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Moisture Buffering in Buildings: A Review of Experimental and Numerical Methods

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Abstract

The moisture buffering capacity in buildings is well known to influence material durability, building-scale energy efficiency, and indoor environmental quality. In this work, we present a comprehensive meta-analysis of experimental studies and a review of numerical approaches concerning the moisture buffering capacity of common building materials. More specifically, we synthesize and analyze reported moisture buffering values (MBVs) of materials from >180 unique characterization experiments. In addition, we classify, compare, and critically discuss experimental methods employed to measure MBV, along with numerical methods that have been used to quantify building-scale benefits. Experimental data indicate that biotic and chemically hydrophilic (*e.g.*, cellulosic) materials exhibit higher MBVs than porous, abiotic (*e.g.*, cementitious) materials, which suggests new opportunities for engineering natural, synthetic, and/or hybrid hydrophilic materials that display hyperactive MBVs. In addition, moisture buffering effects have been shown to yield up to 30% energy savings in certain climates. However, our analysis reveals that more consistent experimental and numerical methodologies are still needed to accurately quantify building-scale benefits. To this end, we identify specific gaps in scientific and technical knowledge and offer suggestions for experimental and theoretical research that is required to advance the collective understanding of moisture buffering and its effects on the energy consumption and indoor environmental quality of residential and commercial buildings.

Keywords: Moisture buffering, building materials, energy efficiency, indoor environmental quality.

1.0 Introduction

Active moisture management in residential and commercial buildings is an energy-intensive process. In 2017, the United States (US) Energy Information Administration reported that building energy comprised 39% of total US energy consumption [1], of which 92% was attributable to residential and commercial building heating, ventilation, and air-conditioning (HVAC) systems alone [1,2]. To maintain indoor environmental comfort, mechanically driven HVAC systems stabilize indoor relative humidity (RH) within specific ranges. In humid climates, for example, dehumidification requires both cooling and reheating air. Buildings with high indoor humidity (*e.g.*, natatoriums) require high degree of ventilation with conditioned air. Dehumidification, ventilation, and conditioning (*i.e.*, heating and cooling) are all energy-intensive processes that are required, in large part, to manage moisture in buildings.

Recent research shows that failing to account for passive moisture absorption and desorption of building materials during building operation can result in up to 210% overestimation of peak heating loads and 59% underestimation of heat flux from latent heat and moisture effects [3]. Over- and underestimations of these magnitudes can lead to the overdesign of HVAC systems in residential and commercial buildings because simulated energy consumption will increase due to increases in thermal conductivity of wall assemblies. Accounting for hygroscopic effects of spruce plywood, for instance, has been shown to yield up to 20-30% energy savings in terms of cooling loads in residential buildings [4–6] . HVAC control strategies that consider passive moisture buffering of building materials have been shown to decrease energy consumption by 14-17% during heating periods [7]. In short, the passive ability of materials to absorb and desorb moisture is important to consider in estimating the peak heating and cooling demands in both residential and commercial buildings.

1.1 *Sources of Moisture in Buildings*

Moisture in buildings originates from several sources, including outdoor air and indoor plants, occupants, and release from high-water-content building materials (*e.g.*, wood, concrete) soon after construction. The moisture content of outdoor air depends heavily on climate zone, which dictates average RH, types and levels of precipitation (*e.g.*, snow, rain), and ground-level moisture. Indoor moisture conditions depend on the type and amount of flora, as well as occupancy levels and associated activities. Humans can generate 115 to 270 grams of water per hour (2.8 to 6.5 kg per day) through respiration and perspiration [8]. Water fixtures (*e.g.*, showers, sinks, toilets) and the evapotranspiration of indoor plants also significantly contribute to indoor moisture levels [8]. High-water-content construction materials will acclimate over time and release moisture into the building. Overall estimates for moisture released in the first year of new construction is ~10 kg per day [9]. More specifically, dimensional lumber utilized at a standard moisture content (*i.e.*, 15% or 19%) can release ~200 kg of water in an average residential single-family home as it equilibrates [9]. Concrete can release ~90 kg/m^3 over two years post-construction [9]. Together, these outdoor and indoor sources of moisture impart non-trivial material, energy, and human health consequences in buildings, which are further discussed in the following sections [6].

1.2 ***Building Health***

Moisture can trigger physical, mechanical, chemical, and biological deterioration mechanisms in building materials that can lead to building-scale damage. This has been a well-known problem for many years, in fact, previous research from over 40 years prior has reported that up to 90% of all construction material and building durability issues are caused by moisture [10]. Specifically, moisture content of hygroscopic structural materials, like wood, affects size (*e.g.*, swelling, shrinkage), strength, and stiffness [11]. Wu *et al.* [12] found that commercially available oriented strand board (OSB) exhibited 31% dimensional swelling with an increase in moisture content of 24%. In terms of mechanical properties, high moisture levels can result in up to 70% loss in allowable strength for wood members [13]. These physical and mechanical effects in wood can be exacerbated by moisture absorption and desorption cycling [14]. Moisture can also lead to other physical, mechanical, and chemical deterioration effects, such as efflorescence [15], hydrolytic and exacerbated UV degradation of polymeric materials [16], chloride-induced corrosion in reinforced concrete [17], and freeze-thaw deterioration [18]. Regarding biological deterioration, moisture can induce localized conditions for mold and fungal growth, which can accelerate material aging [19]. RH is intimately related to mold growth rates, where mold growth depends on the frequency of low and high humidity levels and time of wetness [19]. In a 2001 study led by Klaus Sedlbauer, 250 sources were reviewed to establish mold growth isopleths on common building materials [20]. The LIM (Lowest Isopleth for Mold) begins at 75% RH with up to 2 mm/day of growth at 85% RH and 5 mm/day above 95% RH [20]. Biological deterioration is of critical concern regarding not only the structural integrity of biotic materials (*e.g.*, wood), but also the potential negative effects on indoor environmental quality and associated consequences to human health and well-being.

1.3 *Human Health*

Both high and low levels of moisture in indoor air have been linked to health problems since the early 20th century. In seminal studies, researchers linked dry air from furnace-heated homes in a New England winter to skin and respiratory irritation [21] and to the diminishing health of children in grammar schools [22]. In the 1910s, researchers showed that 40% RH in residential buildings of the era was enough for condensation—and the health-related problems that follow—to occur [23]. Recent research has shown that conditioned air with RH >40% relieves nasal, pharyngeal, and skin dryness and congestion [24]. While low RH causes adverse health effects, excess RH, has also been linked to other respiratory illnesses, such as asthma, wheezing, and bronchial hyper-responsiveness (BHR) [25]. Additionally, high humidity levels can cause occupant discomfort and can alter the perception of indoor air quality [26]. In other words, humans will perceive humid indoor air as heavy, muggy, and uncomfortable and less sanitary to breath. Given that humans spend an average of 90% of their time indoors (*e.g.,* homes, offices, schools) [27] and that high (>70%) or low (<40%) RH imparts measurable health effects [28], confining RH levels to prescribed, acceptable ranges is of critical importance in building operations.

1.4 *Impact and Scope of Review*

Moisture buffering as a passive humidity regulation strategy is both an economical and energy-efficient approach that is currently not fully understood and, consequently, underexploited in building design and construction. This review critically explores the experimental and numerical methods of quantifying moisture buffering effects and estimating their building-scale impact. First, experimental methods employed to measure moisture buffering values (MBVs) of building materials are classified, compared, and reviewed. Empirical MBV data from >180 characterization experiments are synthesized and analyzed to elucidate the physical, chemical, and biological characteristics of materials that display particularly high MBVs. Second, hygrothermal modeling methods for building-scale applications are classified and critically analyzed based on computational expense, convenience, and accuracy. Finally, new, emerging research on the moisture buffering properties of innovative hygroscopic materials is highlighted. We conclude this review by discussing new opportunities and future research directions that are required to advance technical understanding, material development, and computational modeling of moisture buffering effects and to leverage the benefits in the design, construction, and operation of residential and commercial buildings.

2.0 Review of Experimental Methods

2.1 *Characterization Methods*

Moisture buffering value (MBV) is the most well accepted parameter that is used to describe and compare the moisture buffering capacities of different building materials. MBV, defined as the change in mass per square meter per change in RH (g/ΔRH/m^2), is most commonly characterized by a stepwise vapor sorption process—a method that involves a measurement of mass change with discrete increases or decreases in RH over various time steps. MBV is calculated according to the following [29,30]:

$$MBV = \frac{G}{\Delta RH} \quad \text{(Equation 2.1)}$$

where G is the moisture uptake in g/m^2 throughout a prescribed RH cycle.

Figure 1 illustrates the historical evolution of MBV characterization methods. Seminal moisture buffering capacity research was conducted in Germany at the Fraunhofer Institute of Building Physics and at Lund University in Sweden in the late 1960s. By developing the step-response method that is still used to characterize moisture sorption in response to cyclic, time-dependent changes in RH [31], these experiments set the standard for contemporary moisture buffering experimentation. Following these studies, the Padfield method was developed as an alternative to the stepwise model [32]. The Padfield method draws an analogy to thermal capacitance by defining the moisture capacitance of air using the unit of *buf*, which cannot be compared to the more standard MBV unit of g/ΔRH/m^2. The *buf* is reported in meters and refers to the height of 1 m^2 column of air. The higher the moisture capacitance of a material, the higher the *buf* and the greater effective volume of air that can hold moisture. The Padfield method is distinct in that it does not define MBV as an intrinsic material property. The most recent methods that have been developed, including the Japanese Industrial Standard [33], NORDTEST [29], and ISO[34] methods, however, have all used stepwise RH variation as a primary approach to characterize MBV.

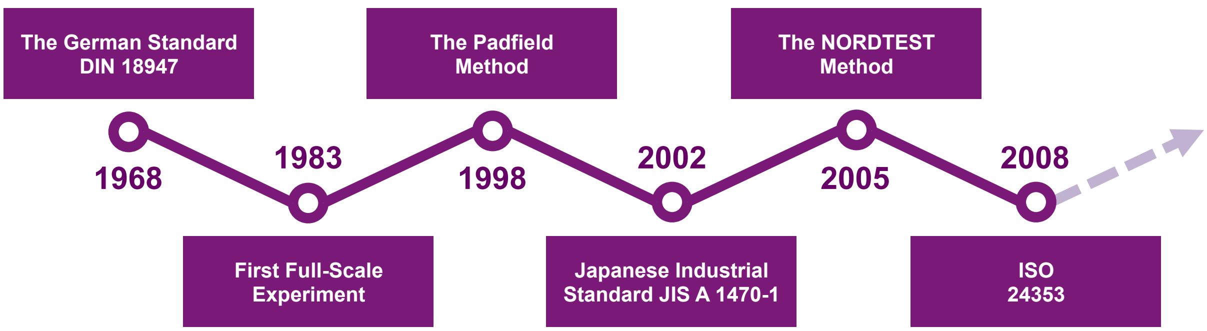


Figure 1. Historical milestones in experimental methods for MBV.

