigate potential issues related to insulation saturation and the increased risk of freezing temperature on the plumbing components.

3.1.2. Control of Condensation

Condensation can arise from either an excessively high dew point, unusually cold surfaces, or a combination of both factors. The indoor dew point is influenced by the balance between the addition and removal of water vapour from the air within a building. Both indoor and outdoor sources contribute to this equilibrium, necessitating mechanical systems with sufficient dehumidification capacity to effectively remove excess moisture and maintain the indoor dew point within acceptable thresholds. To ensure efficient condensation management in hot weather, it is essential to maintain indoor surface temperatures below the dew point within building cavities and enclosed spaces. Achieving this requires the strategic implementation and upkeep of HVAC systems to regulate indoor humidity levels during both the heating and cooling seasons. Building envelopes can be engineered and built to maintain surface temperatures within the assemblies above the dew point throughout all seasons [47]. Airflow through discontinuities (convection) can transport moisture (water vapour) into a wall assembly at a much faster rate than diffusion through materials, making air infiltration or exfiltration a primary driver of moisture transfer and condensation within walls. The direction of airflow, ambient temperatures, relative humidity of the air, and type of wall materials determine whether condensation occurs or materials dry out through evaporation. Airflow, driven by pressure differentials from factors like wind or mechanical pressurization, moves from areas of higher to lower air pressure, potentially causing condensation when warm and humid interior air infiltrates the exterior wall assembly. These airflow paths, often occurring through discontinuities in interior gypsum wallboard, can be direct or circuitous, with direct paths typically maintaining surface temperatures above the dew point and circuitous paths leading to condensation on surfaces below the dew point. Figure 7 shows the direct airflow paths and circuitous airflow paths presented by Hartwig M. Künzel [50]. To mitigate such moisture-related issues, it is crucial to integrate materials, components, and assemblies to establish a continuous air control layer, although some degree of air leakage may still occur.

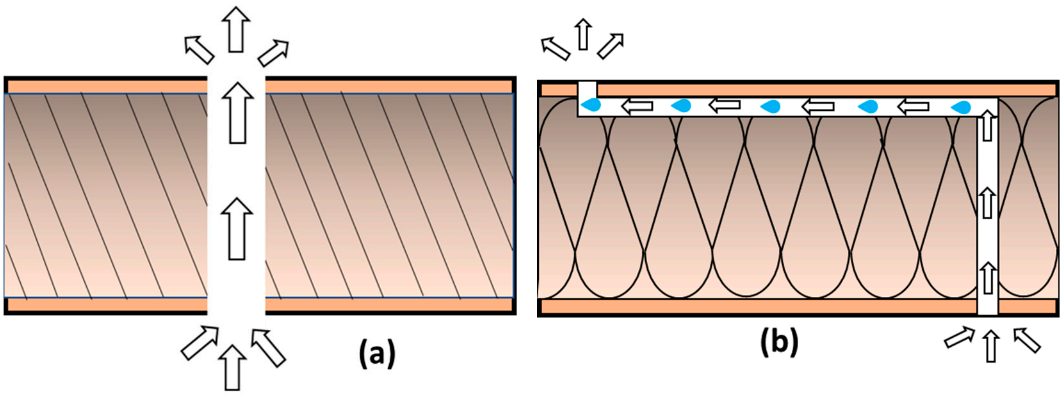

Figure 7. Direct (**a**) and circuitous (**b**) airflow paths (adapted from [50]).

During cold weather conditions, condensation tends to manifest predominantly on the interior surfaces of exterior walls or roof assemblies. The sheathing and cladding positioned outside the insulation and air barrier typically attain temperatures closely aligned with those of the outdoor environment. Consequently, indoor window surfaces, often cooler than adjacent walls, frequently serve as primary sites for condensation occurrence when temperatures drop.

In cold climates, it is imperative to incorporate a vapour-impermeable barrier on the warmer side of a building envelope to impede water vapour diffusion and prevent the buildup of excessive moisture. It is evident that the condensing surface of interest in a building envelope assembly often changes on a seasonal basis. Figure 8 shows two condensing surfaces of interest within an insulated wall assembly under two different seasonal conditions. Recognizing the potential location of condensation is crucial to deploying effective moisture management strategies [51].

