Review

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Influence of omitting the vapor barrier in light timber frame walls with bio-based insulation on the risk of mold growth and indoor climate: A literature review

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Abstract

This paper aligns with the rising interest in improving indoor comfort and health of occupants by moisture buffering with hygroscopic materials and the use of bio-based materials with low embodied emissions. The study focuses on literature on light timber frame walls (LTFW) with bio-based insulation and hempcrete walls, both without a vapor barrier. The aim is to highlight the consequences of omitting the vapor barriers in such wall assemblies and to ensure their durability. This review examines two main questions. Firstly, is there a risk of mold growth in LTFW with bio-based insulation and no vapor barrier? Secondly, are there possible links between these building envelopes and the indoor climate and its potential effects on occupants? The findings show that the risk of mold growth in vapor-open walls depends on the external climate, user behavior and applied materials. It is influenced by several factors such as vapor pressure difference, water vapor resistance ratio, exterior finishing, presence of a ventilated cavity, and the hygroscopic properties of insulation materials. Vapor-open walls exhibit a higher risk of mold growth between insulation and exterior lining compared to walls

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with vapor barriers. Additionally, there is a lack of field studies that visually examine mold growth in vapor-open buildings. While simulations suggest that vapor-open buildings with hygroscopic insulation can buffer interior relative humidity fluctuations, supporting field studies are limited. Further research and field studies are needed to improve the understanding of vapor-open or permeable building and its implications on mold growth as well as on the indoor climate and effects on occupants.

Keywords
Building, wall assemblies, vapor-open, moisture permeable, bio-based, mold growth, indoor climate, moisture buffering effect, hygroscopic materials

Introduction

In the field of building design, there is rising interest in moisture buffering, namely, the buffering of indoor relative humidity (RH) by utilizing the hygroscopic properties of materials. In addition, there is an increasing interest in bio-based building materials in order to reduce embodied emissions of buildings.

Moisture buffering has gained interest due to its potential benefits. Hygroscopic materials can reduce the daily fluctuations of the interior RH by exchanging moisture with the surrounding air. Figure 1 illustrates the RH buffering process in a room for two scenarios: with and without moisture buffering capacity. When vapor is generated in the room for a period of time, for example by the presence of an occupant, the water vapor content graduate rises. This in turn leads to an increase in the RH (assuming a constant temperature). The RH subsequently decreases when the vapor generation stops. The peaks of this fluctuation in RH could be buffered by hygroscopic materials (Salonvaara et al., 2004).

Maintaining indoor RH levels between 40% and 60% can reduce health risks (Bastien and Winther-Gaasvig, 2018; Tran Le et al., 2021), and improve thermal comfort for building occupants (Kurnitski et al., 2007; Tran Le et al., 2021). Furthermore, moisture buffering by hygroscopic materials could result in energy savings, by reducing the need for dehumidification (Zhang et al., 2021) as well as increasing the effective ventilation rate for poorly ventilated rooms (Simonson et al., 2004).

Embodied emissions related to materials, manufacturing, and construction processes, constitute 28% of the CO_2 emissions of the building and construction sector, while operational emissions constitute 72%. The building and construction sector itself is responsible for 39% of global CO_2 emissions (IEA, 2019). In order to reduce operational emissions, the implementation of energy-efficient building standards, for example Nearly Zero Energy Buildings (NZEB), has been adopted. These standards often lead to increased insulation thickness and more elaborate building installations, such as solar panels. As a result, operational emissions have decreased while embodied emissions have stayed the same or increased. Consequently, there is a growing need of new building materials in order to lower

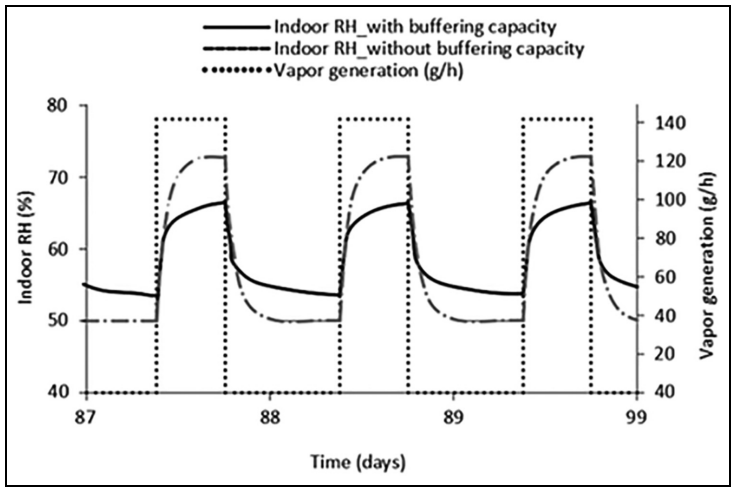

Figure 1. Effect of moisture sorption capacity of hemp concrete on interior RH based on Tran Le et al. (2021).

embodied emissions. This has renewed interest in in bio-based and renewable building materials (Shang and Tariku, 2021).

Moisture buffering is linked to health and comfort benefits, while the application of bio-based materials can reduce the embodied emissions of the building industry. This raises the interest in utilizing the hygroscopic properties of bio-based insulation materials, by vapor-open building (Latif et al., 2014). In the Netherlands especially, there has been a notable surge of interest in vapor-open building, particularly in light timber frame walls (LTFW) with bio-based insulation that omit the vapor barrier. Some commercial entities in the Netherlands claim that vapor-open buildings, utilizing bio-based materials, create a healthier living environment. However, daily humidity fluctuations are primarily influenced by the properties of indoor surfaces and furnishings, with insulation material playing a minimal role due to ventilation air currents and temperature variations affecting relative humidity.

Omitting the vapor barrier in LTFW allows vapor diffusion through the wall . The vapor transport through the wall could increase the risk of mold growth and moisture damage within the wall. Bio-based materials are often more susceptible to mold growth. Excessive moisture reduces indoor air quality through the growth of bacteria and fungi and increases the risk of insect infestation (Lamoulie et al., 2012). Furthermore, the moisture content of materials has a significant impact on their thermal performance (Bastien and Winther-Gaasvig, 2018). In addition, in timber frame constructions, excessive moisture can lead to mold growth within the wood and even wood decay. This leads to a loss of the strength of the wood, potentially endangering the stability of the construction (Ross, 2021). Reasons to omit

the installation of a vapor barrier in a building range from lower costs, reduced environmental impact, and claims of benefits regarding indoor climate and occupant health. In addition, problems arising for unplanned punctual damage of a vapor barrier leading to localized accumulation of water, are not given for vapor-open systems. As a result, parties involved in the decision making of an adopted system should consider associated benefits and risks of either system.

Bio-based insulation are often considered a potentially interesting group of materials for sustainable vapor-open systems, as they are characterized as materials that combine insulating capacities, hygroscopic characteristics while having low embodied energy. In the reviewed literature this group of materials is referred to using various terms such as bio-based, natural, renewable and ecological energy (Latif, Ciupala, et al., 2015; Rode, 1998; Piot et al., 2017). In this article insulation materials with hygrothermal characteristics which are based on an organic resource, such as wood fibers, hemp, straw, flax, are referred to as bio-based insulation materials.

The definition of vapor-open building is unclear in the reviewed literature. However there is consensus that vapor-open buildings allow moisture transport by diffusion through the wall by the use of materials with low vapor diffusion resistance. Vapor-open wall assemblies have to be airtight, to avoid condensation due to air infiltration and to ensure the energy efficiency of a building (Bastien and Winther-Gaasvig, 2018; Simonson et al., 2005). In this article timber frame walls with bio-based insulation material and without a vapor barrier, as well as hempcrete (composite material made of hemp shives, water and binder) walls without a vapor barrier will be referred to as vapor-open.

In this context, this scientific paper addresses two research questions by analyzing the existing literature. Firstly, what is the risk of mold growth in LTFW with biobased insulation without a vapor barrier present? Secondly, are there possible links between these building envelopes and the indoor climate and its potential effects on occupant? Both research questions focus on LTFW with bio-based insulation and without vapor barrier.

Method

In order to answer the research questions, a scoping review was performed. More information about the scoping review approach can be found in Arksey and O'Malley (2005). Scopus (technically oriented) and PubMed (medical oriented) databases were searched, using relevant search terms, both in English and German. The search terms and search strings used, can be found in the Appendix. The German search strings did not result in additional relevant literature. A selection of the found literature was made, based on the titles, abstracts, and inclusion and exclusion criteria. The following inclusion criteria were used:

- Publication type: Peer-reviewed, original research articles.
- Relevance: Papers that assess the effect of hempcrete or LTFW with bio-based insulation, without a vapor barrier, on the indoor climate that may have effects on occupants. Additionally, papers that assess the risk of mold growth in hempcrete or LTFW with bio-based insulation, without a vapor barrier.

The following exclusion criteria were used:

- Language: Studies published in languages that are not within the researcher's language capabilities, namely studies that are not in English, German, or Dutch.
- Relevance: The used search terms resulted in several papers on topics outside the scope of this paper, which were therefore excluded. Examples include studies on Cross-Laminated Timber (CLT) walls, the hygrothermal properties of wood and other bio-based materials, the development of new bio-based materials, airtightness of wood construction, interior insulation of heritage buildings, the effect of damage to the vapor barrier, and the moisture buffering effect of single-layer materials such as wooden cladding, as well as models that research sorption kinetics of bio-based materials.

After screening, based on titles and abstracts, 59 studies were assessed for eligibility. After reading the full articles, 40 publications were excluded based on the criteria mentioned above. The literature set was further expanded through the 'snowball method', which includes the use of literature obtained from experts and references in the reviewed publications. This resulted in 15 additional papers. Included publications were read in their entirety and assessed for relevance to the research question. If relevant, the literature was included in this report. Figure 2 depicts the literature review process and the number of included or excluded papers at different stages.

Relevant information from each included study was systematically collected in a table, including methodology, assessed wall assembly, interior and exterior climate, and key findings.

Literature stock

The applied search strings resulted in a limited number of papers about bio-based vapor-open wall assemblies (see Figures 3 and 4). In total, 626 papers were excluded based on the inclusion and exclusion criteria.

