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Review

Moisture Damage in Hot-Humid Buildings: Drying Deficit, Envelope Moisture Response, Mold Risk Assessment, and Building Adaptation

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Abstract

Moisture damage in buildings has conventionally been discussed mainly in relation to winter condensation in cold climates. In hot-humid buildings, however, deterioration develops under different boundary conditions, including persistently warm and humid outdoor air, frequent rainfall, air-conditioning operation, air leakage, and limited drying after wetting. Climate change is increasing atmospheric moisture loading and weakening nighttime recovery. These changes make hot-humid moisture risks more consequential not only in established hot-humid regions, but also in regions shifting toward more persistently humid climates. This review examines moisture damage in hot-humid buildings as a coupled problem linking climate change, building-envelope moisture response, risk assessment, microbial implications, and building adaptation. Representative scenarios include biological contamination on exterior surfaces, summer condensation and moisture accumulation within envelope assemblies, localized dampness at indoor surfaces and behind furniture, moisture stagnation in semi-enclosed spaces, and material deterioration or performance loss. These phenomena are interpreted not as isolated defects, but as manifestations of drying deficit. The review discusses climatic drivers, building-physics mechanisms, and major moisture and mold risk indices, including the Fungal Index (FI), the VTT Mold Index, isopleth-based approaches, Mold Resistance Design (MRD), and the Dose-Response Simple Isopleth for Mold (DR-SIM). It also highlights implications for envelope design, retrofit, ventilation, dehumidification, and operation. Overall, moisture damage in hot-humid buildings is best understood as the outcome of climate-driven drying deficit.

Keywords: hot-humid buildings; moisture damage; drying deficit; building envelope; summer condensation; mold risk assessment

1. Introduction

1.1. Problem Setting and Knowledge Gap

Moisture damage in buildings has traditionally been framed mainly in relation to winter condensation, inadequate insulation, and cold-climate hygrothermal failure. In hot-humid regions, however, moisture damage emerges under a different combination of boundary conditions. Persistently warm and humid outdoor air, frequent rainfall, cooling-based operation, air leakage, and limited post-wetting recovery act together to maintain dampness at building surfaces, within envelope assemblies, and in concealed spaces. As climate change intensifies atmospheric moisture loading and weakens nighttime drying, these conditions are becoming increasingly important not only in long-established hot-humid buildings but also in regions shifting toward more persistently humid climates [1–3].

From a building-science perspective, the central issue is not humid climate alone, but how persistent moisture loading interacts with building-envelope design, cooling-dependent operation,

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and limited drying capacity. In this review, the term hot-humid regions refers primarily to climates corresponding to Köppen-Geiger C_{fa} and C_{wa} conditions, while also emphasizing their building-environmental meaning. The essential issue is not temperature alone, but the coexistence of high moisture loading and chronically weak drying potential [1–3]. Under such conditions, building parts repeatedly exposed to rainfall, humid outdoor air, leakage-driven moisture transport, or cooling-related temperature depression may remain damp between wetting events. Moisture damage therefore develops not simply because wetting occurs, but because drying after wetting is insufficient.

This issue cannot be explained by climate alone. Traditional architecture in hot-humid regions often incorporated passive climatic responses such as natural ventilation, open plans, solar shading, lightweight construction, and envelope systems compatible with frequent drying [4,5]. By contrast, much of the modern building stock increasingly relies on industrialized materials, low-permeance interior finishes, closed spatial layouts, and air-conditioning-dependent operation, thereby altering the compatibility between buildings and climate [4,5]. At the same time, the spread of air conditioning has been essential for thermal comfort and health protection, but has also changed indoor-outdoor temperature and humidity relationships, surface temperature distributions, window-opening behavior, and airflow patterns within dwellings [6–8].

Several research streams are directly relevant to this problem. The first is building-physics research on heat, air, and moisture transfer in envelopes, including vapor diffusion, air leakage, rain wetting, capillary transport, sorption, and drying [9,10]. The second is the development of moisture and mold risk indicators, including the Fungal Index (FI), the VTT Mold Index, Fraunhofer Institute for Building Physics (IBP)-type isopleth approaches, Mold Resistance Design (MRD), and the Dose-Response Simple Isopleth for Mold (DR-SIM), which are widely used for design comparison and post-processing of measured or simulated conditions [11–21]. The third is indoor microbiology research, in which cultivation-based methods have increasingly been complemented by quantitative polymerase chain reaction (qPCR) and sequencing-based approaches that quantify microbial load and community structure on surfaces, in dust, and in indoor air [22–25]. The major research streams relevant to moisture damage in hot-humid buildings, and their positioning in this review, are summarized in Table S1.

Together, these research streams have shown that moisture damage is not only a water-related problem, but also a coupled problem involving materials, building operation, microbial persistence, and exposure. Nevertheless, these areas have often developed in parallel rather than as a unified framework. Climate-related humidification, envelope moisture transport, microbial accumulation, and operational control are still often discussed separately. As a result, an integrated review is still needed. Such a review should organize moisture damage in hot-humid buildings as a coupled chain linking climatic change, drying deficit, envelope response, risk indicators, microbial implications, and building adaptation.

Several knowledge gaps follow from this fragmentation. First, although climate science has documented increasing atmospheric moisture, rising dew-point and wet-bulb temperatures, and more frequent humid extremes, relatively few reviews have examined how these changes translate into reduced drying potential and chronic dampness in buildings [1–3]. Second, previous studies have often treated moisture damage either as a climatic problem or as a matter of envelope performance, while paying less attention to the role of modernization, cooling dependence, and changing living practices [4–8]. Third, building-physics research and microbiological research remain insufficiently connected, even though surface microclimate, wetness duration, and moisture persistence are central to both [11–15,22,23]. Fourth, the applicability limits of existing moisture and mold risk indices under persistently humid conditions have not yet been systematically compared [11–15,26,27]. Finally, research findings are still not translated sufficiently into integrated implications for envelope design, retrofit, and operation in hot-humid buildings [9,10,28,29].

Despite growing interest in humid-climate building performance, research specifically addressing moisture damage and summer condensation in hot-humid buildings remains fragmented. Existing knowledge has not yet been systematically organized around the specific problem of

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cooling-dominated hot-humid buildings. Clarifying the current state of knowledge is therefore a necessary first step toward developing more reliable assessment methods and practical adaptation strategies. Accordingly, the objective of this review is to provide an integrated framework for understanding moisture damage in hot-humid buildings and in regions shifting toward more humid conditions. Rather than treating moisture damage as a simple consequence of warm climates or as a series of isolated defects, this review repositions it as a manifestation of drying deficit. This framing links changing climatic conditions with changing building-climate compatibility. The review therefore connects climate drivers, envelope behavior, moisture-risk indicators, microbial processes, exposure relevance, and building adaptation within a single conceptual structure.

1.2. Review Scope and Literature Search Strategy

This paper was prepared as a structured narrative review rather than as a meta-analysis. The aim was not to statistically synthesize a single type of experimental result, but to integrate knowledge across climate science, building physics, moisture and mold risk assessment, indoor microbiology, and building adaptation. Literature was identified through searches in Scopus, Web of Science, ScienceDirect, Google Scholar, and selected technical sources from ASHRAE, hygrothermal simulation literature, and building-science organizations.

The literature search combined terms related to climate, building moisture, mold risk, microbial response, and building operation. Representative search terms included “hot-humid climate,” “humid subtropical climate,” “tropical buildings,” “moisture damage,” “building dampness,” “summer condensation,” “interstitial condensation,” “inward vapor drive,” “drying potential,” “drying capacity,” “hygrothermal simulation,” “heat, air and moisture transport,” “HAM modelling,” “mold index,” “mould index,” “VTT Mold Index,” “Fungal Index,” “isopleth model,” “indoor microbiome,” “microbial load,” “surface mold,” “ventilation,” “air conditioning,” “dehumidification,” “retrofit,” and “building adaptation.”

Studies were included when they addressed at least one of the following topics: climatic moisture loading and humidity trends; heat, air, and moisture transport in building envelopes; moisture or mold risk assessment methods; microbial accumulation, persistence, or exposure in damp indoor environments; or design, retrofit, ventilation, dehumidification, and operational strategies relevant to hot-humid or increasingly humid climates. Peer-reviewed journal articles were prioritized, but standards, technical guidelines, foundational books, and widely cited building-science reports were also included when they provided concepts, methods, or design principles directly relevant to the review.

Studies were excluded when they focused only on cold-climate winter condensation without transferable implications for hot-humid moisture behavior, when they addressed purely microbiological processes without a clear connection to building environments, or when they provided general statements on dampness without traceable technical or scientific evidence. Because moisture damage in hot-humid buildings is an interdisciplinary problem, the final selection was based on both geographic and conceptual relevance. Particular emphasis was placed on studies that helped connect climate-driven moisture loading, envelope response, drying limitation, mold risk, microbial persistence, exposure relevance, and building adaptation.