2.2 ***Material- and Building-Scale Experimental Methods for Evaluating MBV***

2.2.1 *The German Standard DIN 18947*

The German-developed standard *DIN 18947* [35], which was developed specifically for characterizing the hygric properties of earthen plasters, is the oldest standard using methods first proposed in 1965 by Kunzel. The prescribed method applies cyclic conditioning of RH between 50% and 80% in 12 hour cycles. Percent-mass changes over that prescribed RH range is used to define moisture buffering capacity. The original German standard has not been widely applied and cited in the literature, as only two of the 188 published experimental tests reviewed in this work employed DIN 18947. However, additional references that were reviewed indicate that this standard has been most often used internally by German industry researchers to characterize and compare hygric performances of different materials [36–38]].

2.2.2 *The Padfield Method*

The Padfield Method, developed by Tim Padfield in 1998, specifically focused on moisture buffering capacity of materials as it relates to historic preservation of buildings [32]. The method prescribes a small, cyclic step-response procedure between 50% and 60% RH. The aim of this method—and what differentiates it from others—is that it quantifies the effect of hygroscopic materials on ambient RH as opposed to the opposite, standard measurement, which quantifies the effect of cyclic RH on changes to material mass. The basic experimental set-up consists of a sealed chamber with a water reservoir and controlled air speed that varies between 0.2-1.2 m/s to ensure adequate mixing. The temperature of the water, adjusted by a thermoelectric heat pump, controls the RH of the sealed chamber. The method assumes that all water lost from the reservoir is absorbed by the test material. While a benefit of this set-up is that any geometry of sample can be tested, one drawback is the water sorption of equipment and air must be corrected in the quantitative analysis to ensure accurate results. As previously discussed, the unit to report moisture buffering was defined as the *buf* in the Padfield method, which cannot be directly compared to MBV [32].

2.2.3 *Japanese Industrial Standard JIS A 1470-1*

Introduced in 2002, the Japanese Industrial Standard (JIS A 1470-1) [33] employs a similar step-response method established by the German Standard DIN 18947. The experimental procedure involves a stepwise preconditioning method that first equilibrates materials at 23 °C and at either 43%, 63%, or 83% RH, prior to a stepwise dynamic conditioning procedure. A minimum sample area of 100 cm^2 is required. Most studies utilize rectangular prism geometries in which all sides except one are sealed with aluminum tape to effectively capture the effects of 1D moisture transport. While similar to the DIN 19847 standard and other methods that followed its development (*e.g.*, NORDTEST), the JIS method is unique. First, there is an equal stepwise cyclic conditioning procedure that involves cycles of 24 hours of high humidity exposure and 24 hours of low humidity exposure. Three cyclic conditioning RH levels are specified: 33% to 53%, 53% to 75%, and 75% to 93% RH. Second, the material surface film resistance (a function of air speed around and geometry of sample) is prescribed as $4.80 \pm 0.48 \times 10^7$ Pa/kg. Third, the material thickness must be equal to the actual, realistic thickness of the product to be tested [38,39], since, as discussed, material thickness can make a significant impact on moisture buffering value [40]. Overall, while this is an established and accepted method, none of the published studies in this review utilized the JIS procedure, as it is not usually referred to in English publications [38].

2.2.4 *The NORDTEST Method*

Since 2005, the NORDTEST Method has been the most popular standard for hygroscopic characterization of materials. The procedure was developed to create a standardized test method that characterized a well-definable and consistent material property. The NORDTEST method established the conventional definition of MBV as it is referred to herein and defined broad categories of MBV from negligible to excellent for commercial comparison of materials (see **Table 1**). During its development, university researchers carried out round-robin MBV tests to evaluate the consistency of experimental protocol across material types. Because results from the round robin tests among universities showed good agreement, the high repeatability and consistency of results propelled the popularity of the NORDTEST method.

Over 70% of the studies reported herein used an official or modified version of the NORDTEST method. The experimental method consists of a 24-hour cyclic RH stepwise variation between 33% RH for 16 hours and 75% RH for 8 hours. A common modification of the NORDTEST method, the *two-bottle method,* was used in research facilities that could not meet the NORDTEST chamber conditioning criteria but used similar principles with slightly different RH values between 50% and 80%. Similar to the JIS method, samples tested using the NORDTEST method must be a minimum of 100 cm^2 of rectangular geometry. However, where the JIS method specifies that the thickness of the sample must be the thickness of the product, the NORDTEST method only states that the sample must have a thickness greater than the calculated theoretical moisture penetration depth (TMPD). This requirement is important, because a study by Roels and Janssen [39] demonstrated through a sensitivity analysis that the main reason for difference in MBV values between JIS and NORDTEST method testing of samples was the sample thickness. For exposure to RH, samples are covered on all but one or two sides with aluminum tape to ensure realistic conditions of exposure to indoor air [29,38]. If two sides are left exposed, the calculated MBV must be divided by two. Samples are generally pre-conditioned at 23 °C and 50% RH until hygroscopic equilibrium by weight is achieved, prior to the test. As mentioned above, the experiment involves cyclic RH variation, which can be achieved using a climate chamber or with salt solutions in sealed chambers. Temperature is held isothermally at 23 °C. As a criterion to stop the test, the NORDTEST and most other methods require a quasi-steady-state equilibrium to be reached in which the change in mass between absorption and desorption steps varies less than a pre-defined threshold [41], since the slope of initial moisture intake is shown to overestimate actual MBV [41]. Additionally, while the NORDTEST method does not specify any ventilation rate for testing, the standard does mention an important inverse relationship between ventilation and MBV and states that the sample surface air speed should be 0.10 ± 0.05 m/s, which corresponds to a surface film resistance of 5.0 x 10^7 m^2-s-Pa/kg [42]. The difference between this value and the 4.8 x 10^7 ± 10% m^2sPa/kg value set forth in the JIS method is important because of the established inverse relationship between surface film resistance and MBV.

Table 1. MBV classification system established by the NORDTEST method [29].

MBV Class	**Minimum Level**	**Maximum Level**
	MBV (g/ΔRH/m^2) 8 hours @ 75% RH and 16 h @ 33% RH	
Negligible	0	0.2
Limited	0.2	0.5
Moderate	0.5	1.0
Good	1.0	2.0
Excellent	2.0	>2.0

2.2.5 *ISO 24353*

The first edition of ISO 24353 [34] was published in 2008 and is based on the JIS method. Similar to the JIS method, samples are prepared with aluminum tape sealing all of the sides except one and must have a minimum surface area of 100 cm^2. Preconditioning occurs at 23 °C and either 43%, 63%, or 83% RH, and step cycles occur over 12 hour periods from 33%-53%, 53%-75%, and 75% -93%. Similar to the JIS, there is no specified method for maintaining RH values, unlike the NORDTEST method that requires a climate chamber or salt solutions. However, these are proven to be the most cost effective and simple experimental setups and used consistently in studies that employ the ISO standard [38]. Given its relatively recent establishment, this method has been rarely utilized and, therefore, scarcely cited in the published studies considered in this review.

2.2.6 *Ultimate Moisture Buffering Value (UMBV)*

UMBV is an adaptation of the NORDTEST MBV [43] that accounts for adverse temperature and humidity conditions that are more representative of four-season climate zones. The high humidity level corresponds to 98% and the low corresponds to 3% with temperatures ranging from 18 to 40 °C. Samples are preconditioned at a standard 23 °C and 50% RH until hygroscopic equilibrium is achieved. Using these parameters, the MBV is calculated and multiplied by a time coefficient, α, determined by the rough frequency of exposure to these conditions in four seasons:

$$UMBV = \sum_{i=I}^{III} \alpha_i MBV_i \quad \text{(Equation 2.2)}$$

where α is the time coefficient, or total hr/day each sample is subjected to the specified RH. The α parameter is simply calculated by t/24 where t varies based on the stage of the UMBV test (see **Table 2**). The resulting equation computes the comprehensive moisture tolerance of the material over three stages that correspond to damp-proofing capability, adsorption, desorption, and instantaneous response capacity, as illustrated in the table below.

Table 2. Summary of UMBV testing conditions.

Stage	Temperature (C)	RH (%)	Time (hr/day)	Practical Application
I	23 ± 0.3	50 ± 0.3	12	Damp-proofing, instantaneous response capacity
II	40 ± 0.3	98 ± 0.3	8	Damp-proofing, adsorption

III	18 ± 0.3	3 ± 0.3	4	Desorption, instantaneous response capacity

2.2.7 *Full-Scale Experimentation*

Despite advances in material-scale characterization, full-scale experimentation is arguably a more accurate method to gather experimental data on moisture buffering capacity or to validate predictive models that quantify energy and environmental benefits of moisture buffering. Intuitively, however, full-scale experiments are more expensive, time-consuming, and rarely reported in the literature. Additionally, completely non-hygroscopic houses do not necessarily exist due to the hygroscopic nature of furnishings and other coating materials [44]. Some full-scale experiments were performed in Holzkirchen, Germany, in which researchers used a large climate chamber to show that moisture buffering capacity of gypsum board could reduce peak humidity up to 44% [31]. Fraunhofer-Institute of Building Physics in Holzkirchen conducted another similar experiment to validate the widely used WUFI software, in which the moisture buffering effects of a reference room covered in aluminum was compared to that a wood-clad test room [45]. Using tracer gases to track ventilation rates and exposed hygroscopic surface area to measure moisture transfer, a test house in Helsinki, Finland, compared a wood-framed home with and without a polyethylene vapor retarder to show 15% RH peak reductions at 27^{o} C, also concluding that material moisture buffering is more effective than increasing ventilation rates from 0.08 to 0.55 ACH [46]. More recently, Shi *et al.* conducted a full-scale experiment to test non-standard building materials by outfitting a typical civil defense shelter in Beijing for field measurements and numerical validation [2]. Allinson and Hall [38] monitored the interior moisture buffering effect of a rammed earth shed. Huibo Zhang *et al.* [45] conducted a moisture buffering experiment under real-world conditions. In a study by Luyang Shi *et al.*, two rooms were set-up within a real home in order to compare a test room to a reference point to evaluate porous ceramic tile, biomass fiber wallpaper, and vermiculite board [46]. Overall, full-scale implementation is a comprehensive practice for eliminating major assumptions and gathering realistic data on the applied moisture buffering effect of a building assembly. However, the drawbacks for space, time, and cost, are significant, which has motivated the industry to develop *in-situ* characterization practices through numerical modeling and material-scale experimentation to define MBV as a material property.