The literature search resulted in 29 included publications, which can be divided into subjects: publications with the subject mold growth of vapor-open bio-based wall assemblies ($n = 15$), publications with the subject of the influence of vapor-open building on the health and comfort of occupants ($n = 12$), and publications that address both topics ($n = 2$). The literature with the subject of mold growth in

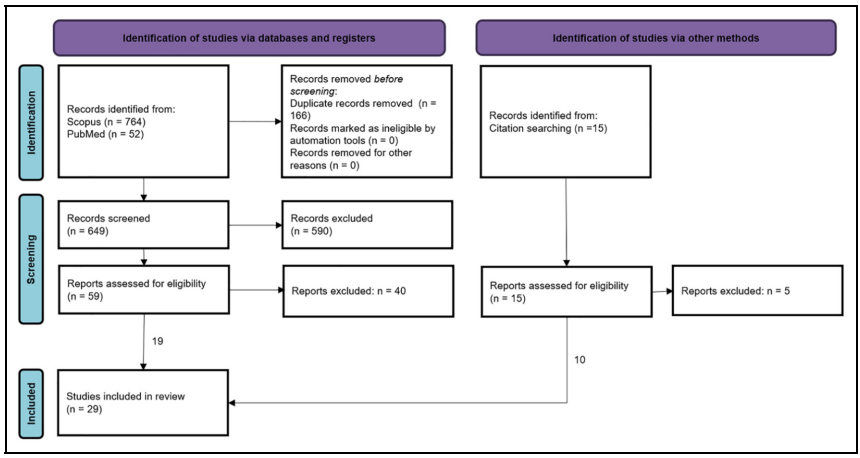

Figure 2. PRISMA flow diagram—literature review process.

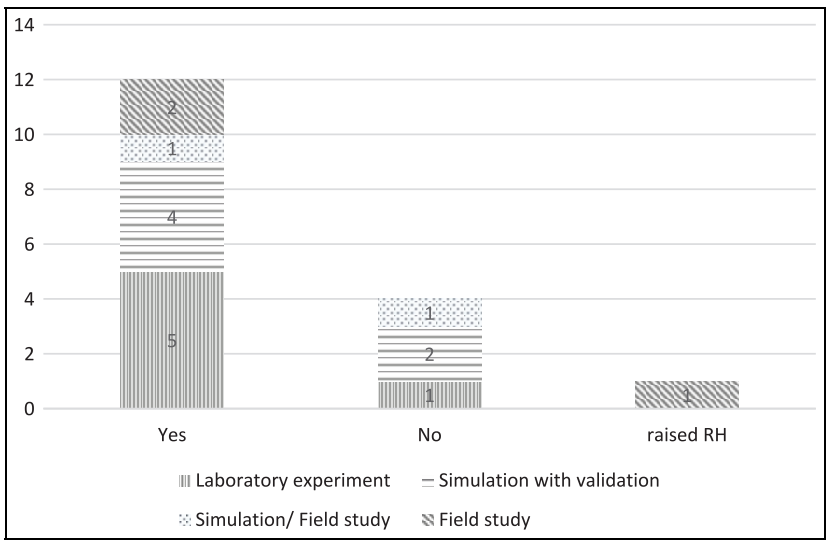

Figure 3. Overview of included literature with the subject of mold growth in vapor-open bio-based wall assemblies and their conclusions. Those that concluded a risk for mold growth in vapor-open bio-based wall assemblies (Yes), those that do not (No), and those that need further examination.

vapor-open bio-based wall assemblies can be categorized by research method such as field study ($n = 3$), combined field study and simulation ($n = 2$), simulation with validation ($n = 6$), and laboratory experiments ($n = 6$). Of these included studies, 12 conclude on an increased risk of mold growth in vapor-open bio-based wall

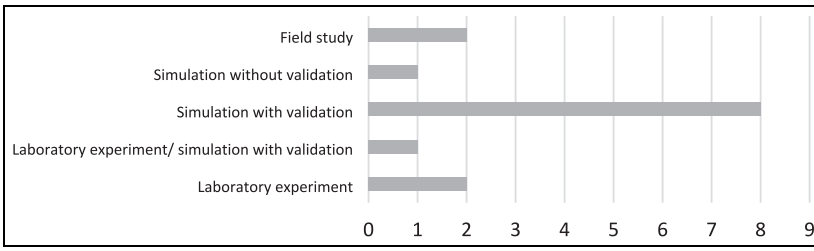

Figure 4. Overview of research methods for publications with the subject of health and bio-based vapor-open wall assemblies.

assemblies, while 4 studies do not (see Figure 3). A majority of studies performed in Europe and with a Nordic climate.

During the literature review no studies were found that directly study the influence of LTFW with bio-based insulation and without a vapor barrier on the health or comfort of building occupants. Studies on thermal comfort often establish a relationship between measured climate and comfort of occupants through the use of questionnaires. However, no studies utilizing this approach were found in relation to LTFW with bio-based insulation and without a vapor barrier. Therefore, literature that examines the effect of vapor-open walls on the interior RH or VOCs (volatile organic compounds) has been included, as well as studies that determined the moisture buffering value (MBV) of LTFW with bio-based insulation and without a vapor barrier. The literature on this topic can be divided into field study ($n = 2$), simulation without validation ($n = 1$), simulation with validation ($n = 8$), combined laboratory experiment and simulation ($n = 1$), and laboratory experiments ($n = 2$; see Figure 4).

Results

Risk of mold growth

Overview included literature. From the included studies, 16 investigated the risk of mold growth in vapor-open bio-based wall assemblies. The boundary conditions taken into account vary significantly between the different studies, such as the exterior climate, indoor climate, and moisture production in the interior. In the field studies the walls were subjected to the outdoor climate and the indoor climate of the respective buildings. In certain studies the house was occupied (Levin and Gudmundsson, 1999; Moujalled et al., 2018; Simonson et al., 2005). The boundary conditions to which the walls were exposed during the laboratory experiments also vary. Three different methods can be distinguished (i) the wall is subjected to outdoor and indoor conditions, often realized by the use of climate chambers, (ii) the assembly is exposed to the real outdoor climate while the indoor climate is simulated by a climate chamber or in a test building, and (iii) the wall assembly is

Table 1. Different methods of simulating boundary conditions in laboratory experiments.

Method	Outdoor conditions	Indoor condition
1	Climate chamber	Climate chamber
2	Outdoor climate	Climate chamber
3	Outdoor climate	Indoor climate of laboratory

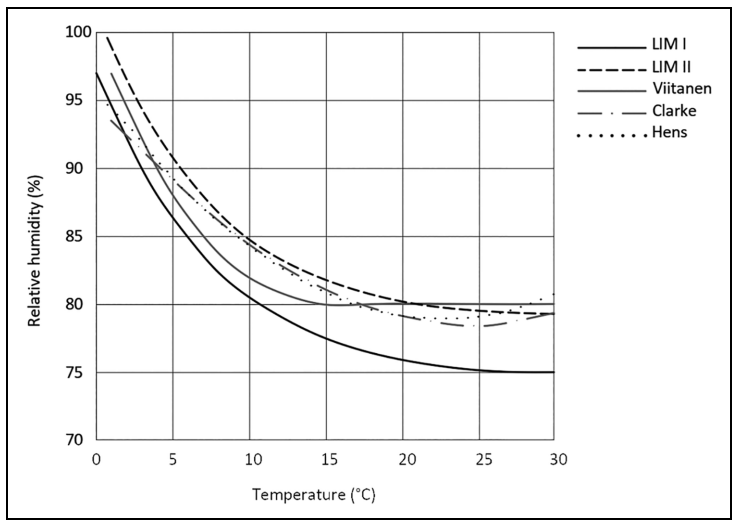

Figure 5. Comparison of different isopleth models based on Viitanen (2011).

exposed to the real outdoor climate and the indoor climate of the laboratory (see Table 1).

In the laboratory experiments, as well as in the field studies, the risk of mold growth was examined based on measurements of the temperature and RH in the wall assembly. The temperature and RH were measured by sensors between different layers of the wall assembly, and at different depths of the insulation layers.

Since mold growth is a relatively inert phenomenon, the majority of the reviewed literature uses mold prediction models to assess the risk of mold growth. The used models are mold index calculations (ASHRAE, 2016) or the method described by Hukka and Viitanen (1999), Ojanen et al. (2010), and isopleth diagrams. Different data for the isopleth diagrams are used in the included literature, namely Viitanen (1996), and Sedlbauer's isopleth for substrate class 1, biodegradable materials (Sedlbauer, 2002). Mold growth can occur when nutrient, mold spores, temperature, and humidity exist simultaneously for a certain time period. These growth conditions for mold can be described in isopleth diagrams. These diagrams describe the germination times or growth rates. Beyond the lowest line in Figure 5, every mold activity stops; under these unfavorable temperature and humidity conditions

spore germination or growth can be ruled out. Building materials are divided into substrate categories, each with different isopleth diagrams. The resulting lowest boundary lines of possible fungus activity are being called the "Lowest Isopleth for Mold" (LIM; Sedlbauer and Krus, 2020). The isopleths slightly differ according to which data is used. A comparison taken from Sedlbauer and Krus (2020) with data from literature determined on building materials is shown in Figure 5. In all of the included literature, the higher risk for mold growth occurs between the insulation layer and exterior lining.

Table 2 presents an overview of the literature on the topic mold growth in bio-based vapor-open wall assemblies, along with the research method and boundary conditions used in the studies and indicates which method is applied for each study.

The built-up of the examined walls varies significantly. The studied wall assemblies can be divided into two groups, namely LTFW (Figure 6) and walls with hempcrete and compressed straw walls (Figure 7). The main difference between these two groups is the position of the wooden studs. The examined composition for each included study is described in Tables 3 and 4 for LTFW and hempcrete/straw walls, respectively.

Findings. In the following section the findings of the included literature are presented, including conclusions, boundary conditions, and author's statements.