The overall conceptual framework of this review, linking climatic change, drying deficit, envelope response, risk assessment, microbial implications, and building adaptation, is illustrated in Figure 1.

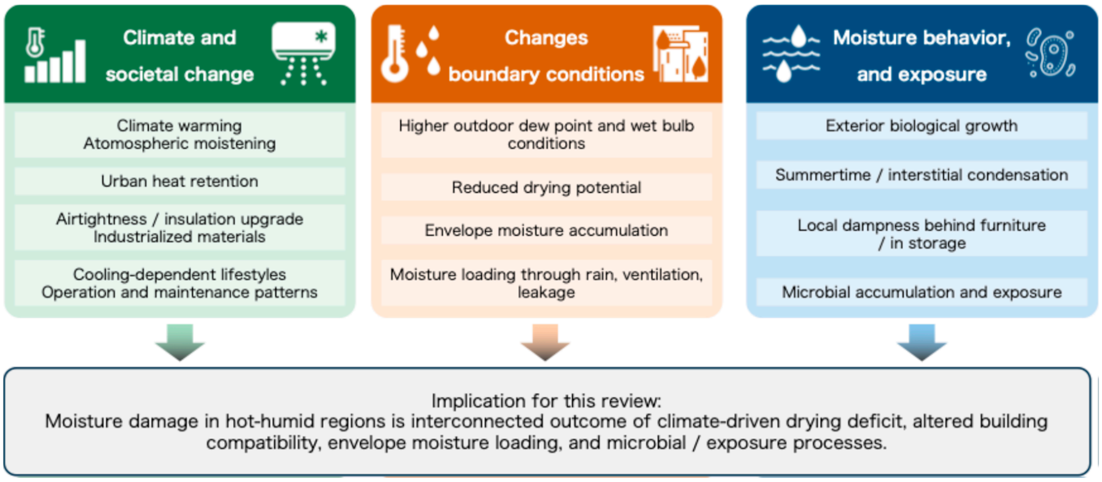

Figure 1. Conceptual framework of moisture damage in hot-humid buildings.

2. Representative Moisture-Damage Scenarios in Hot-Humid Buildings

Moisture damage in hot-humid buildings does not take a single form. Instead, it develops through different combinations of humid outdoor air, rainfall, cooling, leakage, surface wetting, and limited drying after wetting. Whereas winter condensation in cold climates is typically explained by vapor migration from the indoor side toward colder layers of the assembly, moisture damage in hot-humid buildings often involves moisture intrusion from the exterior side, locally cooled surfaces generated by air conditioning, concealed moisture accumulation, and incomplete recovery between wetting events [9,28–31].

A defining feature of hot-humid climates is therefore that moisture damage depends not only on whether wetting occurs, but also on whether the affected building part can dry before the next wetting event. Exterior biological contamination, summer condensation within envelope assemblies, local indoor dampness, and moisture stagnation in concealed or semi-enclosed spaces should thus be interpreted not as unrelated phenomena, but as different manifestations of insufficient drying.

2.1. Biological Contamination on Exterior Wall and Roof Surfaces

Exterior wall and roof surfaces in hot-humid buildings are repeatedly exposed to rainfall, humid outdoor air, dew formation, and weak nocturnal drying. Under such conditions, biological contamination by algae, fungi, and bacteria may develop even in the absence of obvious rainwater leakage into the indoor environment. In many cases, prolonged surface wetness alone is sufficient to sustain discoloration, streaking, visible fouling, and gradual deterioration of surface materials or finishes [30,31].

This type of damage is especially significant because it provides one of the clearest outward signs of incompatibility between envelope response and climate. Surface orientation, solar exposure, coating systems, thermal mass, and surface finish affect not only how easily a surface becomes wet, but also how effectively it can dry [30,31]. Exterior biological contamination should therefore be regarded not merely as an aesthetic issue, but as an indicator of chronically weak drying potential at the building-climate interface.

2.2. Summer Condensation and Moisture Accumulation Within Envelope Assemblies

One of the most characteristic moisture problems in hot-humid buildings is moisture accumulation within walls or roofs during the cooling season. Humid outdoor air may enter assemblies through vapor diffusion, air leakage, or rain-related wetting, and then encounter relatively cool layers created by air conditioning. Under such conditions, condensation or prolonged high material moisture content may develop within the assembly, especially when drying is restricted by impermeable interior finishes or poorly ventilated layers [9,28,29].

This scenario is particularly important because it may progress invisibly. Unlike exterior surface discoloration, concealed moisture accumulation may continue without obvious visual signs while thermal performance declines, materials deteriorate, and conditions favorable to fungal growth emerge within the assembly. Summer condensation in hot-humid buildings should therefore be understood not simply as a condensation event, but as a hidden and potentially cumulative risk linked to cooling-based operation under humid exterior boundary conditions [28,29].

2.3. Local Dampness at Indoor Surfaces and Behind Furniture

Even when room-average temperature and relative humidity (RH) appear acceptable, local dampness may still develop at floor corners, wall-adjacent zones, inside closets, behind furniture, near windows, and around supply air outlets. These locations may experience prolonged high surface RH or thin-film condensation because of locally reduced air circulation, cooling-related surface temperature depression, thermal bridges and other thermal discontinuities, or furniture placement that inhibits convective recovery [7,28].

This type of moisture damage is particularly important because it shows that moisture safety cannot be judged from room-average conditions alone. Buildings may appear thermally controlled at the room scale while still allowing localized dampness to persist at the microclimatic scale relevant to microbial growth. Local indoor dampness in hot-humid buildings therefore reflects the combined effects of climate conditions, cooling, thermal response, airflow limitation, and patterns of furnishing and occupancy.

2.4. Moisture Stagnation in Semi-Enclosed Spaces

Semi-enclosed spaces such as attics, crawl spaces, ceiling voids, service shafts, and cavities behind assemblies may also become persistent reservoirs of moisture in hot-humid buildings. In these locations, humid outdoor air, residual construction moisture, rainwater intrusion, leakage-driven transport, and local temperature depression around ducts or pipes may combine to sustain high-humidity conditions that are not represented by average indoor measurements [10,29].

This scenario is important because it can remain unnoticed for long periods while concealed wetting, material degradation, and microbial source formation progress in hidden zones. In buildings with cooled indoor spaces, the problem may be intensified when high-dew-point air reaches locally cooled surfaces within concealed spaces. Semi-enclosed spaces in hot-humid buildings should therefore be regarded not merely as ancillary zones, but as locations where moisture may accumulate, persist, and later contribute to broader building or exposure problems [10,29].

2.5. Material Deterioration and Performance Loss

Moisture damage in hot-humid buildings should not be limited to visible mold growth or microbial contamination. Persistent dampness can also produce direct material deterioration and performance loss. Depending on the material and location, prolonged moisture exposure may reduce thermal resistance, alter the heat and moisture transport properties of insulation materials, accelerate corrosion of metal components, promote decay or dimensional instability of wood-based materials, weaken gypsum-based boards, cause swelling or deformation of composite materials, and lead to staining, blistering, peeling, or delamination of surface finishes [10,12,28,29,32–35].

This distinction is important because material damage may occur before visible mold becomes apparent. For example, concealed moisture accumulation within wall or roof assemblies can reduce insulation performance, increase the moisture content of sheathing or framing, and create conditions that gradually weaken the durability of the assembly. Moisture uptake in insulation materials can increase effective thermal conductivity and reduce envelope thermal resistance, thereby linking moisture damage directly to energy performance and thermal comfort [34,35]. Exterior surfaces may experience coating degradation, biological fouling, and repeated wetting–drying stress, while interior finishes may show staining, odor, surface deformation, or adhesion failure even when microbial growth is not visually confirmed.

From the perspective of drying deficit, these forms of deterioration share the same underlying structure as mold-related damage. Moisture becomes harmful when materials are repeatedly wetted or maintained at high moisture content without sufficient recovery. Therefore, assessment of hot-humid moisture damage should include both biological outcomes, such as mold growth and microbial persistence, and non-biological outcomes, such as corrosion, decay, finish failure, reduced insulation performance, and shortened service life.