Buenrostro et al. [52] analyzed three different building envelope assemblies: (1) a Novoclimat wall, which included polyethylene foil along with petroleum-based insulating materials; (2) a highly hygroscopic (HH) wall insulated with organic materials; and (3) a cross-laminated timber (CLT) wall. It was observed that the inclusion of a vapour retarder generally maintained safe moisture levels, with the exception of the Novoclimat wall. Despite the critical conditions being reached in this assembly with all vapour barriers, the vapour retarder exhibited the quickest exit from the danger zone and the lowest maximum relative humidity (RH) value compared to other options. While the mould growth assessment criteria were initially developed for wooden materials, the lightweight wood frame of the Novoclimat wall could still be susceptible to mould proliferation. Additionally, walls insulated with bio-based materials, such as the HH and CLT walls, proved to be suitable choices for cold climates, even with permeable vapour barriers [53].

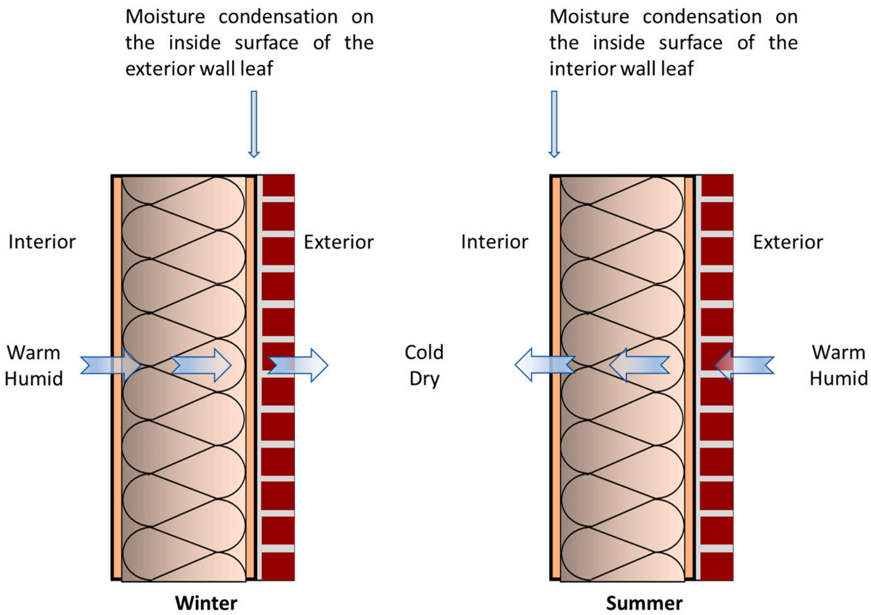

Figure 8. Condensing surface of interest based on seasonal changes (adapted from [51]).

3.1.3. Use of Moisture-Resistant Materials

As moisture sources exist on both sides of the building envelope, all of the components of the building materials are directly or indirectly affected by moisture. It is essential to use moisture-tolerant materials that can withstand repeated wetting in areas that are expected to get wet by design or by accident [53]. Moisture-resistant materials in the building envelope are designed to prevent moisture penetration, while moisture-tolerant materials can endure some exposure to moisture without significant degradation, maintaining their functionality over time. In the first review paper, the components of the building envelope and their functionalities in protecting the building from environmental loads were discussed in detail. The National Building Code of Canada (NBC) outlines the minimum requirements and quality standards for the materials and components used in building envelope assemblies. Consequently, building envelope materials are required to adhere to standards referenced in different sections of the NBC (Table 4) [54].

Table 4. Building envelope materials and the NBC (2020) section relevant to standard requirements.

Building Envelope Component	NBC Section	Standards	Highlights
Cladding	9.27.2.4	ASTM C1178/C1178M [55] ASTM C1396/C1396M [56] ASTM C840 [57]	A clearance ≥ 200 mm shall be provided between finished ground and cladding that is adversely affected by moisture such as untreated wood, oriented strand board (OSB), and hardboard to protect the cladding from moisture [54].
Sealant	9.27.4	ASTM C834 [58] ASTM C920 [59] ASTM C1184 [60] ASTM C1311 [61]	Sealants must possess qualities like adhesion, flexibility, weather, and chemical resistance to maintain their efficacy over time [62].
Drainage gap	A-9.27.3.1	No standard found	Masonry veneer walls have drainage spaces of 25 mm, while cavity walls require 50 mm. For non-masonry walls, open rainscreen assemblies should have a minimum drainage space depth of 10 mm [54].
Sheathing membrane	9.27.3.2	CAN/CGSB-51.32-M	Sheathing membrane must be "breathable" to facilitate moisture dissipation during the drying season. Consequently, the NBC imposes limitations on using materials with both low water vapour permeance and low air permeance on the cold side of the assembly [54].