Latif et al. (2015a) concluded that both types of walls, with and without a vapor barrier are susceptible to mold growth. The research shows that the risk for mold growth is higher in walls without a vapor barrier, as well as in the walls with more vapor-open finishing layers. Throughout the entire duration of the experiment the hygrothermal conditions in the vapor-closed wall were above the 8 days isopleth. Therefore, this wall composition is at risk for mold growth after 8 days. The vapor-open wall with oriented strand board (OSB) lining was above the 4-day isopleth and in the vapor-open wall with gypsum board inner lining was above the one-day isopleth.

During the experiments on two types of vapor-open walls conducted by Latif et al. (2014), the RH between the exterior lining (OSB) and the insulation often rose above 100% RH, indicating internal condensation. Based on Sedlbauer's isopleths, both wall assemblies are at risk for mold growth under the given conditions. The probability and frequency of condensation, as well as the risk for mold growth, are lower in the wall panel with hemp insulation. In both tests, no visible mold formation was found after dismantling the panels. This is most likely due to the short durations of the tests (14–39 days) (Latif et al., 2014, 2015).

The simulations performed by Rode (1998) indicate that there is a risk of mold growth and internal condensation in all considered compositions without a vapor barrier. Only in the vapor-open wall composition with cellulose insulation and a plasterboard as a rain screen, internal condensations did not occur. This is likely due to the low vapor diffusion resistance of plasterboard. According to the authors, the risk of mold can only be avoided with a vapor barrier according.

Table 2. Overview of included literature on mold growth in bio-based vapor-open wall assemblies.

Paper	Method	Interior moistrure load	Indoor climate	Duration	Exterior climate
Latif et al. (2015a)	Laboratory experiment Method 2[a]	90 ± 5% RH for 2 days 55 ± 5% RH for 4 days 40 ± 5% RH for 8–10 days	25 ± 3°C Test hut	14 days	Real outdoor conditions (January and February) of Wales, UK
Latif et al. (2014)	Laboratory experiment Method 2[a]	Varying RH tough out the experiment, around 35 ± 5% RH for 5 days 60 ± 5% RH for 15 days 90 ± 5% RH for 5 days	25 ± 3°C Test hut	39 days	Real outdoor conditions (July and August 2012) of Wales, UK
Rode (1998)	Simulation	November–March: 3.5 g/m^3 April–Oktober: 3.0 g/m^3 Mei-September 2.5 g/m^3 July–August: 2.0 g/m^3	25°C	2.25 years	Climate of Copenhagen, Denmark
Piot et al. (2017)	Laboratory experiment Method 2[a]	March–July: 170–200 g/h, 2–6 h/day June–February: free variation of RH	18°C–25°C	1 year	Real outdoor conditions of Le Bourget de Lac, France South oriented wall
Vinha and Käkelä (2004) and Vinha et al. (2001)	Laboratory experiment Method 1[a]	Autumn simulation: 4 g/m^3 Winter simulation: 6 g/m^3	20°C	6–11 weeks	Shortened simulation of Finnish autumn, winter, and spring conditions
Rose and McCaa (1998)	Laboratory experiment Method 3[a]	Year 1: 50%–50% RH Year 2 and 3: 40% RH	21°C Interieur lab	3 years	Climate of Champaign, US
Bastien and Winther-Gaasvig (2018)	Simulation	Winter 30%–45% Summer 35%–55% Weekdays: 4610 g/day Weekend: 8384 g/day (family of 4)	20°C	2 years	Climate of Lund, Sweden
Lamoulie et al. (2012)	Simulation WUFI	5 g/m^3	Winter: 20°C Summer: calculated bases on sunshine and outdoor temperature	3 years	Climate of Nancy, Brest, La Pesse and Nice, France
Hagentoft and Harderup (1996)	Simulation WUFI	3.5 g/m^3 Variated	21°C	8 years	Climate of Luleå, Sweden
Simonson et al. (2005)	Simulation	2 g/m^3 minimum RH of 35% inside	21°C	NA	Finnish climate
Simonson et al. (2005)	Field study	0.7–1.9 g/m^3 20%–30% RH Winter: 21 ± 3 Summer: 30 ± 7%	21.4 ± 0.5°C in winter and 23.5 ± 1.1°C in summer	2.5 years	Real outdoor climate Helsinki, Finland

(continued)

Table 2. (continued)

Paper	Method	Interior moistrure load	Indoor climate	Duration	Exterior climate
Levin and Gudmundsson (1999)	Simulation	4 g/m^3	Unknown	5 years	Climate Helsinki, Finland
Levin and Gudmundsson (1999)	Field study	1.1, 0.8, and 1.5 g/m^3 and reflects the number of occupants	Unknown	2 years	Climate Helsinki, Finland
Dhakal et al. (2017)	Simulation	User defined typical interior climate for residential building	User-defined for a typical interior of residential buildings	3 years	Climate of Toronto, Canada
Moujalled et al. (2018)	Field study	40%–60% RH	19°C–27°C	4 years	Perigueux, France
Goodhew et al. (2004)	Field study	No moisture production	No heating	2 years	Dartmoor, UK
Thomson and Walker (2013)	Field study /Literature study	No moisture production	No heating	3 years	
Labat and Woloszyn (2015)	Simulation	Non-uniform, based on stochastic approach for one person household. Average: 1.32 g.h/m^3	20°C	1 year, exluding June to September	Grenoble, France

[a]Method as indicated in Table 1

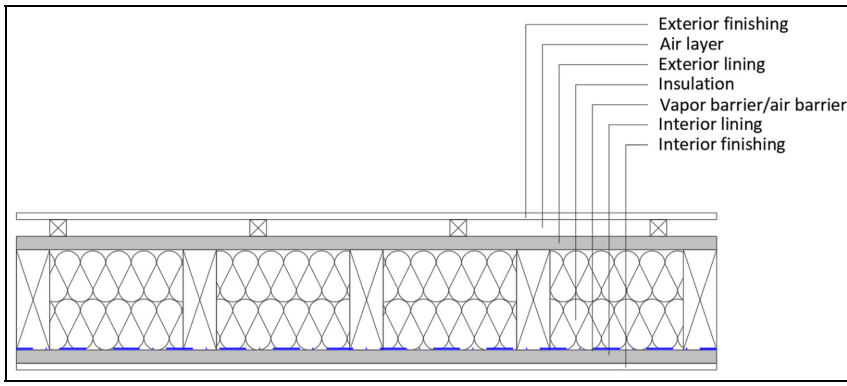

Figure 6. Composition of light timber frame walls (cross-section view from top, fixtures not displayed).

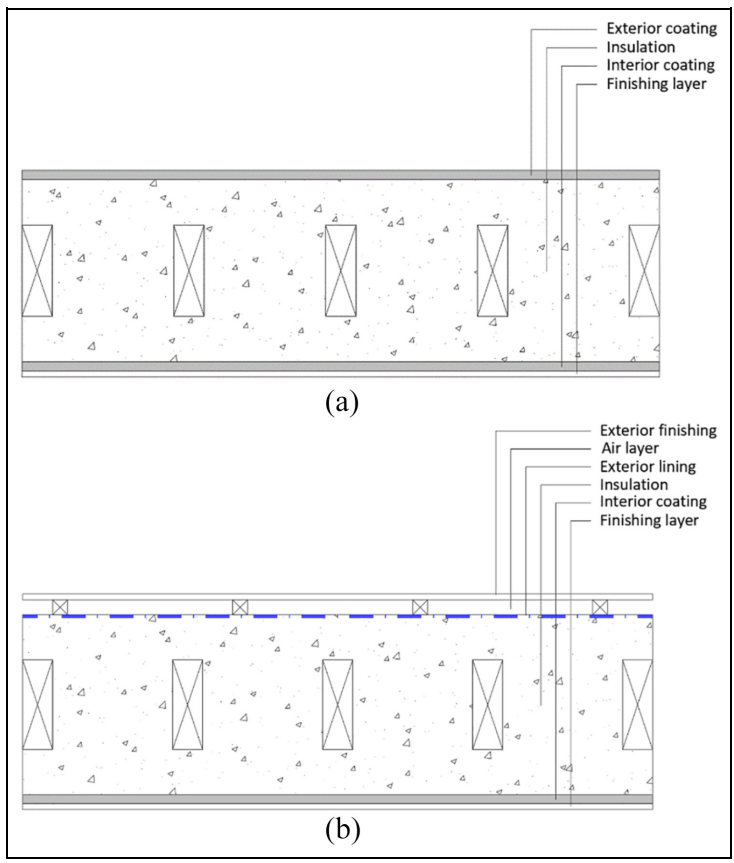

Figure 7. Composition of hempcrete and compressed straw walls: (a) without ventilated cavity and (b) with ventilated cavity (cross-section view from top, fixtures not displayed).

Table 3. Examined wall compositions: timber frame walls—composition according to Figure 6

Paper	Interior finishing	Inner lining	Vapor barrier/air barrier	Insulation	Exterior lining	Exterior finishing
Latif et al. (2015a)	—	Gypsum plasterboard—12.5 mm/B. OSB—11 mm	(No vapor barrier)/ Vapor Vapor barrier—0.5 mm	Wood-hemp insulation—100 mm	OSB—11 mm + Breather membrane	Air layer—25 mm Timber rain screen—10 mm
Latif et al. (2014)	—	Gypsum plasterboard—12.5 mm	—	Hemp insulation—100 mm/Stone Wool insulation—100 mm	OSB—11 mm + Breather membrane	Air layer—25 mm Timber rain screen—10 mm
Rode (1998)	—	(No inner lining)/ unfinished gypsum board—13 mm	(No vapor barrier)/ vapor retarder/vapor barrier (polyethylene)	Cellulose insulation—200 mm/Glas wool insulation—200 mm	Gypsum board 9 mm/ Oil-tempered wood fiberboard—3.5 mm	Air layer Rain screen
Piot et al. (2017)	—	Finishing layer such as pain	—	Prefabricated hempcrete blocks with cement binder	—	2 Types of lime and cement based plaster
Vinha and Käkelä (2004)	—	Gypsum plasterboard—12.5 mm	Bitumen paper/plastic coated paper /plastic—0.2 mm/plastic—0.2 mm + Fir plywood—9 mm	Glass wool—173 mm/ Rockwool—173 mm/ Cellulose insuation—3 mm/Mixed sawdust and chipping—173 mm/Flax insulation—173 mm	Wood fiberboard—25 mm/Rock wool board (IRL)—30 mm/Cellulose insulation board—25 mm/Gypsum board—9 mm/Wood hardboard—4.8 mm/ Weatherization membrane (type 1/2)/Fir plywood—9 mm + Glass wool—25 mm/Plastic—0.2 mm	Air layer - (effect neglected)
Vinha et al. (2001)	—	Gypsum board—13 mm Gypsum board—13 mm + Fir plywood—9 mm Wood fiberboard 12 mm	Bitumen paper/plastic Building paper	Cellulose insulation—145 mm Mineral wool—145 mm	Wood fiberboard—25 mm/Mineral wool—25 mm Mineral wool—30 mm Fir plywood—9 mm	Air layer— (effect neglected)
Rose and McCaa (1998)	2 Layers latex paint	Gypsum board	(No vapor barrier)/ Polyethylene vapor barrier	Cellulose/Fibre glass insulation	OSB	Air layer Timber rain screen (vertical)
Bastien and Winther-Gaasvig (2018)	2 Layers clay plaster—5 mm	Clay board—16 mm	(No vapor barrier) Vapor barrier	Wood fiber insulation—340 mm	Ext. wood fibreboard—60 mm	Mineral cement Plaster—6 mm Lime plaster—6 mm