2.3 *Characterization Methods: Key Assumptions*

In addition to employing different experimental approaches to characterize and report MBV, each method makes key assumptions that affect the general applicability of material-scale MBV to building-scale behavior. As discussed in the next section, very few studies go as far as to experimentally measure the moisture buffering effect of materials within building systems [31,38,45,47,48], and no studies that were reviewed experimentally report building-scale application of highly absorbing materials. However, many numerical studies have relied on material-scale characterization of MBV to estimate the effect of moisture buffering on building energy consumption, thus placing high dependence on the MBV experimental methods to adequately capture moisture buffering capacity of different building materials.

The primary assumptions inherent to a majority of MBV experimental methods—and their potential consequences in terms of building-scale applicability of MBVs obtained by these methods—are as follows:

1. *Stepwise changes in RH are representative of RH changes in indoor environments.* The potential energy savings of moisture buffering come from the ability of materials to passively dampen RH peaks. Hygroscopic materials interact dynamically with indoor RH rather than discretely, as assumed by the stepwise methodology. Therefore, given that RH will vary continuously with moisture content of indoor surface materials and not remain constant for a period of time [49], providing a constantly high or low RH environment to test a material may overestimate the MBV.
2. *The method parameters for number of cycles, temperature, and RH sufficiently provide conditions in which equilibrium can be achieved for all materials.* Test methods specify isothermal conditions, relevant RH steps, and a tolerance for mass variations, representative of quasi-steady state equilibrium. However, this does not directly relate to building applications because the material is not always responding with a MBV corresponding to its quasi-equilibrium state. This assumption is

important, because absorption and desorption can differ—and the calculation of overall MBV can differ – from equilibrium values [29].

3. *Sample thickness is larger than its theoretical moisture penetration depth (TMPD).* Theoretical moisture penetration depth is defined as the point at which moisture content variations are only 1% of those on the surface [29]. Most experiments assume that the TMPD is within the sample thickness without substantiating it being so. A study by M. Rahim *et al.* [40], however, illustrated that MBV continued to increase 0.3 g/ΔRH/m^2 when varying the sample thickness from 3 to 7 cm while TMPD was previously calculated at 3.14 cm. This finding indicates that MBV may continue to increase with thickness, regardless of TMPD.
4. *Moisture diffusivity remains constant throughout testing*. Studies assume moisture diffusivity remains constant within the RH range of 30% to 70%, which is approximately within the bounds used in most MBV studies and realistic conditions for building applications. However, moisture diffusivity is well known to be concentration-dependent [50], and the chemistry of different materials can dictate single or multiple mechanisms of moisture transport (*e.g.*, diffusion, sorption, permeation) [50], which will affect the concentration-dependence of its diffusivity. Therefore, given the wide range of responses of materials to moisture, the static diffusivity assumption imparts unknown variability in the definition of MBV as an inherent material property. Deviations beyond the RH range of 30-70% have also been shown to exhibit significant variations in moisture diffusivity depending on RH [51].
5. *Ventilation and airflow across the sample is negligible*. Ventilation is mentioned in various standards (*e.g.* JIS, NORDTEST), yet not considered homogenously across many studies. For example, Colinart *et al.* [50] and Nguyen *et al.* [51] do not mention the effect of airflow in their testing of hemp concrete and bamboo fibers. However, air flow will affect localizes surface RH. The MBV review of earthen materials by Svennberg *et al.* [31] states that lower air change per hour (ACH) rates will yield higher RH levels, which can inevitably affect the definition of MBV by up to 20%. Shi *et al.* [47] confirmed this by measuring ACH with tracer gases to test the effect of five different ventilation rates on MBV and confirmed that they have a significant impact on measured MBV. These findings not

only illustrates the importance of holding ventilation rate constant in determining MBV, but also suggests that differing ventilation rates in real building applications may account for the inconsistencies between material-scale MBV measurements and building-scale moisture buffering behavior.

2.4 *Meta-Analysis of Experimental Data*

2.4.1 MBV Method Frequency

Despite the wide variety of methods previously described, the NORDTEST method remains the most widely applied—and, therefore, the most comparable—method to characterize moisture buffering capacities of building materials. **Figure 2** illustrates the frequency of different methods applied in the studies reviewed herein. As shown in **Figure 2**, the NORDTEST method was most frequently employed (>70% of studies) to measure MBV, while methods “Not Specified” and the UMBV method were the second and third most commonly applied, respectively. Only five studies employed the Padfield Method, which, as discussed, does not utilize the conventional step-response procedure prescribed by the other methods.

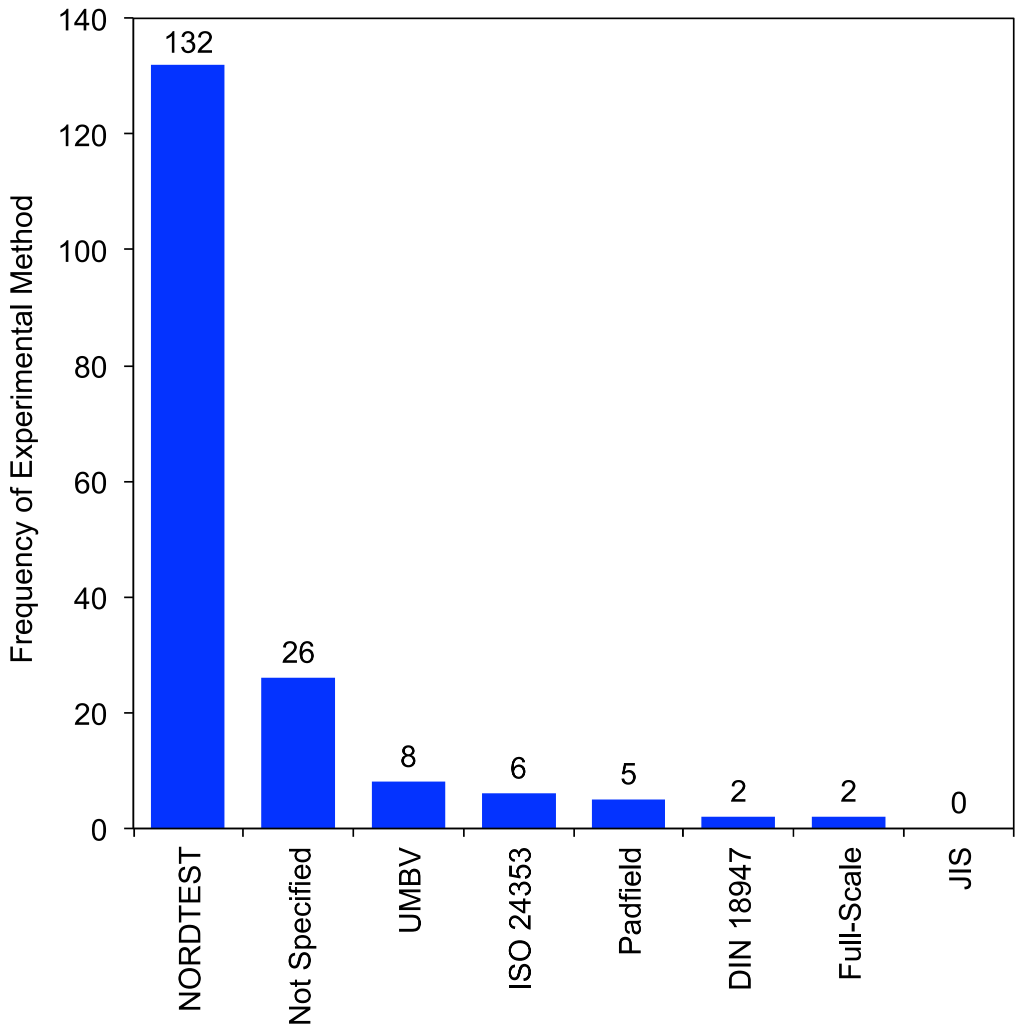


Figure 2. Frequency of methods used to experimentally determine MBV.

2.4.2 MBV Experimental Data

A comprehensive visualization of reported MBVs is shown in **Figure 3**. This chart illustrates how widely MBV varies across individual studies and measurement methods, as well as variation within identical materials and between different materials.

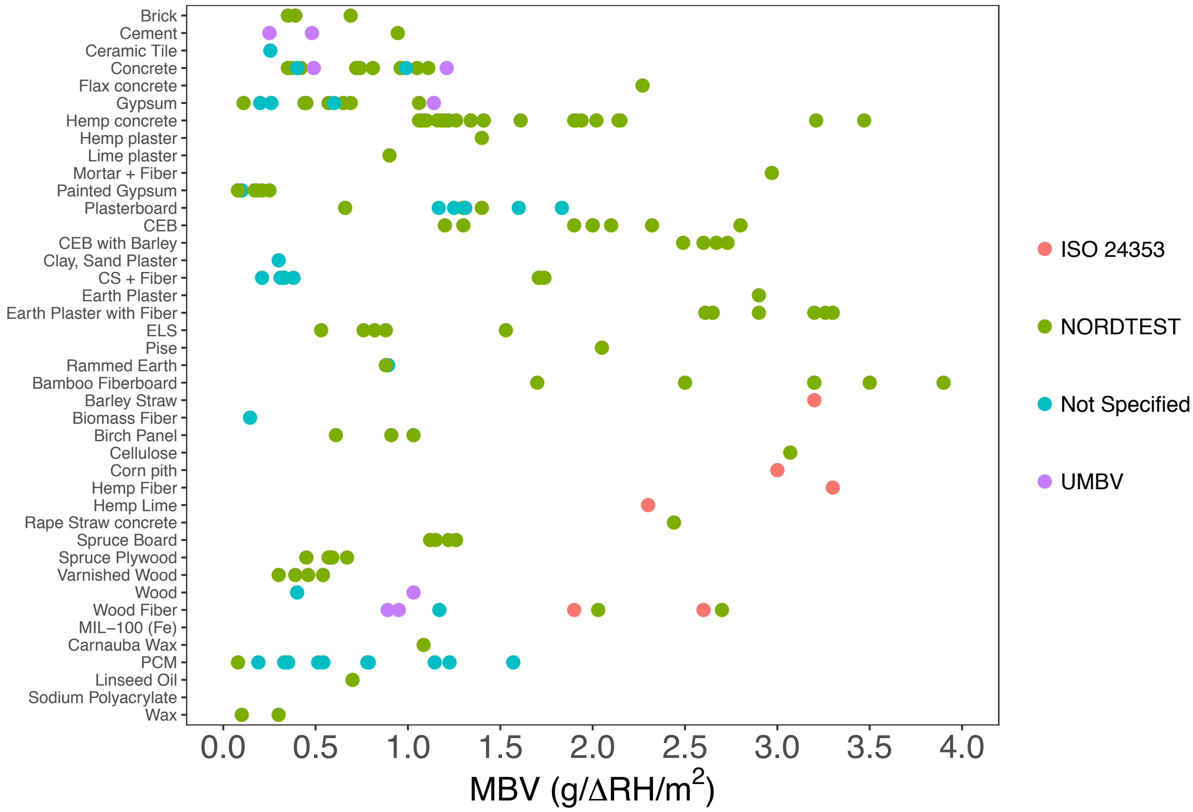


Figure 3. Reported MBV of building materials. CEB = compressed earth block, CS = clay-sand, ELS = engineered local soil, PCM = phase change material [29,30,55–64,40,65–69,42,43,47,48,52–54].