Table 4. *Cont.*

Building Envelope Component	NBC Section	Standards	Highlights
Exterior sheathing	9.23.17	ASTM C1177/C1177M [61] ASTM C1396/C1396M [56] CAN/ULC-S701.1 [63] CAN/ULC-S704.1 [64] CAN/ULC-S706.1 [65]	Exterior sheathing acts as a stable substrate for exterior cladding installation; however, gypsum sheathing, rigid insulation, and fiberboard shall not be used for the attachment of cladding materials.
Air barrier	9.25.3	CAN/CGSB-51.34-M [66]	Effective air barriers are characterized by low permeability and high strength to withstand air pressure loads and enhance durability.
Vapour barrier	9.25.4	ASTM E96/E96M [66] CAN/CGSB-51.33-M [67]	Vapour barriers placed on the interior side of the wall cavity should not have a permeance greater than 60 ng/(Pa×s×m^2) measured in accordance with ASTM E96/E96M to proper control of diffusion [54].
Insulation	9.25.2	ASTM C726 [68] CAN/CGSB-51.25-M [69] CAN/ULC-S701.1 [70] CAN/ULC-S702.1 [63] CAN/ULC-S703.1 [71] CAN/ULC-S704.1 [64] CAN/ULC-S705.1 [72] CAN/ULC-S706.1 [65]	Insulation that is in contact with the ground shall be inert to the action of soil and water and shall be such that its insulative properties are not affected by moisture. When the insulation is exposed to the weather and subject to mechanical damage, it shall be protected by not less than 6 mm preservative-treated plywood or 12 mm cement parging on a wire lath applied to the exposed face and edge [54].

3.2. Moisture Control Design and Hygrothermal Performance Evaluation

Hygrothermal simulation empowers a designer to anticipate the evolving moisture and temperature conditions within a building envelope assembly. Conducting this analysis enhances comprehension of the building envelope's reaction to both interior and exterior surroundings, aiding in the identification of potential issues related to moisture performance.

3.2.1. Hygrothermal Simulation Tools

For predicting and evaluating the hygrothermal performance of buildings, predicting the risk of mould growth, and improving the durability of the structure, an accurate dynamic hygrothermal model for coupled heat and moisture transfer in porous building materials and envelopes is necessary. Hygrothermal simulation tools allow for the establishment of numerical models of building envelope components or a whole building in one or more dimensions. The numerical model will include information on the geometry and material properties of the simulated subject. Climate data can also be added to the simulation to investigate the impact of different climates on the performance of the simulated subject. Parameters related to hygrothermal performance, such as relative humidity, moisture content, and temperature, for different times and locations can be derived from the hygrothermal simulations. Some of the most widely used commercial software used for hygrothermal simulation are listed below in Table 5 [73].

Table 5. Commercial hygrothermal simulation tools.

Simulation Tool	Dimension	HAM Model: Moisture-Driving Potential	Moisture Transfer	Numerical Method	Boundary Conditions at the Surface	Wind-Driven Rain	Material Properties	Customization and User -Defined Code Incorporation
WUFI [74,75]	1D and 2D—whole building	Vapour pressure, relative humidity [76]	Vapour diffusion, liquid transport	Finite Control Volume	Combined constant coefficient for long-wave radiation and convection	Yes	Function of relative humidity	Limited customization, primarily through user data input but not through code-level changes

Table 5. *Cont.*

Simulation Tool	Dimension	HAM Model: Moisture-Driving Potential	Moisture Transfer	Numerical Method	Boundary Conditions at the Surface	Wind-Driven Rain	Material Properties	Customization and User -Defined Code Incorporation
DELPHIN [77]	1D and 2D	Vapour pressure for vapour diffusion, moisture content or water pressure for liquid diffusion (user choice)	Vapour diffusion, liquid transport, moist air movement within the envelope	Finite Control Volume	Combined constant coefficient for long-wave radiation and convection	Yes	Function of relative humidity, thermal conductivity, and vapour diffusivity function of temperature	Moderate customization, especially for post-processing and material definitions, but limited core-code manipulation
BSim [78]	1D—whole building	Vapour pressure [79]	Convection, vapour diffusion	Finite Control Volume	Combined constant coefficient for long-wave radiation and convection; possible to separate the calculations	No	Constant (except water vapour permeability, which depends on relative humidity)	Low-to-moderate customization, limited mainly to boundary conditions and data inputs
IDA-ICE [79,80]	1D	Vapour density	Vapour diffusion, moist air movement within the envelope	Finite Control Volume	Separated convective coefficient (dependent on temperature and slope) and long-wave radiation (view factors)	No	Constant (except water vapour permeability function of relative humidity)	Moderate customization, with flexibility to integrate external tools like Python for enhanced control over simulations
hygIRC [81]	1D and 2D	Moisture content and vapour pressure	Vapour diffusion, moist air movement within the envelope, liquid transport	Finite Control Volume	Constant coefficient for radiation and convection	Yes	Function of relative humidity	Moderate, with some flexibility in defining material properties and boundary conditions
COMSOL [82]	1D and 2D—whole building	Vapour pressure, relative humidity [83], and moisture content	Vapour diffusion, liquid transport	Finite Elements Model	Constant coefficient for radiation and convection	Yes	Function of relative humidity and temperature	High degree of customization and incorporation of user-defined codes, including the ability to add new equations and external integrations

