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A Systematic Review about Building Characteristics as Dampness-Related Indicators

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Abstract

The consistent associations between dampness and health-related problems, such as allergies and asthma symptoms, explain the growing scientific interest in assessing housing characteristics. Due to a growing interest in the built environment, the present study performed a systematic review to investigate the prevalence of dampness related to specific building characteristics. The built environment is gaining significance in population well-being due to the substantial time spent indoors. This aspect is especially notable for specific demographics such as children and the elderly. This research is based on the PRISMA methodology and was conducted through scientific papers research published in independent peer-reviewed journals. This study's key conclusions indicate a strong link between home characteristics and dampness-related risk predictors, such as the age of the building, the building materials, the type of ventilation systems, and other building characteristics. Maintenance and occupants' behaviors through good ventilation practices, such as opening windows, were found to be the main remediation strategies. This research novelty involves the identification of home characteristics and dampness-related risk predictors common to a broad spectrum of studies, which makes it possible to identify measures to overcome these bottlenecks. From the constructive perspective, some characteristics, such as the age of the building, are not possible to modify; however, nowadays, technology and knowledge expertise can be used to minor building characteristics associated with health-related problems.

Keywords

Building characteristics; dampness; mold; PRISMA; systematic review

1. Introduction

Nowadays, approximately 80-90% of the population's time is spent in indoor environments [1]. As a result, exposure to indoor pollutants increases as a direct consequence of people spending more time in contact with indoor air, which is affected by built environment conditions such as materials, ventilation type, location, and others. The built environment conditions are often not associated with occupant's health but with thermal comfort. However, this idea is imperfect and ignores the increasing importance of building materials and constructive technologies in possibly developing occupant health hazards.

In Europe, one in every six dwellings is expected to be affected by dampness or mold problems [2]. Some constructive technology aspects might help to explain these expectations, such as the high heat transfer coefficients of building façade elements that favor dampness and mold existence indoors [3, 4]. The inappropriate or poor choice of building materials resulted from the absence of building thermal comfort guidelines before the 1970s oil crisis [5]. In addition to these factors, the building stock and the building elements in some countries require intervention, which might exacerbate dampness or mold problems indoors [6]. Approaching the building stock retrofit from a holistic perspective may help tackle different problems, making it simultaneously more energy efficient, comfortable, and healthier for occupants, correcting some pathologic situations such as indoor humidity and condensation [7].

Mold growth and development require the co-existence of specific temperature, moisture, oxygen, and nutrient conditions. A study concluded that the minimum ambient humidity required for mold growth ranges between 80% and 95%, depending on other factors such as ambient temperature, exposure time, and substrate materials [8]. Mold in a building does not necessarily constitute exposure [9]. However, several studies indicate that for mold and associated by-products, sensitized groups of moldy buildings are considered a risk factor, particularly due to biological agents, for developing respiratory illness [10, 11]. The fungi genera most commonly detected on building materials are *Cladosporium, Penicillium, Aspergillus, and Strachybotrys* [12]. Notwithstanding, *Alternaria alternate, Aspergillus, Cladosporium, Fusarium, Helminthosporium, Serpula lacrymans*, and *Stachybotrys chartaraum* are considered to be the most frequent fungi species associated with allergy symptoms [9, 13].

Different building characteristics were identified as risk predictors for mold exposure, such as the type of building, building age, and surrounding environment. In addition, building dampness-related exposures include visible mold spots (VMS), visible water damage (VWD), mold odor (MO), visible damp stains (VDS), window pane condensation (WPC), and damp clothing/or bedding condensation (DCB), are identified to be risk factors for allergic symptoms [14]. These dampness-related factors, such as condensations and leak indicators, may signify more microorganisms in the indoor environment than the prior building characteristics [9]. Strong correlations have also been found between VSM, VWD, MO, indicators, and the Environmental Relative Moldiness Index (ERMI) [15]. As home characteristics related to dampness are regarded as predictors of microbial exposure, numerous studies have investigated associations between these characteristics and health outcomes [16]. This association is particularly pronounced in studies on allergic symptoms and respiratory diseases [17-24].