Table 3 reports statistical data for reported MBV, density, porosity, and the method by which MBV was characterized per material reviewed herein. We report different MBVs in **Table 3** for materials that were characterized by different methods.

Table 3. Statistical summary of reported MBV, porosity, and density by material and method. CEB = compressed earth block, CS = clay-sand, ELS = engineered local soil, PCM = phase change material. Note that one standard deviation is used, representing a 67% confidence interval.

Material	*n*	MBV g/ΔRH/m^2	MBV Method	Porosity	Density (kg/m^3)	References
Bamboo Fiberboard	6	3.0 ± 0.79	NORDTEST	N/A	404 ± 85	[53]
Barley Straw	1	3.2	ISO 24353	92%	108	[55]
Birch Panel	3	0.85 ± 0.22	NORDTEST	N/A	600	[29]
Brick	3	0.48 ± 0.19	NORDTEST	N/A	1600	[29]
Carnauba Wax	1	1.1	NORDTEST	N/A	N/A	[58]
CEB	7	1.9 ± 0.54	NORDTEST	N/A	1800	[63]
CEB + Barley Straw	4	2.6 ± 0.10	NORDTEST	N/A	1735 ± 71	[55]
Cellulose	1	3.1	NORDTEST	N/A	N/A	[59]
Cement	2	0.37 ± 0.16	UMBV	N/A	1925 ± 153	[43]
Ceramic	1	0.26	Not Specified	N/A	1740	[70]
	1	0.95	NORDTEST	N/A	1500	[42]
Clay Plaster + Fiber	4	1.7 ± 0.02	NORDTEST	41 ± 2.8%	1544 ± 144	[67]
Clay, Sand Plaster	9	0.31 ± 0.05	Not Specified	N/A	N/A	[56]
Concrete	2	0.85 ± 0.51	UMBV	N/A	1346 ± 1279	[43]
	2	0.70 ± 0.42	Not Specified	N/A	N/A	[71]
	10	0.88 ± 0.56	NORDTEST	70.6%	1335 ± 762	[29,30]
Corn Pith	1	3.0	ISO 24353	98%	48.1	[55]
Earth Plaster	1	2.9	NORDTEST	N/A	1848	[55]
Earth Plaster + Fiber	6	3.0 ± 0.31	NORDTEST	N/A	1362 ± 242	[55]
ELS	5	0.90 ± 0.37	NORDTEST	22.3 ± 2.2%	2076 ± 65	[69]
Fiber Wallpaper	1	0.15	Not Specified	N/A	300	[70]
Gypsum	1	1.1	UMBV	N/A	874	[43]
	4	0.33 ± 0.18	Not Specified	N/A	N/A	[56,61,71]
	10	0.45 ± 0.30	NORDTEST	N/A	977 ± 204	[29,54,59]
Gypsum, Lime Plaster	3	0.14 ± 0.06	NORDTEST	N/A	900	[54]
Hemp Concrete	7	1.89 ± 0.32	NORDTEST	76.4 ± 2.7%	713 ± 645.5	[30,52,64]
Hemp Fiber	1	3.3	ISO 24353	97%	41.1	[65]
Hemp Lime	1	2.3	ISO 24353	83%	286	[65]
Hemp Lime Assembly	19	1.5 ± 0.70	NORDTEST	N/A	610 ± 453	[62]
Laminated Wood	3	0.46 ± 0.08	NORDTEST	N/A	430	[29]
MIL-100 (Fe)	1	15	NORDTEST	N/A	N/A	[68]
Mortar + Fiber	1	3.0	NORDTEST	N/A	N/A	[66]
Painted Gypsum	1	0.33	Not Specified	N/A	N/A	[56]
PCM	1	0.08	NORDTEST	N/A	N/A	[59]
	9	0.81 ± 0.43	Not Specified	80%	793 ± 351	[61,71]
Pise	1	2.1	NORDTEST	24.2%	1870	[57]
Plaster	3	1.1 ± 0.40	NORDTEST	N/A	670	[62,63]
Plywood	1	1.0	UMBV	N/A	N/A	[43]
Rammed Earth	1	0.88	NORDTEST	N/A	1980	[69]
Rape Straw Concrete	1	2.4	NORDTEST	75.1%	1954	[30]
Sand, Lime Plaster	1	0.90	NORDTEST	N/A	1650	[52]
Sodium Polyacrylate	1	9.0	NORDTEST	N/A	N/A	[59]
Spruce Board	4	1.2 ± 0.06	NORDTEST	N/A	430	[29,58]
Spruce Board (sealed)	4	0.35 ± 0.25	NORDTEST	N/A	N/A	[58]
Spruce Plywood	5	0.57 ± 0.08	NORDTEST	N/A	N/A	[29]
Vermiculite Board	1	0.19	Not Specified	N/A	746	[48]
WSE Mortar Assembly	2	0.92 ± 0.04	UMBV	N/A	637 ± 21	[43]
Wood	1	0.4	Not Specified	N/A	N/A	[61]
Wood Fiberboard	1	1.2	Not Specified	N/A	N/A	[71]
	2	2.4 ± 0.47	NORDTEST	N/A	458 ± 4	[62]
Wood Fiber	2	2.3 ± 0.50	ISO 24353	91 ± 7.1%	136 ± 108	[65]

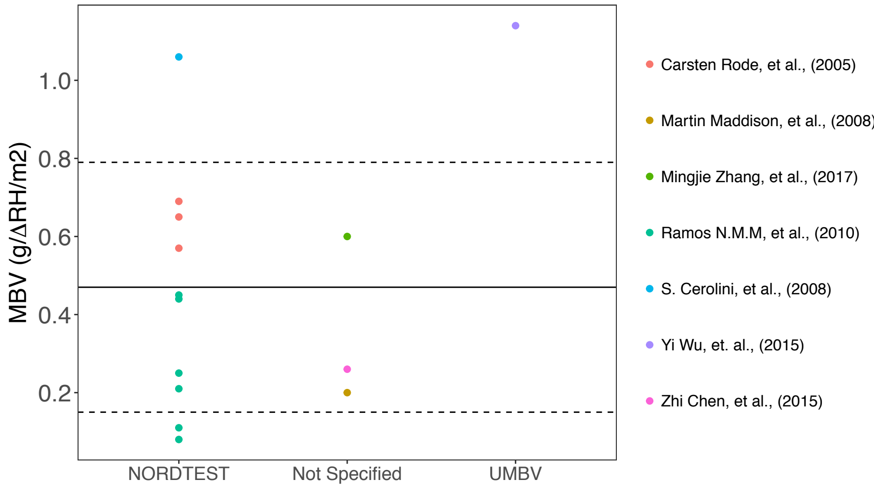
As evidenced by the data presented in **Figure 3** and **Table 3**, high variability exists for the reported values of MBV and other intrinsic material properties. Previous authors have noted that results from hygric experimentation can be significantly affected by differences in the experimental set-up and operator error, while the results can also be affected by other protocol and geometry factors, including number of cycles and sample size [72]. However, some error in results appears inherent to various testing methods regardless of corrections made for minor differences in the experimental set-up. For example, findings from a round robin test with 14 participating laboratories illustrate that sorption isotherm testing is consistent, yet vapor permeability procedures yield significantly different results across labs [73].

Figure 4a-4c highlights the high variability that can arise due to inconsistencies between methods, material heterogeneity, and operator error, respectively. **Figure 4a** depicts variability amongst MBV experimental methods, in which three major methods testing 13 different gypsum board samples were compared. The average across all studies was 0.47 ± 0.32 g/ΔRH/m^2, which represented the largest deviation amongst the three error sources compared. These results are expected because the *method error* also encapsulates *operator error* because seven different studies are compared and no data in which the lab used multiple studies to quantify MBV was available. However, using standard deviation for quantifying error, *method error* still significantly increases the variability of the test even when *operator error* is included.

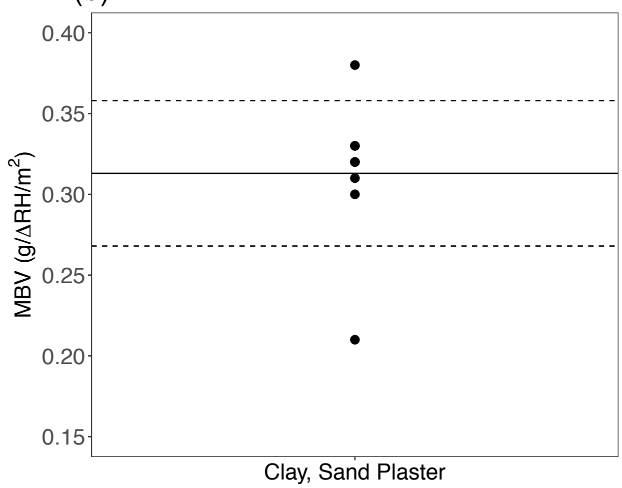
Figure 4b depicts variability throughout a clay and sand plaster material measured multiple times in the same study [56] using the same testing method (in-house climate chamber) to remove any operator or method error. Sample variability resulted in the lowest error with an average of 0.31 ± 0.05 g/ΔRH/m^2. This finding illustrates that there will likely always been an inherent *material heterogeneity error* from physical variability, which can be accentuated by *operator error* and *method error*.

Figure 4c illustrates potential deviations from the mean caused by *operator error*, comparing various spruce board MBV studies from five different universities that all employed the NORDTEST method. The mean MBV obtained was 0.57 ± 0.08 g/ΔRH/m^2 and ranged from 0.67 to 0.45 g/ΔRH/m^2. In these examples, *operator error* is less significant than method consistency, yet more important in terms of variability than *material heterogeneity*. These results agree with findings from previous sensitivity analyses on MBV error factors, which reported that *operator error* is the most significant source of error [72].