3.2.2. Moisture Control Design and Hygrothermal Loads to Consider

The main purpose of building envelopes is to protect the building from external natural weather and to provide a healthy environmental quality for human habitation. Figure 9 shows the moisture loads acting on the building envelope components caused by dynamic hygrothermal parameters and their alternating diurnal or seasonal directions according to the ASHARE Handbook of Fundamentals [73]. It is noticeable that there are considerable daily and annual variations on the external surface which are propagated to a minor extent to the interior surface. Throughout the daytime, the exterior surface heats up by conduction and solar radiation, which leads to the evaporation of moisture from the surface layer. On the other hand, during sunset, longwave (infrared) emissions may lead to an overcooling (cooling down below ambient air temperature) of highly insulated wall systems, and condensation may occur on and within the facade system. Often, several hygrothermal load cycles overlap, such as summer/winter, day/night, and rain/sun. Therefore, a precise analysis of the expected loads should be completed before designing a new building or changing the envelope of an existing construction.

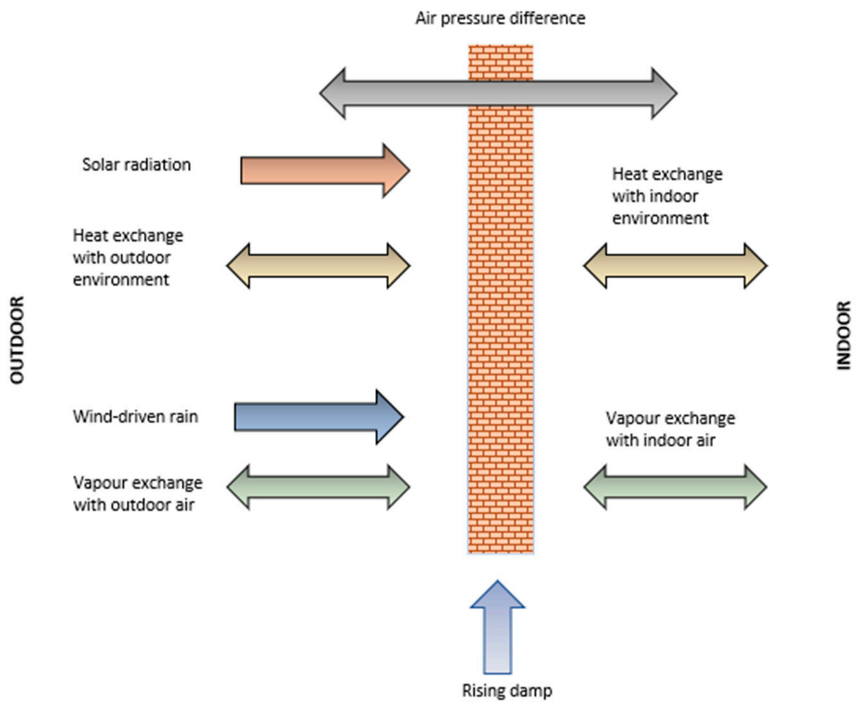

Figure 9. Schematic representation of the moisture loads acting on the building envelope caused by dynamic hygrothermal parameters and their alternating diurnal or seasonal directions [84].