(continued)

Table 3. (continued)

Paper	Interior finishing	Inner lining	Vapor barrier/air barrier	Insulation	Exterior lining	Exterior finishing
Lamoulie et al. (2012)	Finishing layer such as paint	Inner lining	Vapor barrier (S_d = 18, 10, 5, and 0 m, for example, without a vapor barrier)	Glass wool, Wood fiber, Cellulose	Wind bracing panels (S_d of 0.5, 1, 2, 5, 10, and 50 m)	Air layer Permeability to water vapor of the rain barrier (S_d of 0.10 and 0.18 m) + extra interior or exterior insulation
Hagentoft and Harderup (1996)	—	Gypsumboard—13 mm + Airspace 45 mm	(No vapor barrier) Polyethylene film—0.2 mm	Loose fill cellulose insulation—200 mm	Mineral board—50 mm	Air layer 25 mm Facing brick—120 mm
Simonson et al. (2005)	—	Gypsumboard—15 mm or 13 mm	Building paper	Wood fiber insulation—425 mm	Wood fibre board—25 mm	Air gab (50 mm) External wood siding (22 m)
Levin and Gudmundsson (1999)	—	Gypsum board + Spaced boarding	Polypropylene fabric	Cellulose fibre insulation	Gypsum board	Ventilated air gap + Wood siding
Labat and Woloszyn (2015)		Gypsum board - 13 mm	(no vapor barrier)/Vapor barrier—S_d 19 m	Wood fiber insulation - 160 mm/Mineral wool—160 mm	particle board, 10 mm + Water-tight but vapor-permeable membrane	Air layer Ventilated cladding—10 mm

Table 4. Examined wall compositions: hempcrete walls and compressed straw walls—composition according to Figure 7.

Paper	Finishing layer	Interior coating	Insulation	Exterior coating
Dhakal et al. (2017)	—	Lime plaster	Hempcrete	Lime render/ Typar + air space + wood cladding
Moujalled et al. (2018)	Textile cloth	—	Hempconcrete —300 mm	2 Layers lime-sand plaster—30 mm
Goodhew et al. (2004)		Lime plaster	Straw bales	Lime plaster
Thomson and Walker (2013)		Lime based render 30–40 mm	Straw bales	Lime based render 30—40 mm

The simulation method applied in this study does not take the hygroscopic effect of materials into account.

The research of Piot et al. (2017) exposed two hempcrete wall assemblies, with different types of exterior coating, to the outdoor climate and a climate chamber interior over a period of one year. After the experiment, samples from different depths of the hemp concrete were examined in a laboratory. After an incubation period, the microbial growth per gram of the samples was determined. The risk of mold is considered to be negligible in the center of the wall, under the interior coating and under the non-absorbent exterior coating after one year of exposure. However, if a water-absorbent coating is applied to the exterior, there is a risk of mold growth underneath this coating. The test walls were south-oriented due to the available infrastructure, which might have increased the drying capability of the assembly due to increased radiation, compared to north-oriented walls. Moisture production in the interior, the climate chamber, was limited to three months of the experiment.

The doctoral research of Vinha investigated the hygrothermal performance of LTFW for the Finnish climate and the need for a vapor barrier (Vinha, 2008). The research included laboratory tests, practical measurements and numerical simulations. As part of the research a test set-up has been developed to investigate the hygrothermal behavior of the wall under controlled indoor and outdoor conditions. This test set-up consists of two rooms, between which the wall composition is be placed. The exterior wall finishes, such as masonry or wooden cladding, are neglected in these tests. Measurements in test houses showed that the temperature and RH in the ventilated cavity are comparable to the temperature and RH of the outside air, regardless of the facade cladding used and the outside temperature. Since the facade cladding sufficiently shields the package from driving rain, it is be neglected as well. Vinha and Käkelä (2004) tested 57 different wall assemblies with and without excess moisture production in the interior in the test set-up as

described above. The different wall compositions were evaluated for RH and condensation between the exterior lining and the insulation in autumn and winter and its drying capacity in spring. In vapor-open assemblies the RH between the exterior lining and the insulation is about 10% higher than in vapor-closed assemblies. In vapor-open wall assemblies, condensation occurs during winter conditions with excess moisture production in the interior. The risk of mold was calculated according to Viitanen (1996). During the autumn period, there is a small risk of mold formation for vapor-open walls, but not for vapor-closed assemblies with plastic-coated paper instead of bitumen paper as a vapor/air barrier. After experiments, using same methodology for different wall assemblies, Vinha et al. (2001) concluded that there is clearly a higher risk of condensation and mold growth in vapor-open assemblies than in wall assemblies with a vapor barrier. When the vapor diffusion coefficient of the inner lining decreases, the RH between the exterior lining and insulation increases. Based on the laboratory experiments and measurements in test houses as described above, a numerical simulation model has been validated. This calculation takes diffusion, capillary flow, and surface diffusion into account (Vinha, 2008). Results show that the ratio of the water vapor diffusion coefficient of the interior and exterior lining influences the RH between the exterior lining and insulation. The influence of hygroscopic insulation material on the RH is small. The minimum ratio of the vapor diffusion coefficient of the inner lining and vapor barrier to the exterior lining varies widely and depends on the vapor permeability and thermal resistance of the exterior lining. The higher the vapor permeability and thermal resistance of the exterior lining, the higher the vapor permeability of the interior lining can be to avoid mold growth and condensation. The recommendation that the water vapor diffusion coefficient of the inner wall surface should be at least five times greater than the water vapor diffusion coefficient of the outer surface is often not enough to avoid the risk of mold growth.

Rose and McCaa (1998) concluded that the RH in wall assemblies without a vapor barrier is significantly higher than in assemblies with a vapor barrier. After the three years lasting test, the packages were dismantled and visually examined for mold formation. In walls with vapor barriers mold was only found around the air leaks caused by the placement of sensors through the air-barrier. In contrast, walls without a vapor barrier exhibited uniformly distributed mold growth was observed on the inside of the OSB exterior lining.

Bastien and Winther-Gaasvig (2018) show in their simulation that adding a vapor barrier to the wall composition has little influence on the moisture content of the exterior lining. However, this finding goes against their own expectations. When using a non-water-absorbing cement exterior plaster, the moisture content of the exterior lining is the same for compositions with and without a vapor barrier. However, when using a water-absorbing lime plaster as an exterior wall finish, the moisture content of the exterior lining is 5% higher in the assembly without vapor barrier then in the assembly with vapor barrier.

The study by Lamoulie et al. (2012) is takes the moisture content of the wood frame as a boundary condition. Based on simulations in WUFI (Wärme und Feuchte Instationär), a relatively well-known heat-air-moisture simulation tool, they concluded that extra insulation on the inside of the vapor/air barrier often leads to condensation. In contrast, excessive insulation on the exterior side, which helps to prevent interstitial condensation and mold growth. To prevent mold growth in the assembly, the water vapor diffusion coefficient of the vapor barrier must be sufficiently high, and the ratio of the interior water vapor diffusion coefficient to the exterior water vapor diffusion coefficient must have a value of at least five.

Hagentoft and Harderup (1996) simulated a vapor-open and vapor-closed wood frame wall with cellulose insulation for the climate of Lulea, Sweden, using the heat-air-moisture simulation tool 1D-HAM. Their calculation takes into account vapor diffusion and convection but neglects liquid flow. A simplified sorption isotherm has been used. Different amounts of moisture production in the interior have been simulated, to determine the maximum acceptable value. For the studied wall assembly, if the moisture production in the interior is higher than 3.5 g/m^3 there is a risk of mold growth. The study concluded that vapor-open wall assemblies are susceptible to small changes in interior moisture production. After a few years, an increase of 1 g/m^3 can lead to unacceptable moisture conditions and a risk of mold growth. An increase of 1 g/m^3 corresponds to 30% less ventilation or a change in the number of occupants or their behavior.

Simonson et al. (2005) performed measurements in an inhabited test house. The RH during winter, as well as the moisture load in the interior, were fairly low but not atypical for houses in cold climates. The risk of mold growth was evaluated based on studies by Viitanen (1996) and Hukka and Viitanen (1999). Wood was used as the reference material, since it typically is the most mold-sensitive material in the assembly. The moisture content in the assembly rose to high values, but only during periods when the temperature stayed below 5°C. Therefore, the risk of mold was determined to be low in this specific situation. In the same paper, a numerical model to simulate the hygrothermal behavior of a timber frame wall in the Finnish climate was used. These simulations showed that the drying of the wall mainly depends on the ratio between the water vapor diffusion coefficient of the inner lining and the exterior lining, with a minimum ratio of 3:1. Besides, the drying depends on the permeability and absorption capacity of the insulation. According to the simulation, using cellulose insulation instead of mineral wool can shorten the period with conditions suitable for mold growth by 2–5 weeks.