Dampness-related indoor exposure associations were found by numerous studies in different countries or regions [10, 18, 21, 25-30]. The results and conclusions of studies that assess dampness-related exposures and home characteristics are often different. Thus, the household's local climate conditions and indoor environment, as well as the methods employed in these studies, vary greatly and range from questionnaires to visual observation and measurements of biological microorganisms and their associated by-products. In addition, the study design to assess mold- and dampness-related problems in buildings may range from occupants' self-reporting questionnaires to field studies conducting on-site inspections and measurement performance [15]. Moreover, visual inspections and sampling methods are considered effective when assessing mold presence indoors. There is an accuracy level of about 80% correlation between visual inspections and indoor mold growth [15]. However, the sampling and speciation allow for comparing species' indoor biodiversity, but guidelines disagree about the importance of determining the species. Thus, remediation methods are usually the same regardless of the fungi species.

As previously mentioned, dampness-related indoor exposure associations were found in numerous studies; however, the methodologies, results, and conclusions differ significantly, and these associations are still imperfectly understood. This research novelty involves the identification of building characteristics associated with dampness and mold-related exposure common to a broad spectrum of study designs and methodologies, which makes it possible to identify patterns. Most studies focus on the association between building characteristics and health outcomes. Regardless of the importance of these studies, from a constructive perspective, it is crucial to find if there are relevant building characteristics that stand out when considering dampness and mold-related exposure. This study's conclusion reveals that building characteristics can be considered risk factors for mold exposure. However, an interesting inference from this study's conclusions reveals that the importance of the building characteristics associated with risk factors for mold exposure differs according to the geographic location of the study.

The present paper consists of a systematic review explicitly oriented to consider building characteristics associated with dampness and mold-related exposure studies. It aims to (i) summarize and compare different studies performed to investigate the prevalence of dampness and building characteristics, (ii) summarize the different types of methodologies employed, and (iii) synthesize the main conclusions found and the identified home characteristics of risk factors.

This research aims to contribute to a better understanding of home dampness-related indoor environments.

2. Methodology

2.1 Study Search Strategy

The present review followed the PRISMA guidelines methodology [31]. For that purpose, an intensive search of peer-reviewed papers published in scientific journals was conducted between March and May 2023 in 6 multidisciplinary scientific databases: Academic Search Complete, Scopus, Current Contents, Web of Science, Science Direct, and PubMed. The research was also conducted in 8 multidisciplinary scientific magazines databases: Directory of Open Access Journals (DOAJ), Emerald Fulltext, Informaworld (Taylor & Francis), SAGE Journals Online, Wiley Online Library, SpringerLink, Ingenta and SciELO - Scientific Electronic Library Online. The search process was divided into four stages: identification, screening, eligibility, and inclusion. Each phase is explained below:

Stage 1: Consists of defining the keywords that best identify studies conducted on the topic to explore. To potentiate the search results for relevant studies, a combination of two keywords linked by a boolean operator "AND" was performed at the time. The keywords employed in the first stage of the search were composed of single and multiple words: "building* characteristics*," condensation*, dampness, questionnaire*, and "mo*ld growth." The objective of employing keywords composed of more than words was to restrict and limit the search to the pretended objective as much as possible.

At this stage, 962 records were identified in the 14 previously referred databases, and another 34 records were manually inserted. These manually inserted records include scientific reports and books. In the initial stage, 385 records were found to be duplicates. Given the number of databases searched, many repeated records were anticipated. Consequently, 611 unique records were obtained in the first stage.

Stage 2: In the second stage of the work, synonyms for the initial keywords defined in stage 1. Another research was carried out with the synonyms to identify relevant studies not detected in the first search stage. For this purpose, "housing characteristics*" and "residential building*" were set as keywords synonyms of the keyword "building* characteristics*" set in the first stage. Also, the keyword moisture was adopted as a synonym for the keyword dampness set in the previous stage.

Considering the high number of records at this stage, the exclusion criteria were considered at this stage.