Temperature and Humidity

Temperature and relative humidity, which is intrinsically dependent on temperature, are parameters that change continuously and act on both sides of the building envelope. The difference in temperature between the outdoor and indoor causes partial vapour pressure differences that induce vapour diffusion through the building envelope. Diffusion is a much slower method of transferring moisture than airflow. As a result, it is typically a less significant contributor to moisture migration associated with condensation problems than airflow. Another remarkable load is caused by air pressure differences over the building envelope resulting from thermal buoyancy, wind, or unbalanced mechanical ventilation. Interstitial condensation can arise from the convective airflow driven by pressure through unsealed joints or other leaks. To avoid moisture damage, it is essential to block airflow through building assemblies with a continuous air barrier [85].

Solar Radiation

Solar-driven moisture represents an external moisture load on building envelope materials, resulting from the combined influence of rainwater and solar radiation. When the sun heats up wet cladding, the moisture evaporates in both directions with a notable portion also migrating inward, which can increase the moisture content of the assembly layers away from the external layers, as mentioned in the ASHRAE handbook [84]. This is known as “solar vapour drive” and is illustrated in Figure 10. This phenomenon is more dominant in hot and humid summers. It is evident that steady-state diffusion calculation methods are insufficient for capturing this effect due to their highly dynamic nature, necessitating tools capable of modeling the interplay between driving rain events and sunny spells [85]. Field and laboratory studies conducted at the Institute for Research in Construction (IRC), National Research Council Canada (NRC), provide compelling evidence of inward water vapour diffusion across the wall when the exterior surface is heated by solar radiation. A significant temperature rise has been observed on the exterior surface of a south-facing wall, coinciding with increased absolute humidity in the cavity behind the brick, indicating inward moisture movement [86]. Xue Y. et al. [53] investigated moisture accumulation in building envelopes in Hangzhou City in China using a well-validated coupled heat and moisture transfer (HAMT) model. The moisture levels and risks of condensation and mould growth were closely associated with building orientation due to variations in solar radiation intensity and the moisture loads from wind-driven rain. The moisture content in the northward building envelopes was 1.0–10.1% higher than that facing the other orientations, which resulted in higher condensation risks (46.2–173.4% higher) and mould growth (15.8–61.3% higher). This study also revealed that the combination of intense heat flux and external insulations promotes moisture accumulation in building envelopes, leading to a high moisture area in the wall-to-floor thermal bridge and facilitating the growth of mycelia inside the envelopes. Hence, it is advisable to design the thermal insulation layer based on the orientation, and it is recommended to add a vapour barrier layer outside the insulation to mitigate the negative consequences of moisture buildup when utilizing external insulation [54].

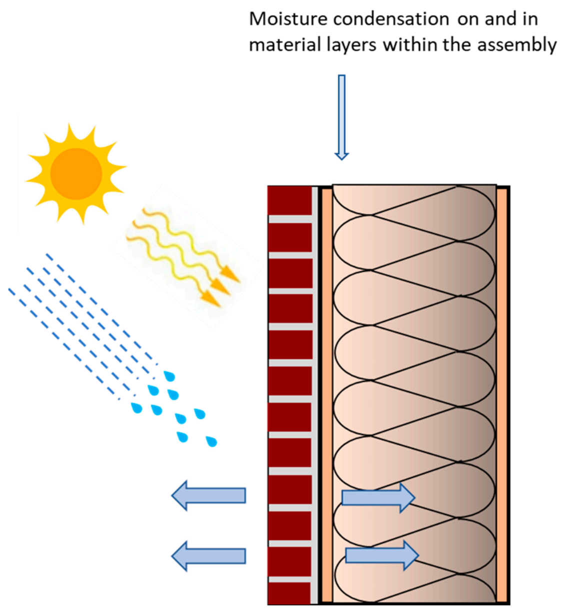

Figure 10. Solar vapour drive and interstitial condensation (adapted from [84]).

Exterior Condensation

Exterior condensation on building envelopes is a result of complex interactions between radiative heat loss, material properties, and environmental conditions. Long-wave radiation exchange in the building envelope refers to the transfer of infrared thermal radiation between the building's outer surfaces and the surrounding environment. At night or during periods of low solar radiation, the building's outer surfaces can lose heat through long-wave radiation more rapidly than they gain it, resulting in a net heat loss. Due to long-wave radiative heat loss, the exterior surfaces of the building envelope can become significantly cooler than the ambient air temperature, potentially reaching the dew point and causing condensation on the outer surface of the building [84]. Structures with high thermal inertia typically do not cool sufficiently to reach the dew point for long periods. However, modern building assemblies with low thermal inertia, such as lightweight roofs or exterior insulation finish systems (EIFSs), are more susceptible to this effect [87]. To address this effect in hygrothermal simulations, it is advised to utilize a comprehensive full radiation balance model. Such a model explicitly calculates the complete radiation balance, thereby enabling the quantitative determination of nighttime overcooling and subsequent condensation loads [88].