(a)


MBV (g/ΔRH/m2)
1.0
0.8
0.6
0.4
0.2
NORDTEST
Not Specified
UMBV
Carsten Rode, et al., (2005)
Martin Maddison, et al., (2008)
Mingjie Zhang, et al., (2017)
Ramos N.M.M, et al., (2010)
S. Cerolini, et al., (2008)
Yi Wu, et. al., (2015)
Zhi Chen, et al., (2015)

(b)


MBV (g/ΔRH/m²)
0.40
0.35
0.30
0.25
0.20
0.15
Clay, Sand Plaster

(c)

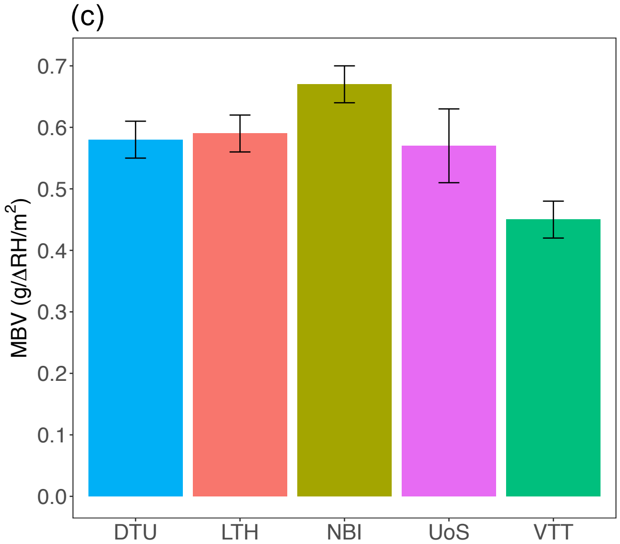

MBV (g/ΔRH/m²)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
DTU
LTH
NBI
UoS
VTT

Figure 4. Variability imparted by **(a) Method:** Gypsum board characterization across different study methods. Dashed lines represent within one standard deviation of the mean (solid line); **(b) Material Heterogeneity:** Variability in MBV of different clay and sand plaster samples. Boundary lines represent one standard deviation of the mean (middle line); **(b) Operator Error:** Spruce Plywood characterization between different testing facilities.

2.4.3 MBV vs. Thickness, Density, and Porosity

The relationship between MBV and thickness, density, and porosity is graphically illustrated in **Figure 5a**, **Figure 5b**, and **Figure 5c**, respectively. As shown in **Figure 5a**, sample thickness did not correlate well with reported MBV. This result was anticipated, given that thickness is an inherent physical property of each sample and directly relates to the total theoretical capacity of that sample to fully absorb moisture throughout the bulk, while MBV is an explicitly characterized surface-dominated capability of materials to passively buffer moisture in the air. A simple least-squares regression shows no relationship between thickness and MBV. This result is most likely due to the fact that most studies are based off of the NORDTEST method which requires a material sample thickness greater than its theoretical moisture penetration depth (TMPD) [29]. However, at least one study shows that moisture sorption capacity can display a linearly increasing relationship with thickness and MBV as thickness is increased past its TMPD [74]. While no argument is made for this correlation, it is hypothesized that moisture, once absorbed by the material, can move into the bulk *via* other transport mechanisms (*i.e.*, capillary action, diffusion). Overall, material thickness is a factor for increasing moisture buffering capacity [74], yet it is not a statistically significant predictor of MBV as shown in **Figure 5a**.

Porosity is an intrinsic material property that is well known to relate to the physical capacity of materials to absorb moisture [29]. As illustrated in **Figure 5b**, a more significant relationship is evident between measured sample porosity and MBV ($R^2 = 0.46$). This result is expected, given that higher porosity indicates a higher propensity for water vapor to not only interact with the material (*i.e.*, increased surface area), but also potentially condense and remain in the void space. While we observed very strong correlations to material densities and porosities reported in the literature (**Figure 5d**), no statistically significant relationship between density and MBV was observed (**Figure 5c**) ($R^2 = 0.02$). No relationship here was expected, given that some materials, like zeolites [60] or perlite [59], may exhibit ultra-high porosities (therefore low density) and, simultaneously, a poor ability to buffer moisture. A Pearson correlation confirmed that porosity is, in fact, the only physical material property significantly correlated with MBV at a statistical significance worth considering (see **Table 4**).

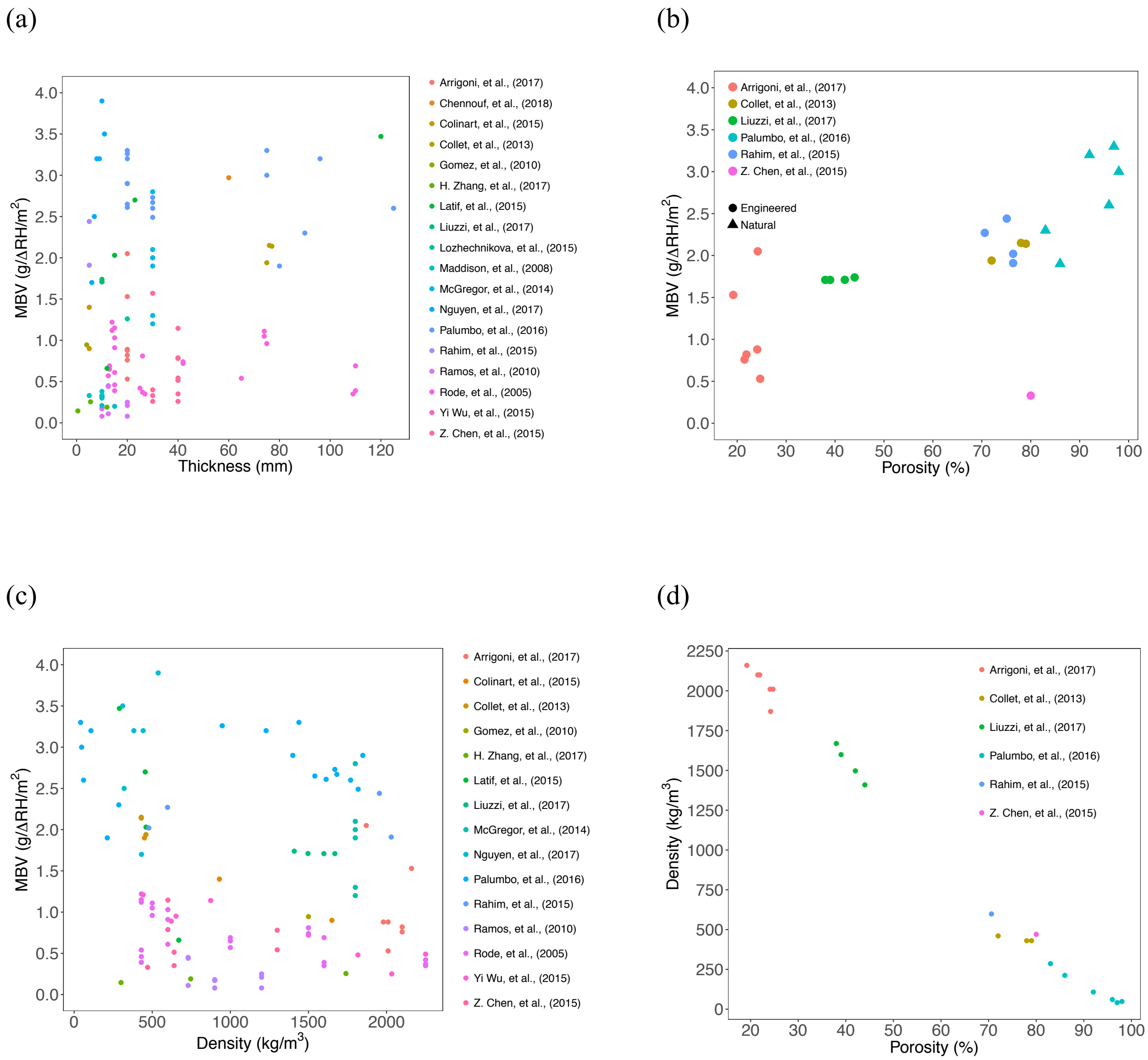


Figure 5. Reported MBV plotted versus (a) sample thickness, (b) porosity, and (c) density. Panel (d) illustrates the inverse relationship between sample porosity and density.

Table 4. Pearson correlation values and associated statistical significance.

		MBV ($g/\Delta RH/m^2$)	Thickness (mm)	Density (kg/m^3)
Thickness	Pearson	0.040	-	-
	P-value	0.738	-	-
Density	Pearson	-0.203	-0.075	-
	P-value	0.090	0.541	-
Porosity	Pearson	0.745	0.512	-0.741
	P-value	0.001	0.051	0.001

2.4.4 Other Reported Properties

All material characterization studies investigated in this review report other material properties that were characterized in tandem with MBV. These material properties can be grouped into two main categories: (1) intrinsic physical properties (*i.e.*, thickness, density, and porosity) or (2) RH-dependent material properties. A summary of all reported material properties—and their respective classification—are reported in **Table 5**.

As shown in **Figure 5**, MBV is difficult to correlate to certain intrinsic material properties (*i.e.*, thickness, density) and, as elucidated through this meta-analysis, even more difficult to correlate to the other RH-dependent material properties listed in **Table 5**. In the reviewed studies, properties that depend on RH (*e.g.,* vapor permeability, moisture diffusivity, moisture capacity) are discussed in their contribution to overall moisture buffering effect and theoretical moisture buffering values. However, we do not attempt herein to relate MBV to these other properties due to the lack of reporting and, for those that are reported, the wide variation of the RH conditions used for their characterization.

Table 5. Summary of hygrothermal material properties

Property	Units	Description
Intrinsic Material Properties		
Sample Thickness	mm	Material sample property generally defined by study parameters.
Density	kg/m^3	Measure of compactness that directly relates to porosity and therefore available space for water sorption.
Porosity	%	Measure of voids in a material and directly related to theoretical absorption capacity of a material. The arrangement and size of these pores affect sorption and desorption mechanisms.
Thermal Conductivity	$\frac{W}{m \cdot K}$	Ability of a material to conduct heat; changes with moisture content and is therefore RH dependent.
RH-Dependent Material Properties		
Moisture Capacity	$\frac{kg_{water}}{kg_{material}}$	Capacity of water that can be held within the pore spaces of a material; determined from the slope of the sorption isotherm.
Water Vapor Permeability	$\frac{kg}{m \cdot s \cdot Pa}$	Time- and vapor-pressure dependent value that describes the resistance of a material to transport vapor.
Moisture Diffusivity	$\frac{m^2}{s}$	Rate at which moisture diffuses into a specific material; dependent on vapor pressure from ambient RH.
Moisture Penetration Depth	mm	Often defined as the thickness at which the moisture content variation is only 1% that of the surface; dependent on vapor pressure from ambient RH.