Over two years, Levin and Gudmundsson (1999) measured the interior climate, temperature, and RH in the north wall of vapor-open homes in Stockholm, Sweden. The interior moisture load of these houses was relatively low. In the wall assemblies of these homes, no condensation or elevated RH were measured. Therefore, the risk of mold growth in these homes was evaluated to be low. Based on these measurements, Levin and Gudmundsson validated a one-dimensional diffusion model that simulates the hygrothermal behavior of these wall assemblies in

the climate of Sweden. According to their model, a higher interior moisture content of 2–4 g/m^3 will result in condensation and the risk of mold growth between the exterior lining and the insulation.

Dhakal et al. (2017) simulated two vapor-open hemp concrete walls with two different exterior cladding systems for the climate of Ontario, Canada. According to the WUFI simulation, the water content remained below 15% in each layer, and therefore, there is no long-term moisture build-up in the wall. The wall assembly with a ventilated cavity absorbed less water and dried faster than the wall with an exterior plaster. No risk of condensation, frost damage, or mold growth was identified for either assembly. However, the amount of moisture production that has been simulated in the interior is unclear.

Moujalled et al. (2018) carried out in-situ measurements, during a 4 year period in an inhabited house located in Perigueux, France. The north and west facades of the office space were examined. Both RH and temperature were measured on the inner and outer surface and at 15 and 25 cm depths of the 30 cm thick hemp concrete. The study concludes that the RH in the wall is on the high side which should be further investigated with regard to the risk of mold growth.

Goodhew et al. (2004) measured the moisture content inside the vapor-open straw bale walls during a period of two years. The building, a storage space, was not heated, and there was no moisture production in the interior. Only at one out of the eight measurement points did the moisture content rise above 20%, a level that is associated with the start of degradation and mold formation of straw. After visual inspection, degradation of the straw was found at the associated location. The moisture content correlates with the rainfall measured at this location of the building. Therefore, the increased moisture content could be due to the moisture-absorbing outer coating rather than to moisture transport by diffusion.

Thomson and Walker (2013) preformed field measurements in an unheated test cabin for 2 years. The temperature and RH in the southwest-oriented wall were measured, as this was the dominant direction for wind driven rain. According to the associated isopleth, defined by the Fraunhofer Institute, hygrothermal conditions where mold growth is possible do occur in this wall. During visual inspection, in which a part of the exterior lime coating was removed, no mold or degradation of the straw was found. However, the discoloration of the straw indicated earlier mold growth. Thomson and Walker (2013) suggest that after the initial period of mold growth, the mold growth may have stopped due to the lack of nutrients.

Labat and Woloszyn (2015) compared vapor-tight an vapor-open wall assemblies, along with relative humidity sensitive (RHS) ventilation and common constant ventilation rate system, based on energy consumption, indoor comfort and durability. The calculated the mold index, based on Hukka and Viitanen (1999), remained zero for most of the time in all four scenarios studied. Therefor is the risk for mold growth not high for any of the four cases. However, in the vapor-closed wall, the mold growth (defined as RHCrit; Ojanen et al., 2010) exceeded 169 h per year near the vapor barrier due to vapor flow from indoors and outdoors. This risk is reduced by using a vapor-open wall configuration and further decreased by

implementing the RHS ventilation system, though it couldn't be completely eliminated. For the vapor-open wall assembly, RHCrit was exceeded 400 h per year at the interface between the outdoor siding and wood fiber.

Influencing factors. The risk of mold growth in vapor-open walls depends on the composition of the wall assembly as well as the boundary conditions. This chapter describes the main influencing factors, as mentioned in the reviewed literature.

The main modes of moisture transport through a wall are liquid flow, capillary suction, air movement (convection) and vapor diffusion. The amount of moisture transported by diffusion is often much smaller than by the three other mechanisms mentioned above. As a result, the risk of mold growth associated with diffusion is also smaller (Bastien and Winther-Gaasvig, 2018). However, vapor-open wall assemblies have to be airtight, to avoid condensation due to air infiltration and to ensure the energy efficiency of a building (Bastien and Winther-Gaasvig, 2018; Simonson et al., 2005).

The most critical point for condensation and mold growth is between the exterior lining and the insulation layer (Vinha, 2008). The moisture content at this point depends on the water vapor diffusion coefficient of the interior and exterior lining as well as on the vapor pressure difference over the wall, caused by the difference in water vapor pressure on both sides. The moisture content in the assembly is increased when, the water vapor diffusion resistance factor (μ-value) of the interior lining is lower and when the water vapor pressure of the indoor air is higher (Simonson et al., 2005).

Water vapor content difference over the wall assembly. The water vapor content difference between the interior and exterior depends on the climate as well as on the interior moisture load. The interior water vapor content depends on several factors, including ventilation, user behavior, and the water vapor content of the exterior air. In winter the exterior water vapor content drops due to the colder temperatures. In many homes in colder climates the interior water vapor content follows this decreasing trend, resulting in low interior RH. This limits the vapor pressure difference over the wall and the risk of mold growth and condensation. However, in case of higher occupancy or use of humidifiers the indoor water vapor content does not follow this decreasing trend. When the RH is kept between the recommended values of 40%–60% during winter the moisture pressure difference becomes significantly higher, resulting in a higher risk of mold growth. For a climate such as in Tampere, Finland, the difference between inside and outside humidity by volume is about 6.5 g/m^3 when a RH of 50% in the interior is chosen as the design value in winter (Vinha et al., 2001). Vinha (2008) proposes a design value of 4–5 g/m^3 for the interior moisture production. This is based on extensive field tests on Finnish single-family houses with LWFS. This is supported by the study of Kalamees et al. (2006), which measured the indoor humidity loads in 101 lightweight timber frame, detached single-family houses in Tampere and Helsinki. The difference between indoor and outdoor air absolute humidity was calculated. The 10% critical level is + 4 g/m^3 in winter ($T_{exterior} \leqslant 5°C$) and + 1.5 g/m^3 during

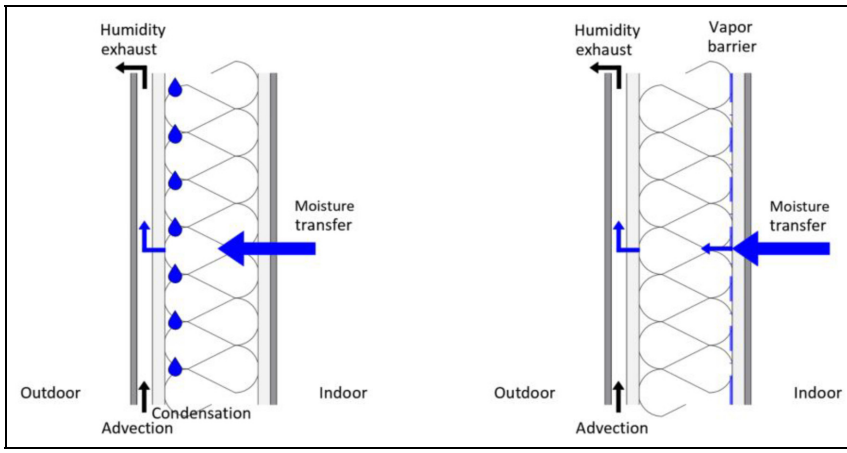

Figure 8. Vapor-open wall assembly (left) and vapor closed wall assembly (right) considering the moisture load is higher indoors than outdoors based on Lee et al. (2020) (cross-section view from the side).

summer ($T_{exterior} \geq 15°C$). For houses with humidification the moisture supply increases with $1\,g/m^3$. However, the used water vapor content for the interior differs in the reviewed literature.

Water vapor resistance ratio. The drying of the accumulated moisture in the assembly depends on the μ-value of the exterior lining. When, the μ-value of the interior lining is lower, more moisture can accumulate. Therefore the μ-value of the exterior should be lower as well, to ensure sufficient drying, as illustrated by Figure 8. The risk of mold growth or condensation in vapor-open wall assemblies therefore depends on the ratio of the water vapor diffusion coefficient of the interior lining to the water vapor diffusion coefficient of the exterior lining (Simonson et al., 2005). This is supported by several publications (Colinart et al., 2013; Thue et al., 1996). In Nordic climates a minimum ratio of five is recommended (Vinha et al., 2001). Nevertheless, simulations by Vinha show that for many wall assemblies this ratio is not sufficient to avoid the risk of mold growth (Vinha, 2008).

A lower μ-value of the exterior lining can, to some extent, compensate for the lower μ-value of the inner lining of vapor-open walls. However, the μ-value of the inner lining must remain above a limit value, which is undefined in the reviewed literature. The limit value depends on multiple conditions, including the thermal performance of the wall. This limit value will be higher for better-insulated walls (Thue et al., 1996).

However, the application of a vapor-barrier can also cause damage. In case of a reverse diffusion flow, from exterior to interior, a vapor-barrier on the interior side of the insulation will prevent drying toward the interior, causing condensation, and risk of mold growth. This situation can occur in unheated summer houses (Bastien

and Winther-Gaasvig, 2018; Latif et al., 2015), in southern climates (Vinha, 2008), and when using high levels of air conditioning (Thomson and Walker, 2013). This phenomena was observed in the simulations of Labat and Woloszyn (2015).

Exterior finishing and ventilated cavity. The drying capability of the wall depends on the exterior finishing of the wall. Several studies show that a ventilated cavity has a beneficial effect on the RH between the exterior lining and the insulation (Dhakal et al., 2017; Lee et al., 2020). In case of exterior plaster, non-water absorbent plaster based on a cement decreases the risk of mold growth compared to lime plaster (Bastien and Winther-Gaasvig, 2018; Piot et al., 2017).

Hygroscopic insulation material. Bio-based insulation materials have hygroscopic properties, meaning these materials exchange water vapor with their environment. This could influence the drying time and RH of assemblies, and therefore the risk of mold growth. Several studies compared the hygrothermal behavior of vapor-open, timber frame wall assemblies with hygroscopic and non-hygroscopic insulation materials.