Wind-Driven Rain

WDR can cause severe damage to buildings, such as mould growth, erosion of building materials, freeze–thaw damage, water penetration, and surface soiling. To minimize moisture-related problems while designing standards for facades, it is essential to understand and quantify WDR with changing climates. Dukhan and Sushama [89] investigated the impact of climate change on WDR loads in Canada for the 2071–2100 future period with respect to the period 1981–2010. This study suggested that wind speed and direction changes are not significant for most parts of Canada except for the northern region. However, large increases in WDR loads (omnidirectional airfield) were predicted for the southeastern and west coast regions. Additionally, the study highlighted a shift in the timing of maximum monthly WDR loads from summer to fall in eastern Canada, posing greater risks for building facades due to low evaporation rates during fall, and suggested the need for specific guidance for designing future WDR loads along with recommendations for building facade materials and insulation. Moreover, the study proposed using regional climate model simulations with higher resolutions and multimodel combinations to better quantify uncertainties and understand the effects of projected changes on building facade performance, aiding in the development of climate-resilient design strategies for the built environment.

Bastien and Winther-Gaasvig [90] investigated the hygrothermal performance of a hygroscopic and permeable building envelope (HPBE) primarily comprising wood and clay, focusing on the influence of driving rain and vapour diffusion. Through hygrothermal simulations on a single-family house with wood and clay components, the study examined the impact of driving rain, plaster capillarity, and vapour barrier presence on moisture content and mould growth within the HPBE. The results highlight the critical role of overhangs in ensuring the durability of an HPBE with capillary-active, lime-based plaster, while overhangs have minimal effects with mineral-cement-based plaster. Incorporating a vapour barrier does not substantially alter moisture content. Plaster type and wind-driven rain exposure emerge as key factors influencing hygrothermal performance, with driving rain inducing 3% moisture content in mineral plaster and 52% in lime plaster. The study emphasizes the need for protective measures against rain for substrates with higher capillary action. Surprisingly, including a vapour barrier yields similar moisture content in exterior wood fiberboard for both plaster types.

Moisture Ingress During Construction Phase

Building materials are often unable to dry out due to tight construction schedules, which has led to an increase in building damage caused by migrating construction moisture. This moisture can either be delivered with the building products or absorbed by the materials during storage or construction. Some building materials, such as cast-in-place concrete, AAC, CS brick, and CLT, contain a significant amount of moisture when delivered. Other materials, such as stucco, mortar, clay brick, and concrete blocks, are either mixed or brought into contact with water at the construction site. Additionally, most building materials may absorb precipitation or groundwater when left unprotected before the enclosure of the building [84].

Solid wood panels made of CLT are sensitive to moisture, and slow or insufficient dry-out of the initial moisture content during the construction phase can generate moisture in the space between wall layers, especially when vapour layers cover the CLT. Herms [91] has proposed three approaches to protect the CLT during the construction phase from weather and moisture: (1) using a temporary tent; (2) for large-scale buildings, covering the ceiling with tarpaulins; and (3) sealing the ceiling elements with self-adhesive membranes. Kukk [92] used a stochastic approach to set limit values for the initial moisture content for

CLT and water vapour resistance of the wind barrier and the air and vapour barrier of CLT external walls. This study concluded that the limit value of the water vapour resistance of the wind barrier should not exceed 0.03 m during the construction phase. In the case of vapour-tight external insulation, the water vapour resistance of the wind barrier should not exceed 0.15 m and the initial moisture content of CLT should not exceed 16% to prevent mould growth risk on the external surface of CLT.