These results, and those from the preceding meta-analysis, indicate that high porosity, in combination with hydrophilic chemistries of natural materials, are ideal physicochemical characteristics that lead to a high MBV. The conclusion is supported by the porosity-MBV relationship illustrated in **Figure 5b**, in which natural, highly porous materials exhibit excellent moisture buffering capacities. As explicated toward the end of this review, findings such as these have accelerated interest in capitalizing on the inherent moisture buffering properties of natural materials in the development of innovative, ultra-high moisture buffering materials and composites thereof.

3.0 Review of Computational Methods

3.1 *Modeling Methods*

3.1.1 *Method Introduction*

In addition to experimental measurements, theoretical models for simulating moisture buffering and predicting their effects at the material and building scale have been formulated and implemented in the literature. These models can be classified as empirical, semi-empirical, and physics-based methods. Empirical methods are phenomenological in their exclusive use of experimental values to inform their formulation. Physics-based models, like coupled heat and moisture transfer (HAMT) models, stem from fundamental physical equations and rely on experimental data solely for validation purposes. Semi-empirical methods combine elements of both empirical and physics-based models. The classification is analogous to the more historical categorization of modeling methods as white box (empirical), grey box (semi-empirical), and black box (physics-based) approaches [75]. Ultimately, these categories help to better understand to what extent the model is being informed by experimental data or fundamentally derived equations and are helpful to consider in the validation and evaluation of these models. Due to a lack of large-scale experimental data and difficulty in even obtaining assembly- or building-scale data, recent models focus on physics-based approaches—an approach that is computationally limiting when the models are scaled in size, resolution, and complexity. We argue that, for the field to advance, a balance must be achieved between these "white box" and "black box" models to result in validated, productive simulation results for modeling the effects of moisture buffering in residential and commercial buildings.

3.1.2 *Empirical Methods*

Empirical methods employed in the literature most often take simplified building models that may or may not include the moisture buffering effects of hygroscopic materials and use a correction factor, additional equations, or experimentally derived coefficients to account for an assumption that holds true in realistic and universal conditions. In effect, this approach calibrates the numerical model to represent practical MBV effects that are necessary for model validation. For example, in one study, researchers reformulated the problem to find a theoretical correction factor. The correction factor was motivated by the fact that

RH variations are not idealized square wave functions in realistic conditions as they are in the MBV characterization experiments [71]. The researchers model RH variation as a quasi-harmonic function and compute a correction factor and subsequent equations for moisture uptake [71]:

$$G_{in} = G_{out} = \beta * MBV_{basic}(H - L) \quad \text{(Equation 3.1)}$$

where MBV_{basic} is consistent with the NORDTEST ideal MBV definition and H and L are the high and low RH levels, respectively. G_{in} is moisture uptake and G_{out} as moisture release, both in kg/m^2.

Equation 3.2 defines the factor β used in **Equation 3.1:**

$$\beta = 0.888 * \frac{[\alpha(1-\alpha)]^{-0.035}}{\sqrt{\alpha}+\sqrt{1-\alpha}} \quad \text{(Equation 3.2)}$$

where α is a unitless time constant derived from high and low RH cycle times. After determining the correction factor, researchers tested the results against a tested and validated hygrothermal model and found good agreement (<3% relative error) [71].

Another strategy based solely on empirical methods is the effective capacitance model in which ambient air capacity is increased to account for the properties of hygroscopic building materials. The effective capacitance method can be within 18% error of a more advanced, computationally expensive software when it comes to component level moisture buffering effect; accurately predicting full-building RH buffering well and less-accurately predicting sudden moisture loadings [76]. Analysis of results displays an influence of hygrothermal materials on zone RH, yet little influence on overall heating and cooling demand [76]. This strategy also relies completely on the assumption that the interior space contains well-mixed air with uniform properties—an assumption that reduces computation time and simplifies the model significantly because an entire air volume of a zone can be represented as a single node where values can be extracted as averages. To improve results without losing simplicity and time, researchers coupled computational fluid dynamics (CFD) and effective penetration depth (EPD) models based on experimental data can calculate localized surface transfer coefficients for the hygric properties of simulated building walls. Adding these coefficient values to the well-mixed model successfully improved the results in cases that the surface transfer coefficient was stable and physically relevant [77].

In summary, the goal of the aforementioned empirical methods is to use experimental data to either create a model or improve the accuracy of a model without having to eliminate its driving assumptions. However, the primary drawback of this approach—and why it is limited in its application—is that empirical data are situational and assembly-specific, especially with a phenomenon like moisture buffering, which is highly driven by geometric factors.

3.1.3 *Semi-Empirical Methods*

Semi-empirical models combine physics-based and empirical methods to create a model that is rooted in derived equations and gleans additional accuracy from inputs from experimental data. Ideally, these methods also combine the efficient, *in situ*, and widespread applicability benefits of physics-based modeling with experimental data to improve accuracy and computational speed. In one example of a semi-empirical model that was employed in the literature reviewed herein, researchers used a lumped model based on effective moisture penetration depth (EMPD) that linked practical MBV to the ideal MBV as a function of moisture effusivity, RH, and air-film resistance [51]. This method uses an equation-based theory in tandem with empirical data of material properties and environmental conditions to inform the model. Using the room vapor balance and a model benchmark (discussed in further sections), the model showed between 1.5% and 50% absolute error depending on material property and material type. For practical MBV, between 7.7% and 44% absolute error was observed, depending on the material. Although large, these results performed better than the pure empirical model. Furthermore, the errors from these types models can be explained better by the quality of model inputs.

For determining quality inputs for a more robust semi-empirical model, an empirical method was developed by Woods *et al.* to extract data by subjecting the materials to square-wave RH profiles and, after validation, showed that the EMPD model can predict RH distributions [78]. In 2018, Woods and Winkler looked at the sensitivity of model inputs for a two-layer EMPD model for determining moisture buffering [79,80]. The two-layer model focuses on short- and long-term buffering layers and assumes cyclic RH variations, resulting in a mass-based moisture buffering determination. A sensitivity analysis showed that the deep material layer, often ignored, is an important consideration in the calculations [81].

However, given the difficulty of gathering data at this material layer, using the combination of experimental data-based surface inputs with physics-based equations for deep-layer moisture transport can be an efficient method for modeling hygrothermal behavior.

3.1.4 *Physics-Based Methods*

Physics-based methods are rooted in fundamental equations that are used to model physical phenomena. These models can quickly increase in complexity (and, therefore, computational expense) as the physical problems become more difficult (*e.g.,* coupled heat and moisture transfer). However, a comprehensive physics-based model can be easily modified to fit a variety of geometries and materials, while experimentally gathered data for empirical models are time-consuming and expensive to modify.

In formulating moisture uptake for numerical modeling purposes, often, Fick's law is used [82].

$$g = -\delta_p\left(\frac{\vartheta p}{\vartheta x}\right) \qquad \text{(Equation 3.3)}$$

where moisture flux, g (kg/m^2-s) is related to water vapor permeability, δ_p [kg/m-s-Pa], and the change of water vapor pressure p [Pa] through a thickness *x* [mm]. As the water vapor pressure changes on the surface of the material (assuming a semi-infinite body, given that thickness is greater than theoretical moisture penetration depth), a vapor flow (moisture diffusion) is induced, and overall moisture content will increase (absorption) or decrease (desorption) over time.

For total moisture uptake, from which the theoretical MBV can be calculated, the moisture flux is integrated, and the water vapor permeability is replaced with b_m [kg/m^2-Pa-s$^{0.5}$], a term that represents surface moisture exchange:

$$G = b_m\, \Delta p\; h(\alpha)\sqrt{\frac{t_p}{\pi}} \qquad \text{(Equation 3.4)}$$

Here, t_p is the moisture interaction time period in seconds, p is vapor pressure in Pa, and α is the fraction of time period where humidity is high, so for the 8/16 hour scheme used in the NORDTEST method, $h(\alpha) = h\left(\frac{1}{3}\right) = 1.007$ because the procedure calls for *high* humidity one-third of the time. This calculation results in a simplified version of the equation that is only applicable in the 8/16 hour scheme [29].

Drawing an analogy to heat transfer, using the moisture flux and total moisture uptake over a certain time period, the moisture effusivity of a material can be defined using a Fourier series to approximate the moisture exchange for a semi-infinite body subjected to a square wave form of moisture variation at the surface. The total moisture uptake G [kg/m^2] from high to low over the time period yields the following equation that is dependent on the ratio of time the material is exposed to the *high* humidity condition [41,83].

$$h(\alpha) \approx 2.252[\alpha(1-\alpha)]^{0.535} \quad \text{(Equation 3.5)}$$

$$G \approx 0.568\, b_m\, \Delta p \sqrt{t_p} \quad \text{(Equation 3.6)}$$

Most studies recognize that, although more simplified, isolating the heat transfer and moisture transfer problems does not accurately describe the behavior of *either* phenomena due to the significant relationships between heat and moisture transport and the material properties that govern the behavior [84]. Therefore, the coupled heat, air, and moisture transfer (HAMT) strategy for hygrothermal modeling remains the prevailing, most accurate method to estimate building energy demands because it simultaneously solves equations for temperature, RH, and vapor pressure using a purely physics-based approach. A scale analysis of governing heat and moisture transfer mechanisms for hemp concrete, for example, shows that, for up to 95% RH levels, these equations are significantly coupled, and the main driver behind moisture movement in the material is the temperature gradient [85]. Above 95% RH (which is albeit unlikely to occur in a building thermal comfort context), liquid transfer and latent heat from phase changes become more significant [85]. Furthermore, a 10% increase in wood moisture content can result in 30% increases in thermal storage capacity due to the high specific heat of water [86]. However, it must be noted that heat and moisture transfer will occur on different time scales, as moisture transfer mechanisms are generally slower than heat transfer, making the computational process even more complex [86]. Overall, to be most accurate, the building energy modeling methodology must consider the significantly coupled effects of heat and moisture transfer through a building envelope, as well as the timescales in which they will interact with mechanical equipment and building loads.