Stage 3: From the papers collected in the previous stages, all the titles were screened to identify and include only those related to the review topic. All the other articles in which the title did not correspond to the purposes of the review were excluded. Afterward, the abstracts of the remaining articles were assessed. The studies with objectives well defined and aligned with the review purposes were selected, while the studies without a well-organized abstract structure or out of the scope of the review were rejected. Only documents aligned with the purpose of the review, with defined objectives and a clear and structured methodology enabling replication of the claimed research results, were considered. Only studies that focus on assessing building characteristics associated with dampness and mold-related exposure were included at this stage, as reflected in the title and abstract. 37 records were excluded due to not completely meeting the prior referred criteria, i.e., having a well-organized abstract.

Stage 4: Consisted in the search and capture of additional studies in the references of the papers selected in the previous three stages. After excluding the duplicates, adding exclusion criteria, and screening both the titles and abstracts, as a part of the in-depth analysis, the references of the studies considered eligible were screened to identify further relevant publications that were not detected in the previous stages of the process.

2.2 Exclusion Criteria

Only studies explicitly identified risk factor predictors associated with home characteristics, and dampness-related indicators were considered.

At this stage, 67 documents were identified. These documents underwent analysis and selection based on the previous criteria. After this process, 37 records were excluded from the initial set of 67 documents, leaving 28 deemed eligible for analysis.

2.3 Eligible Selection

Following the PRISMA guidelines methodology, from the initial 996 documents filtered, 28 met the section criteria requirements and were elected to be included in the analysis. The studies considered were analyzed to assess the quality of the contents, the methodology employed, and the research results and outcomes. Figure 1 represents a synthesis of the results obtained in each stage of the research process until the final 28 documents are included and analyzed in the review.

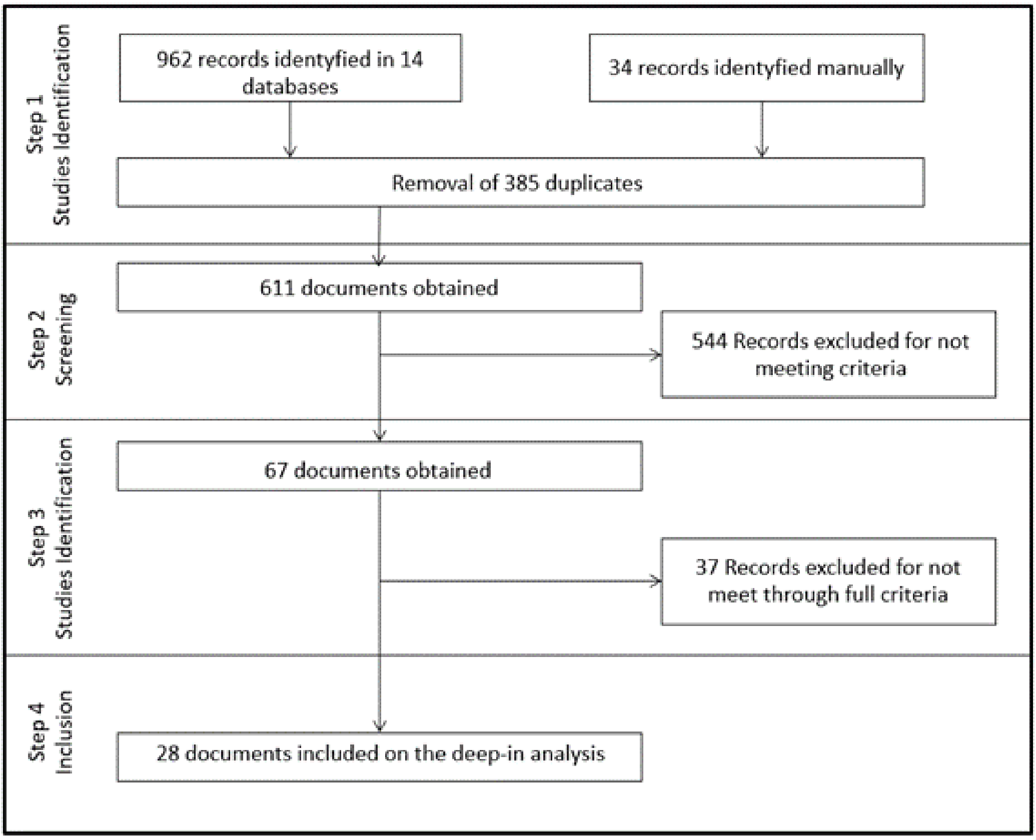

Figure 1 Stages of the literature review process.