Ground- and Surface Water

Ground and surface water are important moisture loads and can pose significant risks to building envelopes if not properly addressed during design and construction [84]. Capillary action can cause groundwater to wick vertically through porous materials like masonry walls, drawing moisture from the ground up into the building envelope and causing damage over time. Proper site grading and drainage systems are crucial to divert surface water away from the building envelope, as poor drainage around the foundation can lead to water infiltration and moisture buildup [93]. Ground moisture can pose significant problems for timber structures with crawl spaces. Unlike concrete slabs or concrete floor panels, timber floors are particularly vulnerable to the high humidity prevalent in crawl spaces. Effective mitigation strategies include installing vapour barriers and insulation on the ground or below the floor, along with ensuring controlled ventilation. The wicking of ground- or surface water into porous walls by capillary action is called rising damp [84]. Apparent rising damp may also be attributed to summer condensation or hygroscopic moisture. In historic buildings, wall contamination with salts can elevate moisture content due to the hygroscopic nature of the salts, which absorb water [94–96]. Old buildings often contain salts, like de-icing salts or nitrates, from previous uses or environmental exposure, which increase the hygroscopicity and vapour diffusion resistance of masonry surfaces, making them appear wet even without water wicking from the ground. Remedial measures for salt-induced moisture issues include using sacrificial plasters or specialized renovation plaster systems. Rising damp is difficult to accurately simulate due to unknown ground moisture conditions and the resistance of mortar joints to capillary flux, limiting the precision of simulation results but still useful for comparing different remedial options [11].

Air Pressure Differentials

Air leakage driven by air pressure differentials across the building envelope is one of the major causes of moisture accumulation within wall and roof assemblies. Air pressure differences can arise from wind, stack effect (buoyancy of warm indoor air), and the operation of mechanical systems like fans and air handlers [84]. Figure 5 shows some possible locations of air leakages from inside or outside a house. When air carrying moisture leaks through gaps, cracks, and penetrations in the envelope, it can transport significant amounts of water vapour. If this moist air encounters surfaces below the dew point temperature within the assembly, condensation will occur, leading to potential moisture damage, mould growth, and the degradation of materials like insulation [85]. The amount of moisture transported by air leakage is typically far greater than what occurs through vapour diffusion alone [97]. Even small air leakage paths, when subjected to normal indoor–outdoor pressure differentials, can allow substantial airflow and moisture convection into the envelope over time. To prevent moisture damage, it is essential to prevent airflow through and within the building envelope using a continuous air barrier. However, achieving complete airtightness is challenging, which makes the hygrothermal impact of airflow significant, particularly under high-pressure differentials such as those found in multistory or mechanically pressurized buildings [85].

Convective moisture ingress, resulting from imperfections in the vapour and/or air control layer, is a multidimensional phenomenon that one-dimensional calculations cannot directly capture. However, using multidimensional simulation tools does not fully resolve this issue, as the precise configuration of leaks is usually unknown, and the complexity of the relevant flow paths exceeds the capabilities of most models [11]. Wang and Ge [98] investigated the effect of air leakage on the hygrothermal performance of three wood-wall-framed walls using an air convection method and air infiltration method under cold climate conditions. However, their approach considered a specific air leakage path, i.e., indoor air entering from the interior at the bottom of the stud cavity and returning to the interior at the top of the cavity, and thus the conclusions are limited to this specific air leakage pattern [98].

3.3. Moisture Control Standard and Guidelines

Moisture control design standards and guidelines are crucial for preventing structural damage and health issues caused by mould and moisture in buildings. They ensure that construction practices are tailored to regional climatic conditions, enhancing the effectiveness and durability of moisture control measures. By providing clear guidelines, these standards help maintain occupant health and safety while optimizing construction costs. Additionally, they support sustainable building practices by promoting methods appropriate for local environments. Moisture control design standards and guidelines differ between countries due to regional climate variations, local building practices, regulatory frameworks, and economic considerations. Globally, countries are progressively striving for full or partial decarbonization of the built environment by 2030, prompting substantial policy shifts. A key outcome for building design is the implementation of minimum energy performance requirements, which has accelerated the adoption of high-performing building envelopes and the application of bio-based materials [99–101]. As new materials, technologies, and construction methods emerge, along with evolving climate patterns and disaster risks, building codes must be updated to incorporate the latest advancements and best practices [102]. Table 6 shows some moisture control design standards and guidelines that are adopted in different countries and regions.

Table 6. Moisture control design standards and guidelines from different countries and regions.

Country/Region	Standard	Type	Scope/Focus
Canada	National Building Code of Canada (NBC) [54]	National Building Code	National model code with provisions for moisture control
	CSA S478 [103]	Guidelines	Guidelines for building durability, including moisture management
United States	ASHRAE 160 [84]	International Standard	Criteria for moisture control design, including moisture accumulation and movement analysis
	International Building Code (IBC) [104]	National Building Code	Comprehensive building code, including moisture control
European Union	EN 15026 [105]	International Standard	Numerical simulation of moisture transfer in building components
	EN ISO 13788 [12]	International Standard	Preventing condensation issues through design and calculation methods
United Kingdom	BS 5250 [106]	International Standard	Comprehensive guidelines for managing moisture, covering condensation, damp proofing, and ventilation
Australia	National Construction Code (NCC) 2019 [107]	National Building Code	Comprehensive building code with moisture management provisions

4. Discussions and Conclusions

Built upon the foundational understanding of moisture ingress explored in the first review, "Moisture Ingress in Building Envelope Materials: (I) Scientometric Analysis and Experimental Fundamentals", this review paper extends the exploration by delving into the mechanisms of moisture ingress and the practical aspects of mitigating moisture ingress in buildings, which is a critical concern for the structural integrity of buildings and the health of their occupants.