While heat flux and coupled HAMT through materials have been more extensively studied and modeled in recent years, the direction of the field continues toward eliminating simplifying assumptions to model more accurately the physical interactions in building-scale applications (*e.g.,* moisture transfer through porous media [87]). To accurately model HAMT through a building envelope and to capture the moisture buffering effect of different interior surface materials, the physical phenomena that each numerical method is modeling (and associated limitations) must be well understood. During the moisture sorption process, for example, water vapor can be transported into porous materials due to vapor pressure differentials and has the capability of condensing with the pores, then moving through the material *via* other mechanisms, such as capillary action. Condensed water also has a propensity to evaporate under certain conditions (*e.g.,* air velocity across a surface [88]). Additionally, moisture concentration and temperature do not stay uniform throughout the entire space, so surface variation and discretized time and space must be thoughtfully considered [89]. As a result, best exemplified in a numerical study of earth-based material validated with experimental data, a hygrothermal model that considers coupled HAMT, pore water pressure, and water phase changes can yield accurately model hygrothermal behavior [90]. Additionally, the researchers used this validated model to evaluate the sensitivity of common modeling assumptions for earth-based material. The authors found it important to consider the impact of temperature on moisture flux and in-pore vapor mass condensation and evaporation. However, for low water permeability materials, simplifying assumptions can be made with high enough accuracy [90].

The last major consideration that was elucidated by this review was the importance of hysteretic effects, namely the difference in sorption and desorption isotherms, which are have emerged as important sorption characteristics to consider when capturing actual hygrothermal behavior. However, only one study that was reviewed included hysteresis in the modeling methodology. Hysteretic effects (although computationally more expensive) yield better correlation to actual building-scale behavior [91].

When modeling the moisture buffering effect of materials in buildings, 24 hour cycles are generally needed before all components can be assumed to have reached steady-state equilibrium [91]. Overall, hygrothermal models can become complex, computationally expensive, and potentially impossible to converge on a solution with user-defined acceptable relative error in this time span due to a variety of inter-related properties. In order to simplify and utilize these models, future development will need to consider the scope regarding accuracy and time-scale for the built environment, in order inform change when compared to traditional construction practices.

3.2 *Numerical Benchmarks*

Given the multitude of different numerical HAMT modeling approaches that have been introduced to the field in recent years, numerical benchmarks based off experimental datasets have been developed to test the accuracy of emerging software. During the IEA ECBCS Annex 41, an international collaborative project to further develop modeling of HAMT, a set of common exercises were developed to test each software [92]. Additional published test cases are available for researchers, such as the benchmark exercises from the European HAMSTAD project, to test the accuracy of their methods. These benchmarking exercises are presented in the HAMSTAD report from 2002 [93] and are used in a study by F. Tariku *et al.* [87] to validate their transient model for coupled HAMT by comparing their model results to analytical results. Judkoff and Neymark go further to recommend that three classifications of test cases should be used for model validation. These cases must include (1) an analytical verification, (2) model comparison, and (3) experimental validation [94]. In addition, Judkoff and Neymark [94] [95] have developed and continuously update [95] the NREL BESTEST base case building developed in IEA ECBCS Annex 21, which has been used to validate models from Rode *et al.* [83], Zhang *et al.* [71], Abadie *et al.* [51], Feng *et al.* [68], and software developed for the IEA Annex 41.

3.3 *Summary of Computational Methods*

Hygrothermal behavior is important to consider in developing more accurate building energy simulation models. Numerical simulation tools enable a relatively fast and low-cost solution to quantify building-scale benefits of materials that exhibit moisture-buffering effects and to predict and mitigate potential moisture accumulation in the building envelope. For example, the ability to predict mold growth potential is an extremely valuable tool compared to costly repairs. Solutions to this particular problem are explored with WUFI-Bio [96], but the concept applies further to numerically predicting condensation in structural layers and reducing ventilation rates based off of feedback from RH sensors.

IEA Annex 41 explored the development of 17 different simulation tools contributed by 39 institutions in 19 countries, and researchers agreed that it is necessary to model the impact of moisture to ensure accurate whole building energy simulation results [89]. The consensus made by top researchers provides further motivation for the continued development of faster, more accurate modeling tools.

In summary, various modeling methods categorized as *empirical*, *semi-empirical*, and *physics-based* have been used to model moisture buffering behavior in buildings. Each method has inherent tradeoffs in accuracy, efficiency, and expense, but progress will entail combining and refining these methods, such as coupling with CFD software to tie together material-scale and building-scale zone interactions [70] or evolutionary strategies with multi-objective searching capabilities [97]. Using advanced numerical tools in tandem with comprehensive, coupled models of HAMT, and a solid understanding of the physical processes at the building-scale and a need to verify and validate computational approaches with benchmark standards, numerical simulation remains a powerful tool that will continue to be exploited to quantify moisture buffering effects on building energy consumption.

4.0 Research Trends and Future Developments

4.1 *Emerging and Growing Importance of MBV*

The results from this meta-analysis indicate not only a growing interest in understanding and characterizing moisture buffering, but also a consensus on the importance of considering moisture buffering effects in building design and operation. As illustrated in **Figure 6**, 75% of all studies that report the MBV of conventional and innovative building materials were published after 2012. The data in **Figure 6** also suggest that a wider variety of materials are being analyzed and studied with respect to their moisture buffering behavior.

It is anticipated that additional MBV characterization studies—especially studies that investigate the MBV of non-conventional building materials—will remain a primary interest (and need) of the field. Currently, state-of-the-art energy-efficient building design emphasizes tight, well-insulated, high-performing envelopes. The importance of ensuring indoor air quality and proper moisture management has grown in proportion to implementing energy-efficient envelope strategies. Tight envelopes reduce infiltration from outside air, frequently necessitating ventilation strategies to ensure sufficient quality of indoor air. Leveraging moisture buffering—and perhaps designing and exploiting the multifunctional potential (*e.g.,* VOC removal) of innovative, high-MBV materials—would alleviate the frequency of air exchanges in buildings. In addition, failures of these high-performance envelopes from mold or water damage are costly. Therefore, managing moisture and preventing damage due to moisture accumulation has grown in significance, especially in cold climates that require mandatory vapor retardation and where moisture swings are large due to significant heating and time spent indoors during the winter months [98].

Given that emerging estimates of energy savings from passive moisture buffering effects have been positive (and non-trivial), it is anticipated that accounting for moisture buffering effects in building design and operation will become more established convention. As more buildings implement building automation systems (BAS), it will be both less expensive and more feasible to include RH-sensing HVAC systems that account for the thermal conductivity and RH variations that occur within hygrothermal materials and assemblies. By combining building energy models with new, innovative materials that exhibit exceptional moisture buffering capacity, additional, passive reductions in building energy consumption could be realized. Studies with hemp-lime materials, for example, show a 5-30% cooling load reduction when using BIM to inform HVAC systems [62]. Similarly, RH-sensing ventilation systems were shown to reduce ventilation 30-40% and energy consumption 12-17% during cooling seasons [7]. In addition, full-scale wall assemblies with various building materials (*e.g.,* concrete, wood studs, hemp-lime) materials were explicitly studied to evaluate hygrothermal effects on energy consumption. Results show that these materials can potentially reduce energy use an average of 15% [4] and, depending on the climate, up to 30% [71].

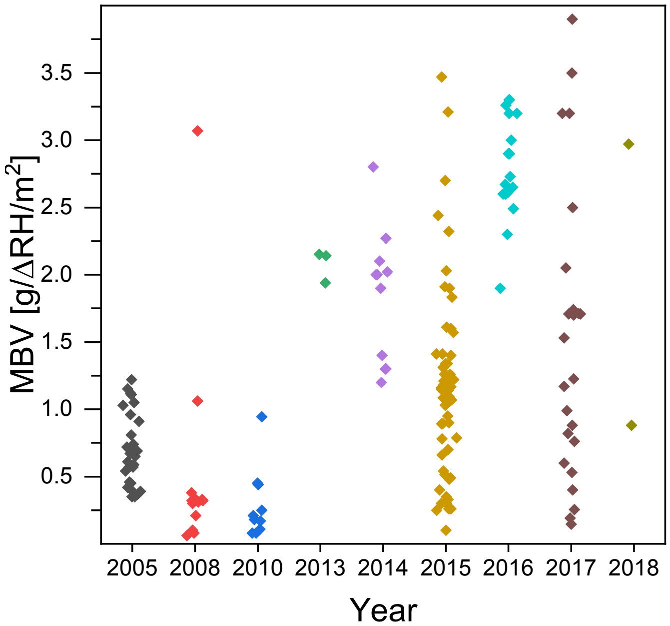


Figure 6. Recent studies that characterize and report MBV.

4.2 *Innovative Materials*

The results from this review indicate that best-performing hygroscopic materials for moisture buffering must exhibit high moisture uptake capacities as well as low desorption temperatures. Studies show that certain materials—especially natural materials—can exhibit over 30 times the MBV of standard building materials (*e.g.*, gypsum, plywood, concrete, plasters) [68], and this increase can impart significant savings in cost and energy to building operation when passive dehumidification through moisture buffering effects are considered. We find that most natural materials have moisture buffering effects in the *excellent* range (see **Table 6**). However, one main drawback is that their variability is higher—expectedly, engineered materials have a more statistically consistent MBV. Earth plasters with the addition of natural fibers and hempcrete mixes exhibit high moisture buffering values while not deviating to far from commonly accepted construction materials. Some more holistic, natural surface finishing products, however, such as natural wax coatings that display high MBVs, can be a cost-effective retrofit to improve the moisture buffering effects of existing buildings.

Novel synthetic materials, like superabsorbent hydrogels, are a promising class of materials that may be engineered to exhibit hyperactive moisture buffering behavior. Superabsorbent polymers (SAPs) are crosslinked networks of ultra-hydrophilic polymers that can absorb up to 100,000% of their dry weight in aqueous solutions [99]. The ability of the polymer to absorb fluids is attributed to the abundance of hydrophilic functional groups present on the polymer backbone, while the crosslinks in SAP networks render the polymer insoluble [100,101]. Commonplace SAPs have been synthesized using ionic acrylate/acrylamide homopolymers and biopolymers, such as alginates, celluloses, and carrageenans [102]. Theoretically, these SAPs can boost moisture buffering with much less surface area compared to other natural or synthetic materials. However, it must be noted that the ultra-high moisture affinity of SAPs may impart slower desorption, which may reduce the ability to buffer moisture when exposed to cycles of high and low RH. This phenomenon also makes some superabsorbent products, like common desiccants, non-ideal as moisture buffering materials [68].