2.6. International Variation and Reported Case Examples

Although the scenarios described above share a common physical structure, their expression differs among hot-humid regions because climate seasonality, rainfall pattern, building type, material practice, cooling dependence, and occupant behavior vary substantially. In humid subtropical regions of East Asia, including Japan and parts of southern China, seasonal cooling, monsoon rainfall, dense urban development, and increasingly airtight or industrialized envelopes may combine to produce summer condensation, local indoor dampness, and moisture accumulation in concealed spaces. Field measurements in Chinese residential buildings have shown that indoor humidity conditions vary substantially among regions and seasons, indicating that moisture-control strategies cannot be generalized from climate classification alone [36]. In tropical Southeast Asia, year-round high humidity and the transition from open, naturally ventilated dwellings to air-conditioned and more enclosed buildings can alter drying patterns and increase the importance of indoor surface microclimates and cooling-related moisture redistribution [5,7,8].

In hot-humid regions such as Florida and the Gulf Coast of the United States, the moisture problem has often been discussed in relation to inward vapor drive, rain exposure, air-conditioning operation, duct leakage, and pressure-driven infiltration [28,29,37]. These conditions are especially relevant to lightweight envelope assemblies and buildings with mechanically cooled interiors. In monsoon-influenced regions such as coastal India, repeated seasonal wetting, porous materials, mixed-mode operation, and highly variable ventilation practices may create moisture risks that differ from those in continuously cooled buildings. For example, a mold-growth study in Mangalore, India, used a heat and mass transfer simulation approach to evaluate mold-growth risk in an autoclaved aerated concrete wall assembly under warm and humid climatic conditions [38].

In tropical and subtropical parts of Brazil, high rainfall, warm temperatures, and long wet periods can support exterior biological contamination, façade deterioration, and indoor dampness. A national-scale analysis of Brazilian façades showed that wind-driven rain and driving-rain wind pressure are important factors for assessing water penetration risk [39]. In addition, studies of subtropical urban façades in Rio de Janeiro have shown that epilithic and endolithic microorganisms can contribute to deterioration of stone surfaces under warm, humid, and polluted urban conditions [40].

These regional differences indicate that hot-humid moisture damage should not be treated as a uniform climatic problem. Instead, it should be interpreted as a set of regionally specific expressions of a shared imbalance between moisture loading and drying capacity. A tropical building that remains naturally ventilated, a subtropical dwelling operated intermittently with air conditioning, and a mechanically cooled building in a humid coastal climate may all experience drying deficit, but the relevant moisture pathways, vulnerable locations, and adaptation measures may differ. Therefore, international comparison is important not only for broadening the geographic scope of the review, but also for clarifying which mechanisms are general and which are context-dependent. Representative regional examples and their dominant moisture mechanisms are summarized in Table S4.

2.7. Common Structure Across Scenarios

Although the scenarios described above differ in appearance and affected building components, they share a common physical structure. Moisture damage becomes chronic not simply because wetting occurs, but because drying is insufficient afterward. Rainfall, humid outdoor air, cooling, leakage, and surface wetting may each act as moisture sources, yet these develop into significant moisture damage primarily when dampness is not removed before the next wetting event [28–30].

In this sense, moisture damage in hot-humid buildings should not be framed simply as a problem of moisture intrusion. Rather, it should be understood as a family of phenomena that emerge in different parts of buildings under conditions of drying deficit. Exterior biological contamination, concealed summer condensation, local indoor dampness, moisture stagnation in semi-enclosed spaces, and material deterioration may appear distinct, but all are underpinned by the same imbalance between moisture supply and drying capacity. This common perspective provides the basis for the following chapters, which discuss climatic drivers, building-physics mechanisms, and the interpretation of moisture-risk indicators. The representative moisture-damage scenarios discussed above, together with their typical locations, governing mechanisms, major signs, and practical implications, are summarized in Table 1.

Table 1. Representative moisture-damage scenarios.

Scenario	**Typical locations**	**Mechanisms/conditions**	**Signs / impacts**	**Implication**
Exterior biofouling	Exterior walls; roofs; shaded and rain-exposed surfaces	Rain/dew wetting; humid air; delayed drying; warm nights; retentive finishes	Discoloration; staining; streaks; coating deterioration	Indicates insufficient surface drying, not only appearance loss
Envelope condensation	Walls/roofs; insulation; gypsum-board rear side; wood substrates	Inward vapor drive; humid-air leakage; cooled layers; poor drying; high dew point	Often hidden; odor; concealed mold; lower thermal performance; deterioration	Design should address inward loading and limited post-wetting drying
Localized dampness	Behind furniture; closets; corners; near windows; cooled surfaces	Local cooling; stagnant air; low air speed; humid-air inflow; insufficient dehumidification	Local staining; odor; condensation marks; mold on finishes	Evaluate local microclimate, not only room averages
Hidden-space stagnation	Attics; crawl spaces; ceiling voids; shafts; hidden cavities	Humid-air stagnation; leakage; residual moisture; pressure differences; poor ventilation	Often hidden; odor; staining; concealed deterioration; microbial source potential	Hidden spaces require inspection, drainage, drying, and pressure control.
Material deterioration	Insulation; sheathing; framing; metals; finishes	Persistent moisture; repeated wetting; blocked drying	Lower insulation performance; corrosion; decay; swelling; peeling	Assess durability loss; not only mold risk

3. Climatic Drivers and Building-Relevant Drying Deficit

To understand moisture damage in hot-humid buildings, it is necessary to consider not only building specifications and operation, but also the climatic conditions that govern wetting and post-wetting recovery. Buildings in such regions have long been exposed to warm and humid summer air, frequent rainfall, and short drying periods. In recent decades, however, these background conditions have been further intensified by rising air temperatures, increasing atmospheric moisture content, higher dew-point and wet-bulb temperatures, and weaker nocturnal cooling [1–3,26]. From the perspective of building moisture damage, the central issue is therefore not warming alone, but the increasing tendency for moisture loading and limited drying to occur together.

In hot-humid regions, moisture damage develops not simply because buildings become wet, but because the time and driving force available for drying are reduced. If temperature rises while air remains relatively dry, drying potential may still remain substantial. In contrast, when higher temperature is accompanied by higher atmospheric moisture content, wet surfaces and moisture-laden materials are less able to recover after rain, leakage, or adsorption. Climate change therefore acts not only to increase moisture loading on buildings, but also to intensify the drying deficit that underlies chronic dampness.

3.1. Operational Definition of Drying Deficit

In this review, drying deficit is used as an integrative building-environmental concept rather than as a single material property or a fixed climatic category. It denotes a condition in which moisture supplied to a surface, material, space, or assembly is not removed sufficiently before subsequent wetting or humid exposure occurs. In this sense, drying deficit represents an imbalance between cumulative moisture supply and cumulative drying capacity over a specified time window [32].

Conceptually, drying deficit can be expressed as follows:

$$DD\Delta t = \int \Delta t W(t)dt - \int \Delta t D(t)dt \quad (1)$$

where $DD\Delta t$ is the drying deficit over the time window Δt, $W(t)$ represents moisture supply through rainfall, vapor diffusion, air leakage, capillary uptake, adsorption, or condensation, and $D(t)$ represents drying through evaporation, drainage, vapor transport, ventilation, radiation, or dehumidification [10,29]. A positive and persistent $DD\Delta t$ indicates that the element or space is moving toward chronic moisture accumulation, whereas a negative or intermittently balanced value indicates that sufficient recovery is occurring between wetting events.

For practical building assessment, this concept should be operationalized using measurable proxy variables rather than a single universal index. At the climate level, relevant proxies include high outdoor dew-point temperature, low vapor-pressure deficit, long periods of high RH, frequent rainfall followed by short drying intervals, and limited nighttime recovery [1–3,26,27]. At the component or surface level, useful proxies include cumulative hours above critical surface RH, time of wetness, and drying time after wetting. Other relevant indicators include persistent high material moisture content, repeated exceedance of mold-relevant temperature–humidity conditions, and 30-day running-average surface RH criteria [11,12,21]. However, these thresholds should be interpreted in relation to material type, temperature, exposure history, and the degree to which drying occurs between wetting events. At the room or concealed-space level, surface RH, local air velocity, pressure imbalance, and the effectiveness of latent-load removal become important [10,28,29,37].

This operational definition does not replace established hygrothermal simulation or mold-risk indices. Rather, it provides a common interpretive framework for connecting climatic moisture loading, envelope response, local dampness, mold-risk indicators, microbial persistence, and building adaptation. It also clarifies why the same wetting event may be harmless in a climate or assembly with sufficient drying capacity, but damaging in a hot-humid context where drying remains chronically weak [41].

3.2. Climatic Characteristics That Intensify Drying Deficit

From a climatological perspective, hot-humid conditions are often represented using Köppen-Geiger classes such as C_{fa} and C_{wa} [1,42]. For building moisture damage, however, climate labels alone are not sufficient. More relevant variables include outdoor vapor pressure, dew-point temperature, wet-bulb temperature, the duration of high-humidity periods, and the frequency with which wetting events are followed by only limited drying. These climatic characteristics are more directly connected to whether wetted materials and surfaces can return toward safer moisture states. The main climatic indicators relevant to moisture damage and drying deficit in hot-humid buildings are summarized in Table S2.