3. Results and Discussion

The results of the previously described methodology allowed the identification of the mold risk factors reported in the selected studies revealed in the supplementary material (Table S1). More than half of the selected studies for analysis originated from two geographic regions: Europe and Asia. While Oceania and North American studies were also considered, fewer studies represented them. No studies were found for Africa and South America, considering the criteria followed by the methodology. Figure 2 represents the global location of the analyzed research.

Figure 2 Location of the literature review studies.

According to [32], temperature, moisture, substrate, and exposure time are considered the most influencing factors regarding mold growth. Spore availability, oxygen, pH, light, surface roughness, and substrate salt content are minor factors. Humidity, temperature, duration of exposure, and type of material (substrate) in which the growth occurs, as well as low ventilation rates and low indoor temperatures, are considered the main risk factors for fungi growth. A European study pointed out that Northern European regions with the lowest temperatures were considered risk factors [2]. Despite some studies considering the environmental parameters as risk factors, the large majority of the studies focused on other aspects such as the ventilation type, the location of the building, the ventilation type, the age of the building, and building materials, among other factors specified in Table S1.

Moisture in building materials and high relative humidity levels may originate condensations in indoor surfaces that might lead to changes in indoor microbial levels and increase occupants' exposure to pollutant sources. Even though the influencing factors for mold appearance indoors may be identified, the mold development process may never occur. According to the results, the broad housing-identified risks vary significantly from study to study. Nevertheless, in this review, it is possible to recognize that some studies in different regions identified the same risk factors.

However, when considering specific geographic areas, in Europe, the building materials were the most often referred to as a risk factor, while in the studies performed in Asia, the age of the building was the most often referred to as a risk factor. However, in both regions and other geographies, building materials and the age of the building were mentioned as risk factors for moisture presence in buildings. Table 1 and Table 2 resume the type of risk factor associated with the main geographies, namely, Europe and Asia.

Table 1 Risk factors for moisture presence in buildings in European studies.

	References												
	[20]	[30]	[33]	[34]	[35]	[36]	[37]	[38]	[39]	[40]	[41]	[42]	[43]
Type of House	X										X		
Building Age	X		X		X		X					X	
Building Material	X	X		X	X				X		X		
Tenancy	X				X						X		
Renovation	X												
Moisture Problems	X			X		X	X		X	X			X
Building Location													X
Heating System		X											X
Ventilation Type			X		X			X					X
Density					X								X
Indoor Activities								X					
Environmental parameters						X	X			X			

Table 2 Risk factors for moisture presence in buildings in Asian studies.

	References								
	[14]	[26]	[29]	[44]	[45]	[46]	[47]	[48]	[49]
Type of House				X					
Building Age			X	X	X	X	X	X	X
Building Material						X		X	
Tenancy									X
Renovation				X					
Moisture Problems		X							
Building Location	X		X					X	
Heating System						X			
Ventilation Type						X		X	X
Density/Area								X	X

Indoor Activities	X			X
Environmental parameters		X		

The studies performed in North America [25, 50-52] and Oceania [53, 54] also identified some of the above risk factors. The age of the building, the building materials, the ventilation type, and previous moisture problems were pointed out in these geographies as risk factors.