Regarding the sources of moisture ingress, rain was identified as the most frequently addressed topic in the literature, accounting for 25% of the publications. Wind-driven rain, a subset of this topic, is studied in 127 publications, representing 7% of all related publications, highlighting its significance as an in-service moisture source.

With respect to the mechanisms of moisture transport, moisture dynamics were analyzed in two phases: liquid and vapour. In the liquid phase, capillary action governs moisture transport due to the presence of pore sizes predominantly smaller than 1 mm in building materials. Numerous studies have explored capillary absorption, with factors such as temperature, pore size, and pore size distribution significantly affecting liquid absorption. In the vapour phase, transport mechanisms include vapour diffusion, surface diffusion, and capillary condensation. However, no publications were found that directly address vapour transport specifically with respect to the condensation stage. Moreover, future research can focus on the multiscale modeling of these mechanisms for moisture tracking and assessing the impact of material nanostructure and coatings on moisture regulation to improve building durability and energy efficiency. It is also important to differentiate bound and free water distributions within the porous materials especially used in buildings to improve the moisture prediction.

Advanced design and hygrothermal performance simulation tools are also presented for their role in predicting and managing moisture-related challenges, allowing for more accurate risk assessments and informed design decisions. Lastly, the importance of adhering to moisture control standards is underscored as critical for ensuring the long-term performance and resilience of building envelopes.

Future research on the mitigation of moisture intrusion should explore self-drying and moisture-adaptive materials to mitigate moisture retention in the construction phase, alongside improved temporary protection measures. Advances in hygrothermal modeling can enhance moisture prediction, particularly for wind-driven rain, solar vapour drive, and condensation risks. The integration of smart materials, bio-based insulations, and AI-driven moisture monitoring could further optimize building resilience. Additionally, studying the long-term impacts of climate change on moisture transport while considering the effect of aging on material properties through service-life prediction will be crucial for developing sustainable and adaptive building solutions.

Author Contributions: Conceptualization, E.E. and M.R.; methodology, M.H.Y., I.L.-C., E.E., E.D. and E.J.; software, E.J., I.L.-C. and E.E.; validation, M.R., M.L. and E.E.; formal analysis, M.H.Y., I.L.-C. and E.J.; investigation, I.L.-C., E.J. and M.H.Y.; resources, M.R., M.L. and E.E.; data curation, M.H.Y., I.L.-C. and E.J.; writing—original draft preparation, I.L.-C., E.J., E.E. and M.H.Y.; writing—review and editing, M.R., E.D., Z.X. and M.L.; visualization, I.L.-C. and E.J.; supervision, M.R., M.L., E.D., Z.X. and E.E.; project administration, E.E. and M.R.; funding acquisition, M.L., M.R. and E.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to extend their sincere thanks to Maurice Defo and Lin Wang for their invaluable support in deepening our understanding of moisture ingress. Their insights and contributions, particularly in highlighting the role of Building Envelope Materials (BEMs), were instrumental in developing this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

^{1}H SS-NMR	Single-sided proton nuclear magnetic resonance spectroscopy
AAC	Autoclave aerated concrete
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEMs	Building envelope materials
CLT	Cross-laminated timber
CS	Calcium silicate
CT	Computed tomography
DVS	Dynamic vapour sorption
EIFSs	Exterior insulation finish systems
FC	Foam concrete
GA	Genetic algorithm
HAMT	Heat and moisture transfer
HH	Highly hygroscopic
HPBE	Hygroscopic and permeable building envelope
IRC	Institute for Research in Construction
LD	Liquid diffusivity
MOUSE	Mobile Universal Surface Explorer
NBC	National Building Code of Canada
NCC	National Construction Code
NRC	National Research Council Canada
OSB	Oriented strand board
RF	Radio frequency
RH	Relative humidity
SHS	Coral and sand concrete
WDR	Wind-driven rain

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