The IPCC Sixth Assessment Report has documented unequivocal anthropogenic warming and intensification of the hydrological cycle, including changes in humidity-related extremes [4]. Willett et al. further developed long-term datasets of humidity-related variables, including vapor pressure, dew-point temperature, and wet-bulb temperature, which are directly relevant to the moisture boundary conditions acting on buildings [2]. For building performance, the important issue is that high temperature and high humidity increasingly occur together. Under these conditions, the vapor-pressure difference that would otherwise promote drying becomes smaller, and materials that have taken up moisture are less able to release it.

Dew-point temperature is especially important because it indicates how close air is to saturation and therefore how small the evaporation driving force may become at wet building surfaces [2]. Representative-city trends further support this interpretation. As shown in Figure 2, summer mean dew-point temperature remains high under present-day conditions and increases further under future climate projections in representative cities, indicating progressively reduced drying potential [43]. When outdoor dew-point temperature is high, the ability of exterior surfaces, claddings, and moisture-buffering materials to dry is reduced.

Wet-bulb temperature is also relevant, not only as an indicator of human heat stress, but as a building-relevant measure of latent cooling load and the practical difficulty of dehumidification. When outdoor wet-bulb temperature is high, ventilation and outdoor-air introduction are less likely to support drying and may instead increase latent moisture loading [2,3].

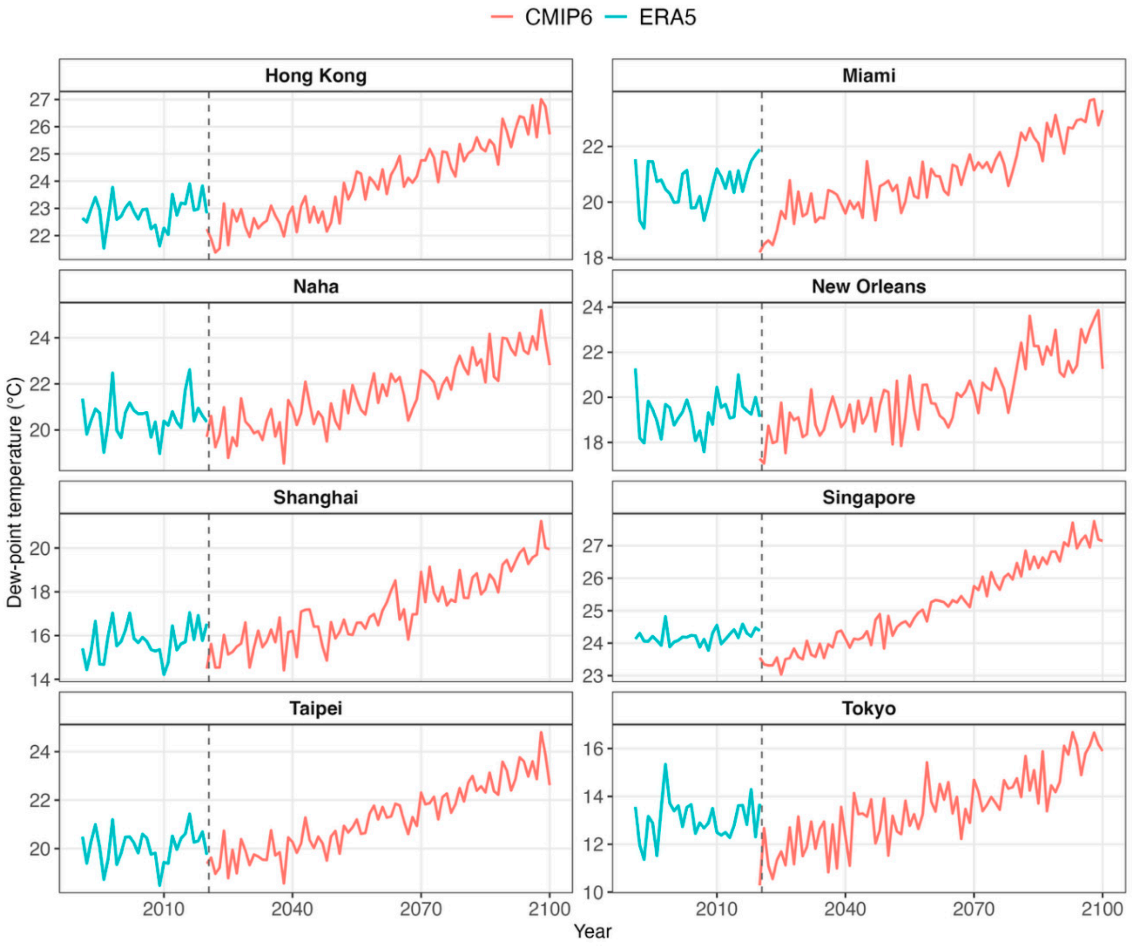

Figure 2. Time series of summer mean dew-point temperature in representative cities. **Note:** Present-day values were derived from the fifth-generation ECMWF atmospheric reanalysis (ERA5) monthly dataset using 2 m dew-point temperature, i.e., dew-point temperature at approximately 2 m above ground level, whereas future values were derived from Coupled Model Intercomparison Project Phase 6 (CMIP6) projections using near-surface air temperature and near-surface RH. Because ERA5 and CMIP6 are different data products with different spatial resolutions, model structures, and bias characteristics, the present-day and future segments should be interpreted as indicative trends rather than as a continuous observational–projection time series. Small discontinuities between the two segments may reflect dataset and model differences rather than abrupt climatic shifts.

3.3. Nighttime Recovery Limitation and Repeated Wetting

Another major climatic feature relevant to moisture damage in hot-humid regions is limited nighttime recovery. Urban climate research has long shown that nocturnal cooling is often weakened in urbanized environments, and that heat-island intensity tends to be particularly pronounced at night [26,27]. For buildings, this means that moisture acquired during the day through rainfall, surface adsorption, or leakage may not be dissipated sufficiently before the next day begins.

This issue is important because moisture damage is governed not only by individual wetting events, but by whether drying between events is sufficient. If nighttime air temperature remains high and dew-point temperature also stays elevated, surfaces and assemblies that become wet during the day may begin the following day from an already damp condition. Repeated carryover of residual moisture thus becomes more likely. In hot-humid regions, this process helps explain the persistence of exterior biological contamination, concealed moisture accumulation, local indoor dampness, and chronic wetting in semi-enclosed spaces.

From a building-environment perspective, weakened nighttime drying should therefore be regarded not merely as a secondary climatic characteristic, but as one of the key processes through which hot-humid climates promote chronic moisture damage. What matters is not only the occurrence of rainfall or humid episodes, but also the shrinking opportunity for recovery afterward.

3.4. Expansion of Hot-Humid Risk Zones

Under future climate conditions, hot-humid risk is expected to intensify not only within regions that are already hot-humid, but also in surrounding regions that have not historically been designed for such conditions. High-resolution Köppen-Geiger maps indicate that climate-zone boundaries are not fixed and that humid-hot conditions may expand geographically under future scenarios [1,42]. From the perspective of building science, this means that moisture-damage vulnerability may increasingly emerge in buildings whose envelopes, systems, and operation were not originally intended for persistent humid loading and limited drying.

The significance of this expansion is not simply that climate zones shift, but that existing building stocks may become mismatched to their changing climatic context. Buildings designed under assumptions of more effective drying, lower dew-point conditions, or less sustained latent load may become progressively more vulnerable as humid exposure intensifies. This issue also has a social dimension. When gridded climate classifications are overlaid with population datasets, the potential number of people living in moisture-risk zones increases markedly from 2000 to 2020 and further toward 2050 [42,44,45]. The global distribution of hot-humid and humidification-related moisture-risk zones, together with the associated increase in population exposure, is shown in Figure 3.