According to the simulations of Simonson et al. (2005), the use of hygroscopic cellulose insulations can shorten the drying period with suitable conditions for mold growth up to two to five weeks, compared to mineral wool insulation. The laboratory experiments of Latif et al. (2014) showed that the risk of mold formation and condensation is lower with hygroscopic hemp insulation than with rock wool insulation, although the use of hygroscopic insulation cannot eliminate the risk.

Vinha et al. (2001) found that, the use of cellulose insulation slows down the increase of RH in the wall assembly during winter. Overall the moisture content corresponds to that of the wall assembly with mineral wool insulation. The use of cellulose insulation cannot prevent the risk of mold growth. Vinha (2008) concluded that the required water vapor diffusion coefficient of the interior lining differs little between hygroscopic and non-hygroscopic insulation materials.

Geving et al. (2015) concluded that wood fiber insulation performs similarly to glass wool with regards to the RH between the exterior lining and insulation. Compared to the wall assemblies with glass wool, the assemblies with wood wool performed worse in winter and slightly better in summer conditions. The examined wood fiber insulation wetted slower but also dried slower than the glass wool.

Vulnerability for mold growth of hemp concrete. According to Walker et al. (2014) little research has been done into the durability of hemp concrete. Hemp concrete is considered to be resistant to mold and insect attack due to the alkaline properties of the lime. Nevertheless, there are several microorganisms that thrive in alkaline conditions. Walker et al. transferred microorganisms to different samples of hemp concrete and created favorable conditions for mold growth. However, mold growth did not occur in the samples. Walker et al. conclude that hemp concrete is resistant to bio-degradation in environments with fluctuating moisture levels, such as those that occur in wall assemblies.

This is in contradiction with the research by Raamets et al. (2021), where straw and hemp concrete were tested according to the ASTM standard D3273 "Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber." Mold growth occurred at 80% RH in the chamber. The study concluded that hemp concrete, like other bio-based materials, is vulnerable to microorganisms.

Influence on Indoor Climate

Overview included literature. Several studies have investigated the influence of hygroscopic insulation materials on indoor climate, particularly in terms of indoor air and interior RH. Tran Le et al. (2021), Niemelä et al. (2017) and Simonson et al. (2004) explored the buffering effect of hygroscopic materials on CO_2 and/or VOCs as well. Most of these studies used simulations with validation based on physical models.

This review focuses on the buffering effect of LTFW with hygroscopic bio-based insulation and without vapor-barrier. Literature that focuses the moisture buffering effect of interior finishing layers alone and those focusing on CLT were excluded. Table 5 provides an overview of the included literature, including the examined wall compositions, applied method, and results.

Various researchers determined the Moisture Buffering Value (MBV) of vapor-open bio-based wall assemblies following the NordTest protocol. The MBV characterizes the moisture buffering capacity of materials. And was developed by the NordTest project (Rode et al., 2005). It quantifies amount of moisture absorbed and released by a material during humidity changes in surrounding air. This phenomenon involves several physical process, such as vapor diffusion, capillary flow, evaporation, and condensation of moisture. The MBV can be used to compare the buffering effect of different hygroscopic materials. However, the buffering effect in a room is not only dependent on the material properties. It is, among other factors, influenced by ventilation and moisture production. The NordTest project developed an experimental test protocol to determine the MBV of materials and systems. Although there are comparable methods such as Japanese Industrial Standard (JIS) and Draft International Standard (DIS; Alapieti et al., 2020), all the included literature applied the NordTest protocol. Table 6 presents an overview of the included literature, including the examined wall compositions, applied method, and results.

Findings. The aim of the reviewed literature is to regulate the RH between 30% and 70%, or even more strictly. This level of RH could reduce asthmatic reactions, mites, fungi, and the survival rate of infectious bacteria and viruses (Bastien and Winther-Gaasvig, 2018; Loomans et al., 2021; Thomson and Walker, 2013).

Lee et al. (2020) and Kurnitski et al. (2007) investigated the buffering effect of vapor-open wall assemblies with cellulose insulation using numerical simulations. Rode (1998) performed a one-dimensional simulation of the heat and moisture transport through a wood frame wall with cellulose insulation, with and without

Table 5. Overview of included literature aimed at determining the buffering effect of vapor-open walls with bio-based insulation.

Paper	Method	Examined wall	Buffering of daily fluctuation
Lee et al. (2020)	Simulation with validation	LTFW with cellulose insulations, vapor-open air barrier, gypsum plasterboard, and gypsum plaster as interior finishing	RH: yes
Rode (1998)	Simulation with validation	LTFW with cellulose insulation and different types of interior finishing	RH (without interior furnishing): yes RH (with interior finishing): no
Shang and Tariku (2021)	Simulation with validation	Hemp concrete with lime plaster as interior and exterior finishing	RH: 60%
Niemelä et al. (2017)	Simulation without validation	Façade open to water vapor diffusion	CO_2: yes RH: yes
Tran Le et al. (2021)	Simulation with validation	Hemp concrete with lime plaster as interior and exterior finishing (Assumption: similarity between transport of moisture and VIC's through porous materials)	VOC: 15% RH: 8.6%
Straube and DeGraauw (2001)	Simulation with validation	Strawbale wall with 1″ lime plaster And cement bound woodfire board with 12.5 mm lime plaster	RH: yes
Simonson et al. (2001)	Simulation with validation	Vapor-open LTFW with different types of air barrier, interior lining, and interior finishing	RH: 15%–35%
Kurnitski et al. (2007)	Simulation with validation	LTFW with cellulose insulation and woodfire board as interior lining.	RH: 10%–12%
Kurnitski et al. (2007)	Field study	46 houses constructed with LTFW	Minimal effect
Simonson et al. (2004)	Field study	LTFW with wood fiber insulation, building paper as air barrier and gypsum board as interior lining.	RH: 21% CO_2: 10% SF_6: 2%
Labat and Woloszyn (2015)	Simulation with validation	LTFW with wood fiber insulation and without vapor barrier, compared to LTFW with mineral wool and vapor barrier	occurrence of RH >60% decreased by 4%.

Table 6. Overview of included literature aimed at determining the MBV of vapor-open wall assemblies with bio-based insulation.

Paper	Method	Examined wall	MBV (g/(m^2% RH))
Asli et al. (2021)	Simulation with validation	Hemp concrete without interior finishing	1.82–3.02
Lelièvre et al. (2015)	Laboratory experiment/ simulation with validation	Hemp concrete with or without interior finishing	Without interior finishing: 1.9 With lime plaster: 1.2
Romano et al. (2019)	Laboratory experiment	Bio-based insulation materials without interior finishing	Wool insulation (type 1): 1.88 Wool insulation (type) 2: 1.23 Saw mill residue: 2.06 Wood fiber insulation: 1.25
Latif et al. (2015b)	Laboratory experiment	Hemp concrete with different types of interior finishing	Without interior finishing: 3.47 With lime plaster: 3.21 With lime plaster and paint: 1.22 With vapor-open air barrier or plaster board: $<$1.61

interior finishing. Shang and Tariku (2021) simulated a hempcrete wall in Heat Air and Moisture Transport (HAMT) and HAMfitplus, for different ventilation rates and occupancy rates. Based on laboratory experiments Niemelä et al. (2017) found a linear relationship between the permeability of water vapor by hygroscopic materials and the permeability of CO_2 by hygroscopic materials. In addition, the RH and CO_2 in a room were calculated using a numerical model. Tran Le et al. (2021) assumed that VOCs and water vapor are similarly transported through porous materials. However, this relationship was not further explored in the publication. A numerical model in SPARK, validated for the buffering of RH, was used to simulate the level of VOCs and the RH in a room. Straube and DeGraauw (2001) performed a numerical simulations as well as a field measurement. However, this field study was not sufficiently described to properly interpret the conclusions. Simonson et al. (2001) simulated a two-person bedroom with vapor-open walls in different climates. Labat and Woloszyn (2015) performed a detailed HAM simulation to study the differences of both vapor tight a vapor-open wall assembly and a relative humidity sensitive (RHS) ventilation system compared to a common constant ventilation rate system. The simulations show that vapor-open wall assemblies do improve comfort, keeping RH longer between 40% and 50%. However RHS had the most significant impact on the indoor RH. Labat and Woloszyn (2015) conclude that the indoor moisture production is mainly balanced by air renewal, making the need for hygroscopic insulation less significant in moisture management.

Two field studies, namely by Simonson et al. (2004) and Kurnitski et al. (2007) have been included in this review. Simonson et al. (2004) performed measurements in the bedroom of a vapor-open test house with a timber frame wall assembly. The wall had an air-barrier of construction paper, wood fiber insulation and a ventilated cavity. In the bedroom, the moisture production of two sleeping occupants was simulated with a humidifier. In addition, tracer gases were added to the room. RH and gas concentrations in the room were measured at different ventilation rates. The experiment was performed twice, once with the rooms as built, and once in the same room when covered with vapor-tight foil. The results show that vapor-open building envelop influences the CO_2, SF_6 and water vapor concentration in the room. The effective ventilation rate improves by 10% for CO_2 and by 2% for SF_6 at the design ventilation rate of 0.5 ACH (air changes per hour). The peak RH at night was reduced by 15% at an average temperature of 27°C, which corresponds to 21% RH at 22°C.

Kurnitski et al. (2007) studied 46 dwellings with timber frame wall assemblies in the Helsinki and Tampere regions of Finland. During July and August, the temperature and RH in the bedrooms and/or living space of these homes were measured. The houses are classified according to vapor-open or vapor-tight wall assembly, hygroscopic or non-hygroscopic interior finishing and type of ventilation. The daily variation of the RH was significantly lower in homes with balanced ventilation and in homes with hygroscopic interior finishings. The presence of a vapor barrier in the wall assembly had no significant influence on the daily variation in temperature, RH, or absolute humidity in the studied dwellings. However, the variation in RH between the houses themselves was greater than the variation found between hygroscopic and non-hygroscopic walls. This indicates that the buffering indicated by simulations may be reduced by the opening of windows and furniture, as these are factors that are mostly not included in simulations.

The majority of the literature considered concludes that vapor-open walls with hygroscopic insulation can buffer daily peaks in RH in the interior. This buffering varies between 8.6% (Tran Le et al., 2021) and 60% (Shang and Tariku, 2021). An overview of these simulation results can be found in Table 5.