The joint analysis of results indicates that the age of the building is the risk factor more often considered. Studies from different geographies have shown that more recent buildings tend to have fewer moisture signs indoors [45, 48, 55]. Older buildings represent a higher risk factor for the development of indoor fungi regardless of the geographic region. These results make sense because there is a link between building age, constructive technologies, and the materials used in the building envelope. Materials used in older buildings, if not properly insulated, may favor conduction processes and lead to condensations in indoor surfaces of the building façade. The appearance of water on interior surfaces is one of the necessary conditions for mold to develop in these materials. Facades are the elements with the most exposed area. However, all the remaining building envelopes, such as slabs with ground contact and ceiling slabs in direct contact with water sources, must be properly insulated to avoid outdoor sources, such as water rain infiltration. One study refers to the building’s main material facade being in stone, a characteristic of older buildings, as a risk factor [35]. However, water provenience indoors may have different types of manifestations and origins.

The age of the building and its association with the type of materials and the house’s condition were some of the referred risk factors. A nationwide questionnaire survey in Korea aimed to identify the key factors affecting mold growth in residential buildings and detected those older dwellings with north-oriented facades and poorly maintained properties represented physical characteristics associated with indoor mold growth [47]. In China, two studies, one performed in Chongqing, identified that building construction period, house site, and home position constitute a risk factor, while another study performed in 454 Shanghai residences identified that residences built before 2000 represented a risk for mold growth indoors [29, 48]. In Europe, a study performed in several countries concluded that older buildings were a risk as well as some studies performed in several locals of Sweden, such as Stockholm and Värmland, identified that older buildings and multifamily houses were also identified as potential risk factors [20, 34, 35, 42]. In Cincinnati, Ohio, on-site home visits detected those older homes had a higher moldiness index [52]. In New Zealand, a study also identified that poorer conditions of the house, housing stock with more than 22 years, lack of exposure to sunlight, and having no insulation are risks. Most of the referred studies were performed through occupants’ questionnaires; some were self-reported questionnaires; nevertheless, studies conducted with inspector visits to households and collection of samples reached identical conclusions.

Building materials were also considered to be high-risk factors. The type of glazing and wooden window frames was also identified as risk factors for mold growth [30, 48]. These results are linked with the materials used, which are inherently associated with the age of the building if no retrofitting was previously done. Windows with single glass panes have a higher probability of indoor condensation when the indoor temperature is superior to the outdoor temperature. The material frame is usually attached to the type of gazing, and it is not common to see double-glazing windows with wooden frames; thus, the framing technology evolved, and currently, PVC and aluminum are the most common. The heating systems also play a significant role in indoor pollutant emissions but may also impact fungi development indoors [56, 57]. Other identified risk factors include heating systems, such as unflued gas and electric heaters. These may produce water vapor, contributing to humidity and dampness in the house.

Various regions have identified additional risk factors, such as building location and residing on the ground floor. [14, 43, 48]. Ground humidity occurs due to the contact of building materials with high capillarity on walls and water from the soil and manifests through stains on walls. The absence of insulation and the direct contact between the ground slabs on the floor may be favorable for water infiltration on materials in direct contact with the ground. A study of 8.918 Swedish dwellings associated houses with a concrete slab on the ground built before 1983 to mold risk formation [20]. The same study identified that flat-roofed houses built in the 1960s and 1970s were risky. A study performed in northern Texas through a self-reported questionnaire on home characteristics by parents of children aged between 1 and 8 years reached the same conclusion [25]. Another study also performed in the USA considers basement water sources as another risk factor [51]. Water insulation must be a necessary condition for avoiding envelope materials from being moistened; however, materials may have some water-vapor permeability characteristics to avoid indoor produced water-vapor from remaining inside. Other studies identified floor coverings such as ceramic tile floors, plastic floors, wall-to-wall carpet or tile floors, and PVC as flooring material as potential risk factors for indoor mold growth development [30, 34, 39, 48]. Most flooring materials mentioned are impermeable, which may favor condensation's appearance, leading to mold formation and growth.