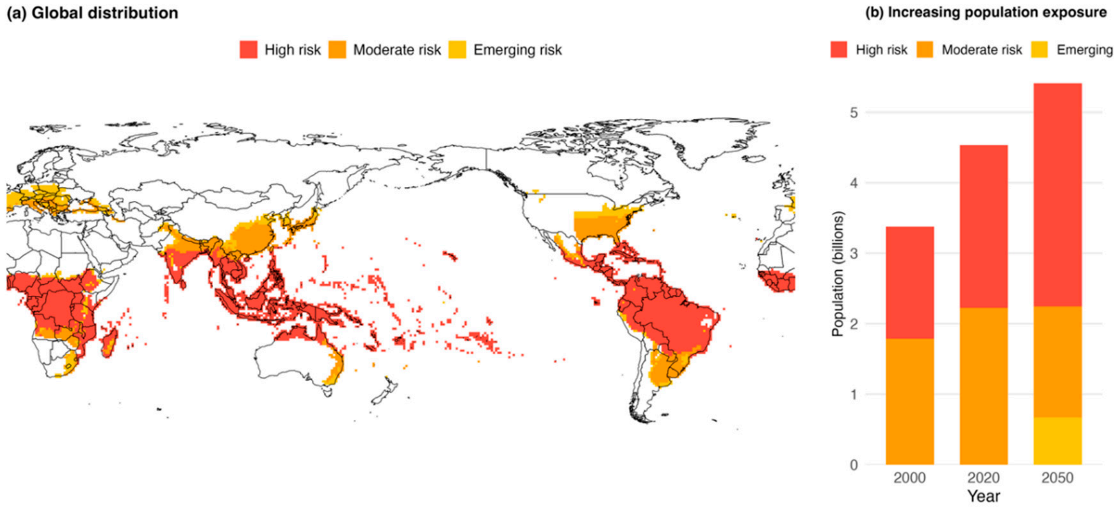

Figure 3. Global distribution of hot-humid and humidification-related moisture-risk zones and associated population exposure: (a) global distribution of risk categories derived from climate classification; and (b) estimated population exposure in 2000, 2020, and 2050.

Accordingly, the study of moisture damage in hot-humid regions should not be limited to present-day subtropical or tropical settings alone. It is equally relevant to regions that are moving toward more persistently humid conditions and in which existing buildings may increasingly experience moisture problems not anticipated in their original design context.

4. Moisture Transport, Accumulation, and Limited Drying in Building Envelopes

To understand how climatic conditions are translated into moisture damage in buildings, it is necessary to examine the physical mechanisms through which moisture enters, moves within, accumulates in, and is released from building envelopes. In hot-humid buildings, humid outdoor air, rainfall, cooling, air leakage, and moisture storage within materials act together to shift the moisture balance toward the wet side [9,10,28,32]. The key issue is therefore not only whether moisture enters the envelope, but whether the moisture that enters can subsequently leave it. Figure 4 summarizes the major transport and storage mechanisms through which moisture enters, accumulates in, and is released from building envelopes.

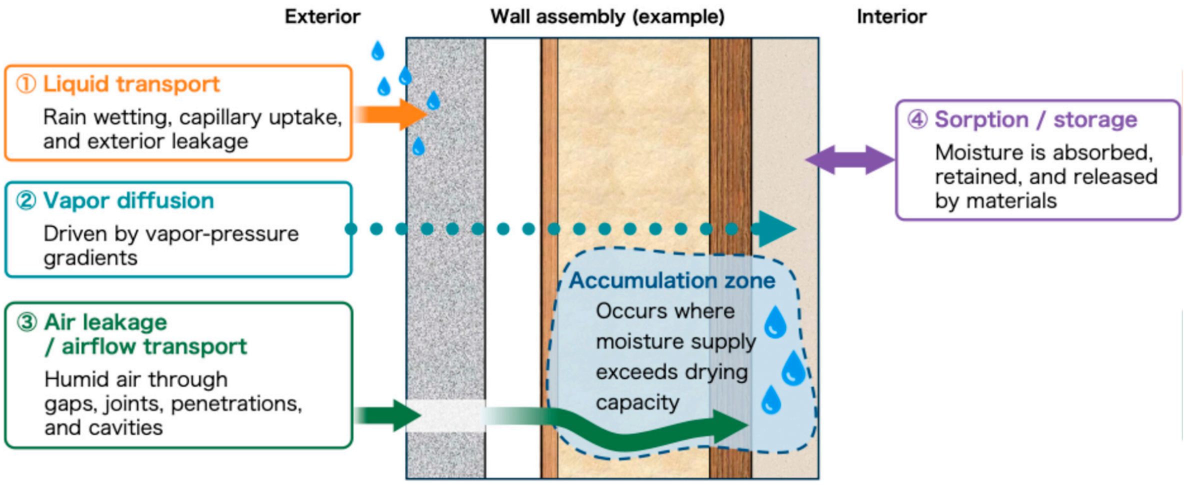

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Figure 4. Schematic representation of major moisture transport and storage mechanisms in building envelopes. Liquid transport is shown primarily at exterior layers or interfaces. Arrows indicate typical directions of moisture entry or redistribution and do not imply that all mechanisms reach the indoor surface directly.

In cold climates, moisture damage has often been framed in terms of vapor migration from the indoor side toward colder layers during winter. In hot-humid buildings, by contrast, the dominant patterns may be reversed or more complex. Moisture may enter from the exterior side under high outdoor vapor pressure, while cooling lowers temperatures near the interior side and thereby promotes condensation or prolonged high RH within the assembly [28,29,32]. Under such conditions, even modest wetting may become problematic when drying is chronically weak.

4.1. Relation to HAM-Based Hygrothermal Modelling Frameworks

The drying-deficit framework proposed in this review is closely related to established heat, air, and moisture (HAM) modelling approaches. HAM-based hygrothermal models describe transient heat and moisture transport in building components under specified indoor and outdoor boundary conditions [32,41,46]. These boundary conditions include temperature, relative humidity, vapor pressure, rain exposure, radiation, material properties, and surface transfer coefficients. Such models provide physically based outputs such as temperature distribution, RH, vapor flux, liquid transport, and material moisture content, which are essential for evaluating where and when moisture accumulation occurs.

The drying-deficit concept is not intended to replace HAM-based simulation tools such as WUFI or DELPHIN. Rather, it provides an interpretive framework for reading their outputs under hot-humid boundary conditions. Hygrothermal simulation allows designers and researchers to predict the temperature and moisture conditions that may occur within a building envelope assembly over time, while also requiring careful attention to input assumptions, material data, and boundary conditions [41]. In cold-climate assessment, attention often focuses on whether winter vapor diffusion or air leakage causes condensation at cold layers. In hot-humid buildings, however, the key concern is often whether humid outdoor air, rain-related wetting, and inward vapor drive during cooling produce persistent high RH or material moisture content that cannot be relieved before the next wetting or humid exposure event [28,29,32].

From this perspective, HAM simulation results should be interpreted not only in terms of peak condensation or maximum moisture content, but also in terms of drying time after wetting, cumulative hours above critical surface or material RH, persistence of high moisture content near cooled layers, and the balance between inward moisture loading and available drying pathways. These variables connect transient hygrothermal simulation to the operational definition of drying deficit introduced in Section 3.1. They also align with moisture-control design approaches that evaluate moisture damage risk in relation to climate, construction type, material response, and HVAC system operation [47].

This connection is particularly important for hot-humid design and retrofit because small changes in material layering, vapor resistance, cavity ventilation, rain exposure, airtightness, or indoor cooling setpoints can change both the location of moisture accumulation and the direction in which drying is possible. Therefore, physically based hygrothermal modelling should be used not only to check whether condensation occurs, but also to evaluate whether the assembly has sufficient recovery capacity under repeated wetting and chronically humid boundary conditions.

4.2. Moisture Entry and Accumulation Under Hot-Humid Boundary Conditions

A useful way to understand envelope moisture behavior in hot-humid buildings is to consider the balance between moisture supply and drying capacity [10,41,46]. Moisture supply may come from humid outdoor air, rain penetration, leakage-driven convection, capillary redistribution, or adsorption into porous materials. Drying capacity depends on the outdoor and indoor boundary conditions, material permeability, drainage paths, ventilation pathways, and the temperature and vapor-pressure gradients acting across the assembly.

Moisture damage becomes chronic when moisture supply repeatedly exceeds the capacity of the building part to dry. This balance-based perspective is especially important in hot-humid climates because the external conditions that support drying are often weakened by high outdoor humidity, frequent rain, and warm nights. As a result, moisture accumulation should not be understood simply as the outcome of isolated failures such as leakage or condensation, but as the cumulative result of repeated wetting under limited recovery conditions.

4.3. Major Transport Mechanisms

Moisture behavior in building envelopes can be understood through four major processes: vapor diffusion, airflow-related moisture transport through leakage, liquid transport, and sorption/storage in materials [9,10,32]. These processes do not act independently. In hot-humid environments, they often overlap and interact, especially when drying remains limited for extended periods.

Vapor diffusion occurs in response to vapor-pressure gradients. Under hot-humid summer conditions, outdoor vapor pressure often exceeds indoor vapor pressure, particularly when indoor spaces are cooled. This may drive moisture inward rather than outward, in contrast to the conventional winter pattern emphasized in cold-climate condensation control [28,32]. Under these conditions, vapor-control strategies imported directly from cold climates may become problematic if they restrict inward drying.