Different researchers experimentally determined the MBV of wall assemblies according to the NordTest protocol (Latif et al., 2015; Lelièvre et al., 2015; Romano et al., 2019). Asli et al. (2021) determined the MBV using a numerical simulation of the NordTest protocol. Asli et al. (2021), Latif et al. (2015), as well as Lelièvre et al. (2015) determined the MBV of hempcrete with and without different types of interior finishing. Romano et al. (2019) determined the MBV of several bio-based insulation materials and PET-insulation. The results can be found in Table 6.

Influencing factors

Moisture penetration depth. The buffering effect mainly depends on the properties of the interior finishing and the most inner couple of centimeters of the wall assembly. The amount of hygroscopic and vapor-permeable material required to achieve

the buffering depends on the penetration depth of the moisture. This requires further research (Simonson et al., 2004). This is in agreement with Latif et al. (2015) who calculated the penetration depth of different bio-based insulation materials between 6 and 12 cm. Piot et al. (2017) estimated the penetration depth for daily fluctuations of RH for unfinished hemp concrete to be 5.8 cm. Straube and DeGraauw (2001) concluded that in a simulation a material thickness greater than 4–6 cm has little or no influence on the buffering effect. However, the penetration depth for plasterboard is only 0.5 cm (Rode, 1998).

Influence of the interior lining. The studies of Rode (1998) and Shang and Tariku (2021) indicated that the interior finishing between the hygroscopic insulation and the interior air has a significant effect on the buffering effect. Rode (1998) stated that the buffering effect becomes insignificant as soon as the moisture exchange between insulations and indoor air is hindered by a materials with higher water diffusion resistance. For example, 13 mm plasterboard as interior lining will negate the buffering effect. Shang and Tariku (2021) concluded that the buffering effect decreases significantly when (latex) paint is applied. However several studies do not take the interior finishing into account (Asli et al., 2021; Romano et al., 2019).

When a hygroscopic interior lining is used, the hygroscopic insulation and/or vapor barrier behind this interior lining still has little effect on the buffering effect. After all, hygroscopic materials that are placed closest to the interior in the wall structure have the greatest impact on the RH of the indoor climate. Therefore, it is probably not necessary for the entire wall assembly to be vapor-open and hygroscopic to achieve the buffering effect. When a hygroscopic interior lining and finishing are used, the interior RH is almost unaffected by the vapor permeability of the layer behind the interior lining, namely the vapor barrier. A vapor-open wall assembly with hygroscopic insulation and non-hygroscopic, but vapor-permeable interior lining preforms similarly to wall assemblies with a hygroscopic interior lining (Simonson et al., 2001, 2004).

The large-scale field study Kurnitski et al. (2007) concludes that the presence of a vapor barrier in the wall assembly had no significant influence on the daily variation in temperature, RH, or absolute humidity in the 46 LTFW dwellings that were studied. However, the daily variation of the RH was significantly lower in homes with hygroscopic interior finishings.

Moisture production and ventilation rate. The actual buffering of the daily variation of interior RH is a complex phenomenon. It does not only depend on the material properties and exposed surface of the hygroscopic insulations. But also the moisture production in the interior, the ventilation, and interior finishing layer have a significant influence on the buffering effect. The buffering effect increases as the occupancy, and thus the moisture production, increases. The buffering effect increases as the degree of ventilation decreases (Shang and Tariku, 2021).

Discussion

Risk of mold growth

The included research presents a large variety of assessed wall assemblies, climates, and boundary conditions, making it difficult to draw general conclusions. However, the majority of included studies indicate an increased risk of mold growth in vapor-open wall assemblies, namely between the exterior lining and the insulation (Goodhew et al., 2004; Hagentoft and Harderup, 1996; Lamoulie et al., 2012; Latif et al., 2014; Latif, Ciupala, et al., 2015; Levin and Gudmundsson, 1999; Rode, 1998; Rose and McCaa, 1998; Thomson and Walker, 2013; J. Vinha and Käkelä, 2004; J. O. Vinha et al., 2001). This research is mainly conducted for Nordic climates.

The moisture load in the interior influences the risk of mold growth in the wall assembly. Vinha (2008) and Kalamees et al. (2006) indicate that a minimum moisture production of $4\,g/m^3$ in winter should be taken into account in Nordic climates. This corresponds to the French design standard of $5\,g/m^3$ (Lamoulie et al., 2012). However, certain studies do not take this into account. For most studies that found no risk of mold growth in vapor-open wall assemblies, the interior moisture load was low or unclear (Dhakal et al., 2017; Piot et al., 2017; Simonson et al., 2005).

The field measurements of Goodhew et al. (2004) found mold growth in the straw bale wall assembly but concluded that this might be due to rain load rather than vapor diffusion. Since there was no heating or moisture production inside the building. The same conclusions could be drawn for the field study of an unoccupied straw bale building as described in Thomson and Walker (2013).

This topic was mainly addressed through laboratory experiments, where the risk of mold growth is determined based on the measured RH and temperature in the wall assembly. The disadvantage of this method is the short time span. Furthermore, the resistance to mold growth varies between different bio-based insulation materials. This has not always been taken into account, most studies do not study the suitability for mold of the used (insulation) material.

Simulations do provide a long-term perspective, but some inadequately explained assumptions make it difficult to assess the reliability of the simulation. Additionally, discrepancies between numerical heat and mass transfer models and experimental data, particularly occur for highly hygroscopic or biobased materials (Busser et al., 2018). However, in all included studies, the simulations are validated.

The review identifies gaps in the existing literature, particularly the lack of a consistent definition of vapor-open or permeable building. Only a few publications have addressed the relationship between mold growth and its influence on material properties and performance of the wall assembly in the long-term. Only Latif et al. (2014) and Latif, Ciupala, et al. (2015) studied the insulating properties of the wall assembly under increased RH due to the omission of the vapor-barrier. However, research on the progression of mold growth and durability of vapor-open wall assemblies is lacking. Furthermore, there is a lack of large-scale field studies and field studies with visual examination of mold growth in vapor-open buildings. The

studies of Rose and McCaa (1998), Goodhew et al. (2004), and Thomson and Walker (2013) do visually examine mold growth in test buildings, but only Rose and McCaa (1998) applied an interior moisture load. This gap in the literature might be due to the long duration and destructive character of such field studies.

Influence on Indoor Climate

This review focuses on vapor-open timber frame walls with bio-based insulations and vapor-open hempcrete walls. Research into buffering finishing layers and CLT walls was excluded.

The majority of the included literature on the relation between occupants and vapor-open building focuses on the relation between hygroscopic insulation materials and parameters of the indoor air, such as RH, CO_2, and VOCs. The main focus lies on RH. These studies focus on the buffering of the daily fluctuation of these parameters. The buffering effect and permeability can help maintain indoor air quality by reducing pollutants and keeping the relative humidity within a known comfortable range. No research that investigates the relationship with indicators for the actual health of occupants and user experience has been found. Literature in the field of thermal comfort often establishes the relationship between measured indoor climate parameters and the experience of users. This relationship was not found in the reviewed literature.

The relationship between vapor-open assemblies and the buffering of certain indoor air parameters is generally investigated using numeric simulations (Table 5). These simulations indicate that the magnitude of the buffering effect mainly depends on the properties of the interior finishing and the most inner couple centimeters of the wall (Simonson et al., 2005). For example, using a finishing layer that is too vapor-tight can negate the buffering effect of hygroscopic insulation (Rode, 1998; Shang and Tariku, 2021). Simulations show that the buffering effect decreases with increasing ventilation. However, it is unclear whether it reduces the need for ventilation (Shang and Tariku, 2021).

Based on the included literature, it is unclear how significant the buffering effect of hygroscopic insulation materials will be in practice. The buffering of RH or VOCs by hygroscopic materials is a complex physical phenomenon where several influencing factors play a role. After all, simulations are an ideal representation of reality in which factors such as furniture and opening windows are neglected. The field study of Kurnitski et al. (2007) indicates that in practice the buffering effect will probably be smaller than expected in the simulations.

Conclusion

The majority of the reviewed literature indicates an increased risk of mold growth in the included bio-based vapor-open wall assemblies in comparison with vapor tight wall assemblies. There is, however, insufficient information about the risk of mold growth in vapor-open wall assemblies under real life conditions. The research

on mold growth in vapor-open wall assemblies is mostly based on laboratory experiments and simulations. No scientific research was found with visual examination of mold growth under real life conditions. The limited field studies that have been conducted have a low interior vapor pressure in winter. As Hagentoft and Harderup (1996) concluded, the risk of mold growth might occur in case of an increased interior vapor pressure, which might happen due to a change in user habits, number of occupants, or change in ventilation rate.

Within the wall assembly, the highest RH and consequently the highest risk of mold growth is found between the insulation layer and the exterior lining. It can be concluded that the ratio of the water vapor coefficient of the interior and the exterior lining must be sufficiently high to ensure sufficient drying and prevent mold growth. The water vapor coefficient of the inner lining must also be sufficiently high. Based on the reviewed literature, no specific water vapor coefficient value can be concluded. This value will depend on numerous influencing factors such as external climate, user behavior, ventilation, composition of the wall etc.

The risk of mold growth in LTFW with bio-based insulation without a vapor barrier is influenced by several factors, including the vapor pressure difference over the wall, the water vapor resistance ratio, the exterior finishing, presence of a ventilated cavity and the hygroscopic properties of the insulation materials. The risk of mold growth in the wall is therefore dependent on the external climate and user behavior which affects the water vapor pressure over the wall, as well as on the materials applied in each layer of the wall structure. Therefore, it is recommended to conduct hygrothermal simulations for each project.

In the included literature, no relationship was found between vapor-open building with bio-based materials and the observed indoor climates and their effect on the occupant. The reviewed literature frequently examined the effect of hygroscopic materials on relative humidity in the interior. Based on the included literature, no clear conclusion can be drawn about the influence of vapor-open building on the health and comfort of occupants. The effect of vapor-open building on interior RH is mainly studied by the use of numerical simulations. Based on the reviewed literature, it is unclear how significant the buffering effect of hygroscopic insulation materials will be in practice. The study of Kurnitski et al. (2007) indicates that in practice the buffering effect will probably be smaller than expected in current numerical simulations.