As illustrated in **Table 6**, this review elucidated an increased interest in testing more innovative materials. **Table 6** lists the MBV of innovative materials and categorizes their moisture buffering behavior according to a *negligible*, *limited*, *good*, and *excellent* scale. New materials range from new composites made from traditional building materials (*e.g.*, clay and mortar plasters) with fiber reinforcement to highly absorbent SAP materials (*i.e.*, sodium polyacrylate). Although MIL-100, a metal organic framework, and sodium polyacrylate, a commercial SAP, do exhibit high moisture buffering values of 15 g/ΔRH/m^2 and 9 g/ΔRH/m^2 respectively, they are not yet commonly used as building materials and may not prove cost-effective or viable for achieve adequate interior surface finishes [59,68].

As expected, the MBVs of these new materials vary significantly. On one hand, studies of the carnauba wax particle, a natural, hydrophilic material that traps water on its rough surface, show it can boost MBV of traditional lacquered spruce board from 0.3 g/ΔRH/m^2 to 1.1 g/ΔRH/m^2 [58]. On the other hand, adding wetland phytomass in the form of typha or wool chips does not necessarily improve the MBV above the 0.3 g/ΔRH/m^2 value baseline of plain clay plaster [56], yet while adding olive fibers can increase the MBV to a value of 1.7 g/ΔRH/m^2 [67]. An improvement in MBV is expected, given the moisture affinity of natural fibers, as previously discussed, but this result is not always the case.

In fact, **Figure 7** shows that on average, natural materials have higher moisture buffering effects (1.75 g/ΔRH/m^2) than abiotic materials (1.075 g/ΔRH/m^2). In distinguishing abiotic versus biotic materials; wood, organic fibers, starches, earth and clay plasters, and plant derivatives were considered biotic materials. Concretes, bricks, and gypsum, and other inorganics were considered abiotic materials, and any combination, including finish coatings (paints and lacquers) were viewed as a hybrid. With a 63% increase in MBV on average when using natural, bio-based materials, exploration of more organic materials will likely be the focus of future moisture buffering studies.

Table 6. Summary of MBVs for non-conventional, innovative building materials.

CSP = Clay, Sand, Plaster.

Material	MBV [g/ΔRH/m^2]	Performance Category	Reference
CSP + 2 wt% Typha Wool	0.32	Limited	[56]
CSP + 2 wt% Typha Chips	0.32	Limited	[56]
CSP + 1 wt% Typha Wool and 0.5 wt% Chips	0.38	Limited	[56]
Carnauba Wax	1.085	Good	[58]
Linseed Oil	0.7	Moderate	[58]
Thick Wax Film	0.1	Negligible	[58]
Sodium Polyacrylate	8.97	Excellent	[59]
Cellulose	3.07	Excellent	[59]
Bamboo Fiberboard	1.7	Good	[53]
Bamboo Fiberboard (70%) and Bone Glue (30%)	3.2	Excellent	[53]
Bamboo (70%) and Sodium Lignosulfonate (30%)	3.5	Excellent	[53]
Rape-Straw-Lime Concrete	2.44	Excellent	[30]
Flax-Lime Concrete	2.27	Excellent	[30]
Hemp-Lime Concrete	2.02	Excellent	[30]
Mortar + Date Palm Fiber	2.97	Excellent	[66]
Clay Plaster + Olive Fibers	1.739	Good	[67]
MIL-100 (Fe)	15	Excellent	[68]

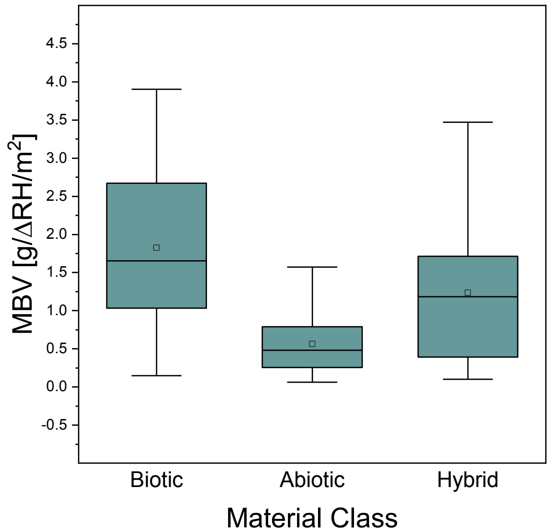


Figure 7. Comparison between biotic, hybrid, and abiotic material moisture buffering effects.

Given the high MBVs of biotic materials, living organisms are another emerging category of highly innovative materials that may find application in buildings as moisture buffers. While plants provide carbon dioxide (CO_2) and aesthetic benefit to indoor environmental quality, plants also evapotranspire and are well known to add high humidity loads to the air [9,103–107]. Other benign living organisms, such as lichen or moss, may have a potential to serve a moisture buffering—and perhaps many other—beneficial functions to indoor environments. Such beneficial functions beyond moisture buffering could include carbon storage and sequestration, aesthetics, occupant comfort, improved indoor air quality (*e.g.*, VOC sequestration) and an ability to indicate toxic levels of environmental pollutants [108].

As one example, lichens possess exceptional moisture absorptive properties and abilities to sequester CO_2 and trap harmful pollutants. Lichen are not plants but rather a symbiotic organism comprised of fungi and algae and/or cyanobacteria. Since lichen are not plants, they do not evapotranspire nor impart excess water to the air that can increase the moisture load and contribute to more health problems and mold potential. Regarding moisture capacity, cyanobacteria-based gel lichens are able to absorb 2000% water compared to their dry weight [109,110]. These indoor water sorption properties are especially useful in cold climates where increased time spent indoors leads to higher moisture loads. In addition to potential moisture sorption properties, lichens are known for their interaction with airborne pollutants. Studies show that lichen are the best accumulator of polyaromatic hydrocarbons (PAHs) that are detrimental to indoor air quality and found in high concentrations during wet winter conditions [111]. Because of this, the extraction of metals and organic pollutants in lichen show that it can serve as a bio-indicator of pollutant concentrations that directly related to indoor environmental quality. Furthermore, a specific study of the species *Ramalina maciformis* also shows photosynthesis will increase with increasing water content, thereby increasing the uptake of CO_2 [112]. It must be noted, however, that, at a certain maximum water content, CO_2 uptake is inhibited, but these levels are not representative of indoor RH but of those found in heavy rain [111].

While true application of living materials may be more than a decade away, the majority of new materials that are emerging in the field include composite formulations of natural, hydrophilic materials, such as olive fibers, rape straw, date palm fibers, flax, and hemp, with inorganic matrices, like earthen clay plasters. However, more innovative materials, such as bamboo and wax particles, have yielded MBVs in the *excellent* range and will likely garner more attention in future studies.

4.3 *Advances in Building Energy Modeling*

In 2008, the IEA ECBCS Annex 41 identified the major problems yet to be solved in modeling heat, air, and moisture transfer [113]. The final remarks emphasized (1) establishing a balance between physical phenomena, (2) incorporating multi-dimensional and/or transient affects, and (2) using distributed calculations for computational efficiency. From 2008 to the present, advances have been made to address some of these significant problems, while some remain to be solved in relation to moisture buffering.

Balancing physical phenomena (*i.e.,* heat, air, and moisture) has been addressed in multiple ways by coupling software [77] and simultaneously solving heat and moisture transfer equations [90]. Coupled computational fluid dynamics (CFD) software with numerical models for solving heat and moisture transfer can now connect building elements with indoor space [113], whereas previous models made the common assumption that interior spaces act as one well-mixed zone. The well-mixed zone assumption, while physically inaccurate, has be improved with CFD [77], thereby balancing physical phenomena instead of focusing specifically on building element interactions with heat and moisture.

Incorporating multi-dimensional and transient effects can now be considered, but these effects are not always included due to precedent and computational expense. Models can incorporate multi-dimensional heat transfer and extend heat flux to a moisture flux analogy to include multi-dimensional moisture transfer effects through building envelopes [114]. However, transient effects (*e.g.,* transient material properties, increased moisture loads in the first two years of construction) are not often considered. This current omission should be evaluated in the future for its importance, as moisture cycling is well-known to degrade materials. In addition, many other factors, like abrasion, hysteresis, and damage, can alter the time-dependent hygroscopic properties of materials that are originally included and assumed pristine in the modeling process.

The IEA ECBCS Annex 41 also elucidated a need for niche programs that address specialized concerns related to moisture buffering in buildings (*e.g.,* furniture-scale mold problems). This distributed calculation method would save computational time and model complexity, allowing for more advanced modeling techniques to be employed (*e.g.,* 3D heat and moisture transfer, software coupling, degradation-induced transient material properties) on a variety of scales. However, distributed modeling inputs would need to be based off full-scale modeling results to capture realistic physical phenomena—an effort that would be a significant contribution to the field.

5.0 Conclusions

This review highlights the materials, methods, and modeling methodologies related to the moisture buffering effect in buildings and its potential impacts on human health, indoor environmental quality, energy consumption, and occupant comfort. A multitude of materials in recent years have been characterized with respect to their moisture buffering capacities. While the most commonly employed NORDTEST method has emerged as the primary standard for materials characterization of moisture buffering value (MBV), differences in experimental facilities, material heterogeneity, and operator error remain sources of measurement error for reported MBVs. Multiple sources indicate that operator error is the principal source of MBV variability. Materials-scale characterization studies of MBV are by far more common than assembly- or building-scale moisture buffering experimentation. However, results from the limited large-scale experiments and numerical studies conducted to-date report that passively controlling RH fluctuations through the moisture buffering capacities of hygroscopic materials—in a similar fashion in which thermal fluctuations are controlled with the thermal buffering effects of insulating materials—has clearly demonstrated non-trivial building energy savings potential. These findings highlight grand opportunities not only to develop and characterize novel materials with hyperactive MBVs, but also to fully understand, leverage, and quantify (*e.g.*, measure, model) the effects of moisture buffering effects at the assembly and building scale with improved accuracy.

More specifically, the results of this review highlight a clear, future trend in materials research, development, and characterization on porous, natural, biotic (*i.e.*, biological), and/or chemically hydrophilic (*e.g.*, superabsorbent polymers, carnauba wax) materials that exhibit high moisture buffering values (MBVs). In addition, improving the speed of HAMT modeling, while maintaining physical representativeness, will better inform building design, operation, and/or retrofit when the effects of moisture buffering are considered. These numerical models have the potential to be coupled with commercially available computational fluid dynamics software to improve assumptions and increase overall accuracy in their prediction of hygrothermal performance and energy savings potential.

In summary, it is evident from the literature reviewed herein that moisture buffering can yield tangible benefits by proactively considering (and designing for) the moisture buffering effects of hygroscopic materials. Future developments in materials, measurement techniques, and modeling approaches will only maximize the benefits of moisture buffering to reduce building energy consumption and further improve indoor environmental quality.

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