Air leakage may transport substantially larger amounts of moisture than diffusion and is often a critical pathway in hot-humid buildings [9]. Even small leakage paths may carry moisture-laden outdoor air into wall cavities, attic zones, crawl spaces, or service spaces. This becomes especially important when cooled indoor spaces are under negative pressure, since humid outdoor air is then readily drawn inward through cracks, penetrations, and interfaces. Localized hidden moisture loading may therefore occur even when overall thermal performance appears adequate.

Liquid transport includes rain wetting, minor rainwater penetration at exterior layers or interfaces, capillary transport, and retained water at surfaces or material contacts [10,32]. In hot-humid buildings, rainfall events are frequent and may recur before drying is complete. Repeated small-scale rewetting can therefore sustain chronically high moisture content even without dramatic leakage events. For this reason, moisture safety depends not only on preventing water entry, but also on providing drainage and recovery pathways once wetting occurs.

Sorption and moisture storage in porous materials further affect both short-term fluctuations and long-term accumulation [10,32]. Moisture-buffering behavior may moderate indoor humidity over short timescales, but when high humidity persists and drying is limited, the same materials may function as reservoirs that retain moisture over long periods. In hot-humid climates, the role of sorptive materials must therefore be evaluated in relation to their actual drying opportunities and their position within the envelope.

4.4. Drying Limitation as the Governing Principle

The central physical issue in hot-humid moisture damage is not moisture entry alone, but limited drying potential. Drying is governed by vapor-pressure difference, temperature, airflow, radiation, material permeability, drainage, and ventilation pathways [10,28,32]. In many temperate climates, periodic dry conditions allow wetted assemblies to recover at least partially. In hot-humid climates, however, high absolute humidity, high dew-point temperature, frequent rainfall, and weak nighttime cooling often reduce the strength and duration of drying conditions.

This means that moisture problems in hot-humid buildings are best interpreted as failures of recovery rather than only failures of exclusion. A wall, roof, or surface may tolerate a certain amount of wetting if sufficient drying follows. The same wetting load may become problematic if recovery is blocked by climate conditions, impermeable finishes, concealed geometry, or weak airflow. This perspective is important because it shifts the discussion from isolated defect events toward a more general building-physics understanding of chronic dampness.

4.5. Cooling, Ventilation, and Pressure-Related Moisture Loading

Cooling, ventilation, and pressure control play a particularly important role in hot-humid buildings because they shape where moisture risk becomes concentrated. Cooling lowers temperatures near the indoor side and may create locally cool surfaces within envelopes, behind furniture, around ducts, or near supply outlets [10,28]. When moisture from humid outdoor air reaches such surfaces, prolonged high surface RH or condensation may occur.

Ventilation in hot-humid buildings has a dual character. It is necessary for indoor air quality, yet it may also introduce moisture when outdoor air has high absolute humidity [10,28]. The assumption that greater ventilation automatically improves moisture safety does not hold under such conditions. What matters is not ventilation rate alone, but when ventilation occurs, under what outdoor conditions, and whether latent load is controlled through dehumidification.

Pressure differences and leakage pathways further complicate this issue. If indoor spaces are cooled and operate under negative pressure, humid outdoor air may be drawn into wall cavities, attics, crawl spaces, or service zones [9,28,29,37]. Moisture risk therefore depends not only on vapor resistance, but also on airtightness continuity, pressure control, and the interaction between planned ventilation and unintended airflow paths.

Taken together, these mechanisms show that moisture accumulation in hot-humid envelopes rarely results from a single process. Rather, it emerges from the combined action of diffusion, leakage, liquid transport, sorption, and insufficient drying under boundary conditions shaped by humid climate and cooling-dependent building operation.

5. Moisture and Mold Risk Assessment in Hot-Humid Buildings

Because hot-humid buildings are frequently exposed to persistently elevated humidity and limited drying, moisture-damage risk cannot easily be judged from experience alone. Quantitative indices derived from time histories of temperature, RH, and surface conditions have therefore been widely used for design comparison, performance evaluation, and post-processing of measured or simulated conditions [11–21]. These methods provide a useful means of interpreting hazardous environmental conditions, even when direct microbiological measurements are not available.

At the same time, it is important to recognize that most moisture and mold risk indices do not represent microbial quantity itself. Rather, they indicate environmental suitability for growth or moisture-related hazard. This distinction becomes especially important in hot-humid climates, where high humidity may persist for long periods and where many indices tend to remain on the high-risk side, saturate, or lose discriminatory power [11–15,17,18]. The central question is therefore not simply which index is most accurate, but what each index represents and how it should be interpreted under persistently humid conditions.

5.1. Categories of Assessment Methods

Moisture-damage assessment methods may be grouped broadly into threshold-based approaches, empirical growth-index approaches, isopleth- or germination-based approaches, cumulative and recovery-sensitive approaches, and probabilistic approaches [11–21]. These groups differ in what their outputs mean and in how useful they are under different climatic conditions.

Threshold-based methods evaluate the duration for which conditions exceed critical limits, such as high RH, condensation occurrence, or time of wetness. Their advantage lies in their clarity, but in hot-humid buildings they often remain in the risky range for long periods and therefore offer limited discrimination once critical conditions have been exceeded.

Empirical growth-index approaches, including FI and the VTT Mold Index, express risk as a continuous index derived from temperature and humidity histories [11,12,16,19–21]. These methods are useful because they allow comparative interpretation rather than a simple binary judgment. However, under persistent humid exposure, they may remain chronically high or saturate.

Isopleth-based approaches, such as IBP-type models, define combinations of temperature and RH at which growth becomes possible [15,18]. These are particularly useful for identifying growth-permissive regions on the temperature-humidity plane but are less effective on their own for representing long-term accumulation and recovery under chronic moisture stress.

Cumulative and recovery-sensitive approaches, including MRD and DR-SIM, attempt to incorporate not only humidity exposure but also drying and delays in renewed growth after drying [13,14]. These are conceptually closer to the structure of hot-humid moisture problems, yet they still assume that some meaningful drying occurs. Probabilistic approaches are promising in principle because they address uncertainty explicitly, but their practical application in hot-humid contexts remains limited by data availability [17,18]. The major moisture and mold risk assessment methods discussed in this review, together with their main outputs, treatment of drying or recovery, strengths, and interpretive limitations under hot-humid conditions, are compared in Table 2.

Table 2. Major moisture and mold risk assessment methods.

Method	Output	Drying / recovery	Interpretation under hot-humid conditions
Threshold	Hours above RH, temperature, or condensation limits	Counted mainly as time below/above threshold	Simple screening, but weak for growth stage and material response
FI	Fungal favorability from temperature–RH history	Responds to humid episodes; limited recovery representation	Useful warning index, but may remain chronically high
VTT	Mold growth stage, usually 0–6	Includes material sensitivity and retardation/decline under dry conditions	Useful for envelopes, but may saturate under sustained humidity
IBP-type	Growth-permissive temperature–RH range	Mainly threshold/isopleth based	Clear growth boundary, but limited cumulative-history treatment
MRD	Mold resistance/risk under varying climate	Includes climate variation and resistance concept	Design-oriented, but depends on material/exposure assumptions
DR-SIM	Dynamic mold-risk dose	Includes dose accumulation and drying-related delay	Captures dynamic exposure, but validation under chronic hot-humid exposure remains limited
Probabilistic	Probability of occurrence	Can include climate/material uncertainty	Useful for uncertainty, but data-intensive

Note: Drying does not necessarily remove biological risk after germination or visible growth. Models differ in how they treat non-exceedance, retardation, decline, delayed regrowth, and probabilistic risk reduction.

5.2. Characteristics and Positioning of Fungal Index and the VTT Mold Index

FI is an empirical index developed in Japanese indoor environmental research to express the favorability of an environment for fungal growth based on temperature and RH history [16,19,20]. A notable strength of FI is its sensitivity to transient humid episodes and condensation-related conditions, which makes it useful in residential contexts where short-term humid spikes are important. However, FI does not explicitly account for material type or fungal species, and in hot-humid climates it may remain persistently high, thereby functioning more as a warning-type indicator than a fine comparative metric.

The VTT Mold Index is a semi-empirical approach derived from the work of Hukka, Viitanen, and colleagues [11,12,21]. It represents mold growth stage on a scale from 0 to 6 while incorporating temperature, RH, and to some extent material sensitivity. Compared with FI, it offers a more structured representation of growth stage and material response. At the same time, because it was developed in the context of building envelopes that generally experience some degree of drying, its discriminatory power may also decrease under persistently humid hot-humid conditions where the index may reach high levels relatively early.