Some authors enumerate the provenience of moisture sources and their possible consequences [57, 58] and state that dampness in buildings is a risk factor for the increment of several health effects. Generally, factors that increase indoor humidity levels were found to be directly related to mold formation. High indoor air humidity, water leakage or damage and odors, high temperatures and humidity levels throughout the year, high locality rainfall association of odor, and signs of high humidity were some risk factors associated with mold growth [25, 29, 35, 40, 53]. Moisture may have different sources, such as condensation, plumbing accidents, water leakage, or rain. The user's behaviors and activities generally cause moisture from indoor sources. It is reflected in the incensement of relative humidity indoors, which may lead to condensation on walls or windowpanes. Regarding occupants' activities and behavioral factors, several studies conclude that bathing, washing, and drying clothes could potentially increase mold risks at home [41, 50, 54]. Occupancy density [30, 35] or tenancy [20] are other risk factors associated with user behaviors.

Regardless of the moisture origin caused by occupants or the absence of ventilation, ventilation may play an important role in fungi development; the lower the ventilation rates, the higher the water vapor and the air pollutants [56]. Natural ventilation or the absence of mechanical systems was also identified as a risk factor in different performed studies [34, 43, 48]. Ventilation performs a vital role; thus, it enables the removal of the excess of vapor and pollutant sources. Buildings with natural ventilation and windows closed during the daytime may represent a risk factor due to the indoor accumulation of water and pollutants. Mechanical ventilation systems ensure that the indoor air is healthier without excess water vapor or pollutants, thus assuring permanent air change. Nevertheless, mechanical ventilation represents an increase in housing energy consumption that could be unnecessary if occupants were aware of that, and ventilation through opening windows was demonstrated to reduce mold risk in buildings effectively. Indeed, most of the studies propose remediation strategies for opening the windows or keeping a sufficient air-exchange rate for removing the production of humidity by the occupants [14, 36, 47]. Central air-conditioning systems with indoor air recirculating and air conditioning are also recommended [25, 52].

Besides some strong indicators that have been found regarding the indoor mold risk in households, most of the studies were performed through self-reports or technicians' filled-in questionnaires. The major limitation of this type of study is that validated instruments regarding home characteristics and dampness-related questionnaires are not available [59]. Furthermore, as previously referred, some inclusion criteria were considered; besides being a part of the study methodology, it is recognized that some other relevant studies that did not fully meet the requested criteria were excluded.

4. Conclusion

Dampness-related exposure associations were found in numerous studies. However, the methodologies, results, and conclusions differ significantly, and these associations remain imperfectly understood. This literature review novelty involves the identification of building characteristics associated with dampness and mold-related exposure common to a broad spectrum of study designs, methodologies, and different geographies, which makes it possible to identify patterns. The results suggest that specific indicators are frequently associated with particular housing factors, including the age of the building, the building materials used, the type of ventilation and heating systems, and the presence of previous moisture signs. The identification of these building characteristics might represent a predictor for mold growth risk and indoor dampness. Other factors such as the housing design (the type of house, location, orientation) also represent a predictor for mold growth risk. Regulations for new buildings focus on some aspects, i.e., the minimum levels for building insulation according to geographic location and climate conditions. Nevertheless, attention to tightness and low ventilation rates is needed, as well as access to sunlight and site drainage.

In addition, the building age is highly referred to as a risk factor for mold growth risk and indoor dampness. Paradoxically, the regulation focuses on new buildings, not existing ones. It is vital to give attention to existing buildings, particularly the older ones. Further to building design, attention should also be devoted to maintenance, information, and education of occupants; thus, these may play an important role in maintaining humidity levels through good ventilation practices such as opening windows. Further work on this topic is necessary, considering the diversity of building characteristics across different regions and the few studies performed, particularly in some geographic regions.

Nomenclature

VMS	Visible Mold Spots
VWD	Visible Water Damage
MO	Mold Odor
VDS	Visible Damp Stains
WPC	Window Pane Condensation
DCB	Damp Clothing/or Bedding Condensation
ERMI	Environmental Relative Moldiness Index

Author Contributions

The author did all the research work of this study.

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Competing Interests

The author has declared that no competing interests exist.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Table S1: Summary of identified mold risk factors associated with housing characteristics.

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