Further research is needed about the risk of mold growth in vapor-open wall assemblies under real life conditions, including investigating real-life interior vapor pressure in different climates, examining the long term performance and durability of vapor-open wall assemblies and the applied bio-based materials. Additionally, more research is needed to better define the relationship between the indoor and the buffering of RH by vapor-open buildings or hygroscopic materials.

It should be noted that the drawn conclusions have limitations as the found wall assembly builds show significant differences. Therefore, future research should consider to evaluate wall assemblies that vary with respect to the presents of vapor barriers and the existence of interior finishing layers in order to establish the effects

of the different layers. Additionally collected data could further be used to improve existing models or employ artificial intelligence to estimate the behavior wall assemblies.

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Appendix. Search strings

Mold	Condensation	Vapor-open	Construction	Bio-based	Health/comfort
Fungus	Condensation	Vapour open	Building envelope	Bio-based	Health
Fungi	Critical moisture level	Vapour diffusion	Wall	Organic	Well-being
Funguses	Humidity	Vapour transmission	Building assemblies	Renewable	Symptom
Mould	Moisture problems	Vapour permeability	Building structures	Natural	Symptoms
Mold	Moisture infiltration	Vapour transfer	Building component	Bio-based	Percent dissatisfied
Mildew	Water infiltration	Vapour barrier	Building material	Bio aggregate	Indoor humidity
Rot		Vapour absorption	Building materials		Indoor climate
		Vapor-open		Wood	Quality of life
		Vapor diffusion		Timber	
		Vapor transmission		Seaweed	Sick building syndrome
		Vapor permeability		Mycelium	
		Vapor transfer		Hemp insulation	
		Vapor barrier		Straw insulation	
		Vapor absorption		Cork insulation	
		Moisture migration		Wood fibre insulation	
		Moisture transport		Compost	
		Moisture permeability		Hemp lime	
		Permeable		Cellulose	
		Diffusion open		Hemp fibre	
		Diffusion-open			
		Breathable		Wood fiber insulation	
		Breathability		Hemp fiber	
		Hygroscopic			
		Moisture buffering			
		Mass transfer			
		Hygroscopicity			

1	mold—vapor open—bio-based	*("fungus" OR "fungi" OR "funguses" OR "mould" OR "mold" OR "mildew" OR "rot") AND ("vapour open" OR "vapour diffusion" OR "vapour transmission" OR "vapour permeability" OR "vapour transfer" OR "vapour barrier" OR "vapour absorption" OR "vapor open" OR "vapor diffusion" OR "vapor transmission" OR "vapor permeability" OR "vapor transfer" OR "vapor barrier" OR "vapor absorption" OR "moisture migration" OR "moisture transport" OR "moisture permeability" OR "permeable" OR "diffusion open" OR "diffusion-open" OR "breathable" OR "breathability" OR "hygroscopic" OR "moisture buffering" OR "mass transfer" OR "hygroscopicity") AND ("building envelope" OR "wall" OR "building assemblies" OR "building structures" OR "building component" OR "building material" OR "building materials") AND ("bio-based" OR "organic" OR "renewable" OR "natural' OR "bio-based" OR "bio aggregate" OR "wood" OR "timber" OR "seaweed" OR "mycelium" OR "hemp insulation" OR "straw insulation" OR "cork insulation" OR "wood fibre insulation" OR "compost" OR "hemp lime" OR "cellulose " OR "hemp fibre" OR "wood fiber insulation" OR "hemp fiber")*
2	condenstation—vapo open—-bio-based	*("condensation" OR "critical moisture level" OR "humidity" OR "moisture problems" OR "moisture infiltration" OR "water infiltration") AND ("vapour open" OR "vapour diffusion" OR "vapour transmission" OR "vapour permeability" OR "vapour transfer" OR "vapour barrier" OR "vapour absorption" OR "vapor open" OR "vapor diffusion" OR "vapor transmission" OR "vapor permeability" OR "vapor transfer" OR "vapor barrier" OR "vapor absorption" OR "moisture migration" OR "moisture transport" OR "moisture permeability" OR "permeable" OR "diffusion open" OR "diffusion-open" OR "breathable" OR "breathability" OR "hygroscopic" OR "moisture buffering" OR "mass transfer" OR "hygroscopicity") AND ("building envelope" OR "wall" OR "building assemblies" OR "building structures" OR "building component" OR "building material" OR "building materials") AND ("bio-based" OR "organic" OR "renewable" OR "natural" OR "bio-based" OR "bio aggregate" OR "wood" OR "timber" OR "seaweed" OR "mycelium" OR "hemp insulation" OR "straw insulation" OR "cork insulation" OR "wood fibre insulation" OR "compost" OR "hemp lime" OR "cellulose" OR "hemp fibre" OR "wood fiber insulation" OR "hemp fiber")*
3	Vapor open—bio-based—health	*("vapour open" OR "vapour diffusion" OR "vapour transmission" OR "vapour permeability" OR "vapour transfer" OR "vapour barrier" OR "vapour absorption" OR "vapor open" OR "vapor diffusion" OR "vapor transmission" OR "vapor permeability" OR "vapor transfer" OR "vapor barrier" OR "vapor absorption" OR "moisture migration" OR "moisture transport" OR "moisture permeability" OR "permeable" OR "diffusion open" OR "diffusion-open" OR "breathable" OR "breathability" OR "hygroscopic" OR "moisture buffering" OR "mass transfer" OR "hygroscopicity") AND ("building envelope" OR "wall" OR "building assemblies" OR "building structures" OR "building component" OR "building material" OR "building materials") AND ("bio-based" OR "organic" OR "renewable" OR "natural" OR "bio-based" OR "bio aggregate" OR "wood" OR "timber" OR "seaweed" OR "mycelium" OR "hemp insulation" OR "straw insulation" OR "cork insulation" OR "wood fibre insulation" OR "compost" OR "hemp lime" OR "cellulose" OR "hemp fibre" OR "wood fiber insulation" OR "hemp fiber") AND ("health" OR "well-being" OR "symptom" OR "symptoms" OR "percent dissatisfied" OR "indoor humidity" OR "indoor climate" OR "quality of life" OR "sick building syndrome")*

Condensation	Vapor open	Construction	Bio-based	Health/comfort
	dampregulerend bouwen	bouwen		
	dampdiffusie open bouwen			
Kondensation	Dampfdiffusion	Bauhülle	Biobasiert	Gesundheit
Feuchtigkeitsgehalt	Dampfdurchlässigkeit	Gebäude	Organisch	Wohlbefinden
Feuchtigkeit	Dampfübertragung	Bauteil	Natürlich	Symptom*
Feuchtigkeitsprobleme	Dampfsperre	Baumaterial	Bioaggregat	Luftfeuchtigkeit
.Wassereinbruch	Dampfoffen	Wand	Holz	Raumklima
	Dampfübertragung		Meeresalgen	Lebensqualität
	Feuchtigkeitstransport		Myzel	
	Diffusionsoffen		Strohisolierung	
	Hygroskopizität		Henfisolierung	
			Holzfaserdämmung	
			Korkisolierung	
			Hanfkalk	
			Zellulose	
			Hanffaser	

1	schimmel—dampopen—constructie—bio-based	*("Pilz*" OR "schimmel" OR "mehltau" OR "verrotten") AND ("Biobasiert" OR "Organisch" OR "Natürlich" OR "Bioaggregat" OR "Holz" OR "Meeresalgen" OR "Myzel" OR "Strohisolierung" OR "Henfisolierung" OR "Holzfaserdämmung" OR "Korkisolierung" OR "Hanfkalk" OR "Zellulose" OR "Hanffaser") AND ("Dampfdiffusion" OR "Dampfdurchlässigkeit" OR "Dampfübertragung" OR "Dampfsperre" OR "Dampfoffen" OR "Dampfübertragung" OR "Feuchtigkeitstransport" OR "Diffusionsoffen" OR "Hygroskopizität") AND ("Bauhülle" OR "Gebäude" OR "Bauteil" OR "Baumaterial" OR "Wand")*
2	condensatie—dampopen—constructie—bio-based	*("Kondensation" OR "Feuchtigkeitsgehalt" OR "Feuchtigkeit" OR "Feuchtigkeitsprobleme" OR "Wassereinbruch") AND ("Dampfdiffusion" OR "Dampfdurchlässigkeit" OR "Dampfübertragung" OR "Dampfsperre" OR "Dampfoffen" OR "Dampfübertragung" OR "Feuchtigkeitstransport" OR "Diffusionsoffen" OR "Hygroskopizität") AND ("Bauhülle" OR "Gebäude" OR "Bauteil" OR "Baumaterial" OR "Wand") AND ("Biobasiert" OR "Organisch" OR "Natürlich" OR "Bioaggregat" OR "Holz" OR "Meeresalgen" OR "Myzel" OR "Strohisolierung" OR "Henfisolierung" OR "Holzfaserdämmung" OR "Korkisolierung" OR "Hanfkalk" OR "Zellulose" OR "Hanffaser")*
3	dampopen—constructie—bio-based—gezondheid	*("Dampfdiffusion" OR "Dampfdurchlässigkeit" OR "Dampfübertragung" OR "Dampfsperre" OR "Dampfoffen" OR "Dampfübertragung" OR "Feuchtigkeitstransport" OR "Diffusionsoffen" OR "Hygroskopizität") AND ("Bauhülle" OR "Gebäude" OR "Bauteil" OR "Baumaterial" OR "Wand") AND ("Biobasiert" OR "Organisch" OR "Natürlich" OR "Bioaggregat" OR "Holz" OR "Meeresalgen" OR "Myzel" OR "Strohisolierung" OR "Henfisolierung" OR "Holzfaserdämmung" OR "Korkisolierung" OR "Hanfkalk" OR "Zellulose" OR "Hanffaser") AND ("Gesundheit" OR "Wohlbefinden" OR "Symptom*" OR "Luftfeuchtigkeit" OR "Raumklima" OR "Lebensqualität")*