Both FI and the VTT Mold Index therefore remain useful in hot-humid buildings, but their outputs should be read carefully. High values do not necessarily provide a nuanced ranking of alternatives once chronic humidity dominates. Instead, they often indicate that the environment has shifted into a regime where drying is already insufficient and where environmental hazard is persistent. Figure 5 presents an example time series showing how field-measured surface temperature and surface RH can be interpreted using representative moisture and mold risk indices.

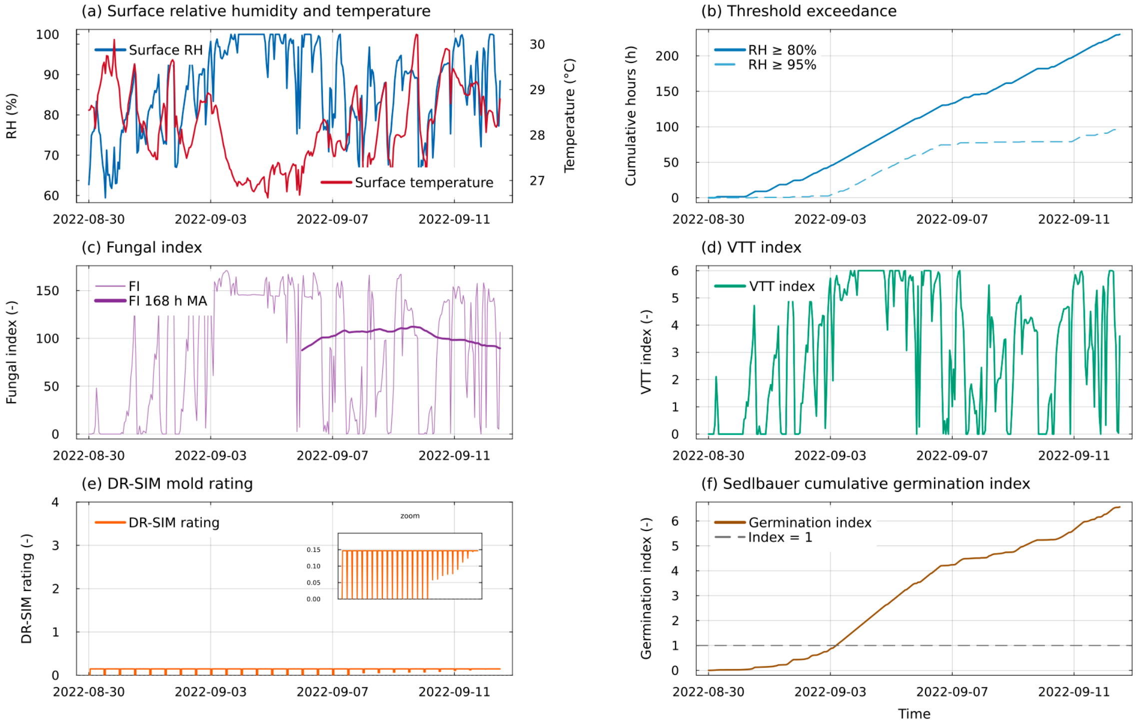

Figure 5. Example time series of surface hygrothermal conditions and representative moisture/mold risk indices, including threshold exceedance, FI, VTT, DR-SIM, and Sedlbauer-based indicators, calculated from field-measured surface temperature and surface RH. Data are from the author's own field measurements in a reinforced-concrete dwelling in Okinawa, Japan, and are used here as an illustrative example of index behavior rather than as a validation dataset.

5.3. Significance of IBP, MRD, DR-SIM, and Probabilistic Approaches

IBP-type models are valuable because they clarify the boundary at which fungal germination or growth becomes possible [15,18]. Their conceptual clarity makes them useful for identifying whether instantaneous conditions have entered growth-permissive regions. However, they are less suited on their own to describing cumulative burden or the practical consequences of repeated wetting under weak recovery.

MRD and DR-SIM are more directly relevant to hot-humid conditions because they attempt to integrate cumulative exposure, varying climatic conditions, and some form of recovery or delayed renewed growth [13,14]. In this sense, they move closer to the actual problem structure of drying deficit than simple threshold exceedance alone. However, the interpretation of drying in mold-risk models requires caution. Drying or low-RH periods may slow further growth, delay renewed growth, or reduce an index value depending on model formulation, but they do not necessarily eliminate biological risk once germination or visible growth has occurred. Fungal structures may survive unfavorable periods and resume growth when favorable temperature–humidity conditions return [11,12,21].

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This distinction is especially important in hot-humid buildings. If drying periods are short, weak, or spatially limited, they may not be sufficient to interrupt the cumulative development of risk even when a model formally includes a drying or decline function. Therefore, for hot-humid assessment, the key question is not simply whether drying is represented in a model, but whether the actual building element, surface, or concealed space experiences drying that is strong and long enough to produce meaningful recovery.

5.4. Shared Applicability Limits Under Hot-Humid Conditions

Although FI, VTT, IBP, MRD, and DR-SIM differ in formulation and output type, they share a common interpretive challenge in hot-humid environments. Because humid exposure is sustained and drying is weak, many models tend to remain on the wet or high-risk side [11–18,21,47]. This is useful for signaling that hazardous conditions exist, but it may reduce resolution when the purpose is to compare subtle design alternatives or operational differences.

Importantly, these high outputs should not simply be dismissed as model failure. In many cases, they reflect the fact that the drying or recovery processes represented in the models may be too weak, too short, or too infrequent under actual hot-humid building conditions to reduce risk meaningfully. Under these circumstances, model outputs should be interpreted not only as predictions of growth stage or hazard, but also as indicators of the severity and persistence of drying deficit. Comparative applications of mold-growth models also show that risk classification can vary depending on the selected model, material assumptions, climate file, and evaluation criterion, reinforcing the need to interpret model outputs as decision-support indicators rather than direct measurements of microbial contamination [48].

5.5. How Moisture/Mold Risk Indices Should Be Interpreted

At least three points are important when interpreting moisture and mold risk indices in hot-humid buildings. First, it is necessary to distinguish whether a model output mainly represents threshold exceedance, growth stage, cumulative hazard, or probability of occurrence. Second, persistent high values or saturation should be understood as reduced discriminatory power under chronic humidity, rather than only as methodological defects. Third, these indices should not be treated as final evidence on their own, but should be interpreted together with microbial measurements, material response, and exposure relevance.

In this sense, moisture and mold risk indices remain valuable in hot-humid assessment, but primarily as comparative and interpretive tools. Their greatest usefulness lies not in providing a single definitive answer, but in helping to characterize how hazardous environmental conditions are formed, sustained, and limited by drying deficit.

6. From Hygrothermal Hazard to Microbial Load and Exposure

Moisture and mold risk indices describe conditions that are favorable for microbial growth, but they do not directly represent the amount of microbial material actually present on surfaces or the degree to which occupants are exposed. In parallel, the same hygrothermal conditions may also contribute to material deterioration and performance loss. The pathways linking hygrothermal conditions with microbial accumulation, exposure, and material deterioration are conceptually illustrated in Figure 6. This distinction is fundamental in hot-humid buildings, where environmental hazard may remain high for long periods, while actual microbial accumulation and exposure are shaped additionally by deposition, retention, resuspension, cleaning, material properties, and airflow patterns [22,24,25].

Accordingly, moisture damage in hot-humid buildings should be understood through multiple connected but non-equivalent layers: hygrothermal indicators describe environmental suitability; surface microbial load describes accumulation and persistence; community structure describes ecological response to environmental history; and airborne concentration and transport relate more directly to exposure. These layers are linked, but they are not interchangeable.

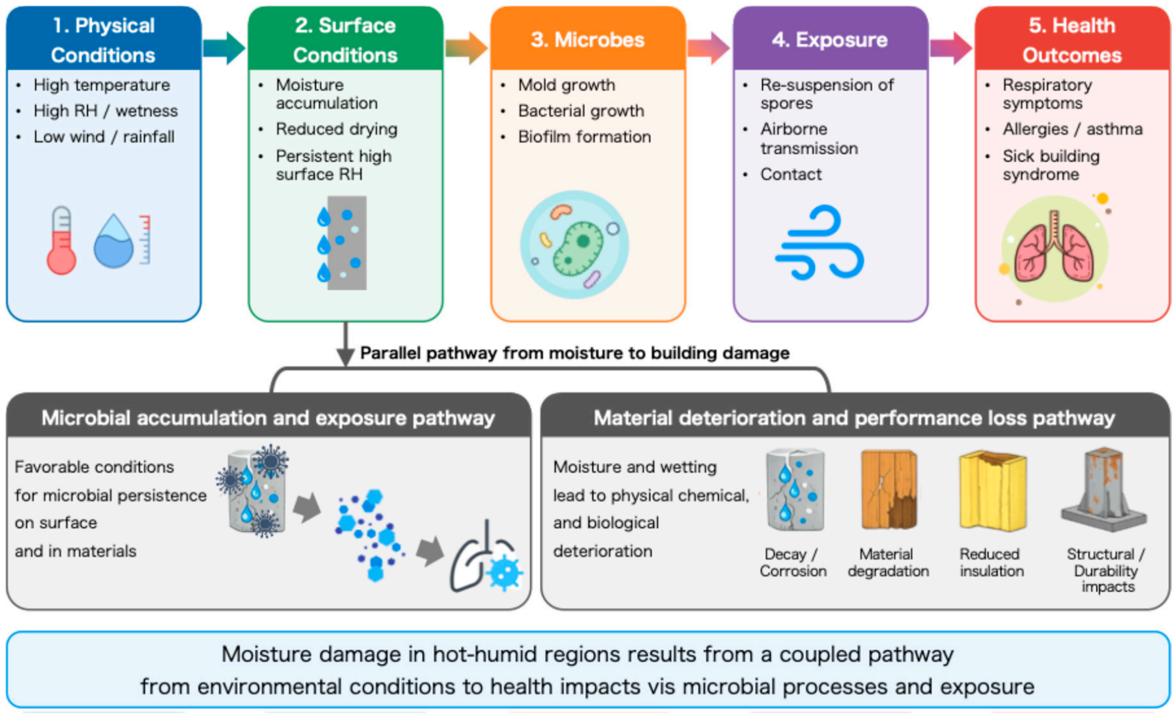

Figure 6. Conceptual pathways linking hygrothermal conditions with microbial accumulation, exposure potential, and material deterioration or performance loss.

6.1. Sources and Persistence of Indoor Microorganisms

Indoor microorganisms do not arise from a single source. They are influenced by outdoor air, ventilation pathways, occupants, pets, clothing, settled dust, and growth or persistence on interior surfaces [22–24]. In hot-humid buildings, these influences are further modified by the coexistence of humid outdoor boundary conditions, cooling, localized dampness, and limited recovery after wetting.

Microorganisms detected on indoor surfaces do not necessarily indicate only in situ growth. They may also include deposited spores, cell fragments, and DNA residues remaining from past wet periods [22,25]. Surface microbial load should therefore be interpreted as an accumulated record shaped by deposition, persistence, and removal, rather than as a direct snapshot of current environmental conditions alone.

6.2. Microbial Growth Thresholds, Time Scales, and Surface Conditions

The transition from hygrothermal hazard to microbial accumulation depends on whether favorable temperature–humidity conditions are sustained for a sufficient period at the relevant surface or material. Mold growth is commonly related to surface RH, temperature, substrate sensitivity, nutrient availability, spore availability, and exposure duration rather than to room-average air conditions alone [11,12,15,18,21,49]. Therefore, a short-term exceedance of a humidity threshold does not necessarily lead to measurable microbial accumulation, whereas repeated or prolonged exceedance can support germination, growth, survival, or residue accumulation.

In hot-humid buildings, this distinction is particularly important because the relevant exposure may occur at local surfaces, inside assemblies, or in semi-enclosed spaces rather than in the room air measured at a central location. Behind furniture, inside closets, near cooled surfaces, at duct-adjacent zones, or within cavities, surface temperature and surface RH may differ substantially from room-average conditions. These local microclimates can determine whether spores remain dormant, germinate, continue growing, or persist after growth has slowed.

The time scale of microbial response also differs from the time scale of hygrothermal fluctuation. Temperature and RH can change within minutes or hours, whereas microbial load measured by culture, qPCR, sequencing, or dust analysis may reflect cumulative exposure over days, weeks, or longer. For this reason, hot-humid moisture assessment should consider not only instantaneous RH or temperature, but also wetness duration, cumulative high-RH exposure, drying intervals, and the persistence of material moisture.

6.3. Why Hygrothermal Indicators and Microbial Measurements Do Not Coincide

Hygrothermal indicators and microbial measurements do not necessarily coincide because they represent different aspects of the moisture-damage process. Hygrothermal indices describe whether the environment is favorable for initiation, growth, or persistence, whereas microbial measurements reflect what remains on a surface or in air after deposition, growth, death, fragmentation, cleaning, and resuspension have all taken place.

The interpretation also depends on the measurement method. Culture-based methods represent viable and culturable organisms under selected laboratory conditions, but they may underestimate non-culturable or stressed microorganisms. Quantitative PCR can detect microbial DNA from both viable and non-viable cells, spores, and fragments, and therefore may reflect cumulative deposition and persistence rather than current growth alone. Sequencing-based community analysis describes relative community structure, but not necessarily absolute microbial load unless combined with quantitative methods. Airborne measurements are more directly related to inhalation exposure, but they are highly sensitive to resuspension, airflow, sampling duration, occupant activity, and filtration [22–25,50,51].

At least five factors are particularly important. First, airborne deposition may increase surface DNA or particle counts even when growth does not occur locally. Second, time-history effects matter because DNA, spores, fragments, and residues may remain after favorable conditions have passed. Third, material properties influence settlement, moisture retention, nutrient availability, and persistence. Fourth, local microclimate often differs from room-average conditions. Fifth, operation and maintenance—including cooling pattern, airflow, ventilation, window opening, filtration, and cleaning frequency—strongly affect what remains on surfaces and what becomes airborne again [22–25].

For these reasons, there may be cases in which hygrothermal indices are high but microbial quantity does not increase proportionally, as well as cases in which microbial load remains elevated after environmental indices have declined. This mismatch should not be interpreted simply as model failure. Rather, it reflects the layered structure of the problem. A comparison between physical indicators and microbial measurements in hot-humid buildings is provided in Table S3.

6.4. Community Structure as an Ecological Response Layer

In hot-humid environments, moisture-related microbial problems may appear not only as increased quantity, but also as shifts in community structure. Persistent humid conditions, repeated wetting, and weak drying may favor taxa that tolerate high water activity or repeated humid exposure, while differences in building openness, ventilation pathways, cooling dependence, and surface materials may influence which communities are repeatedly introduced, retained, or selected [22–25].

Community-structure analysis is therefore useful not merely for identifying which microorganisms are present, but for interpreting the environmental and operational history that has shaped the observed assemblage. For example, differences between outdoor-air-dominated, occupant-associated, dust-associated, and dampness-associated communities may indicate different source and transport pathways. However, community composition should not be interpreted as a direct measure of exposure or health risk without information on absolute abundance, viability, particle size, resuspension, and transport to occupied zones.

In this review, community structure is therefore positioned as an intermediate ecological response layer. It helps connect hygrothermal history and microbial persistence, but it should be interpreted together with quantitative microbial load, physical moisture indicators, and exposure-related measurements.

6.5. Moisture Damage from the Perspective of Exposure

Moisture damage matters not only because it affects materials and microbial persistence, but also because occupants may be exposed to spores, fragments, cells, and metabolites derived from damp or contaminated surfaces. This exposure relevance is consistent with health-oriented reviews showing that damp indoor environments are associated with increased risk of respiratory symptoms and related adverse outcomes, even when the responsible microbial pathways are not reducible to a single measured indicator [50,51]. Even here, however, the amount present on a surface is not the same as the amount inhaled. Exposure depends on resuspension, airflow, human movement, filtration, and the connection between microbial sources and occupied zones.

This point is particularly important in hot-humid buildings, where cooling-dependent operation may alter airflow fields, create stagnant zones, and change the transport pathways between hidden sources and occupied spaces. Some concealed damp zones may remain poorly connected to breathing zones, while other surfaces—such as floors, filters, or locations near supply airflow—may contribute more directly to airborne exposure. Moisture-damage assessment in hot-humid buildings therefore requires not only building physics and microbiology, but also an exposure-oriented perspective on how material from damp sources moves toward occupants.

6.6. A Hierarchical Interpretation Framework

Based on the above, moisture damage in hot-humid buildings can be interpreted hierarchically across at least four levels:

(1) **hygrothermal hazard**, represented by moisture or mold risk indicators;
(2) **surface microbial load**, represented by DNA or cultivable counts;
(3) **community structure**, representing ecological response to environmental history; and
(4) **airborne concentration and transport**, representing exposure potential.

These layers are complementary rather than competing. The goal is not to reduce them to a single metric, but to interpret how drying deficit, localized dampness, microbial persistence, and exposure are linked across space and time. This layered framework is especially important in hot-humid buildings, where sustained environmental suitability does not necessarily translate linearly into microbial load or exposure, but nevertheless creates the conditions under which both may become important.

7. Implications for Envelope Design, Retrofit, and Building Operation

The preceding discussion makes clear that moisture control in hot-humid buildings cannot be reduced to isolated condensation checks or to single-component improvements. Moisture loading, hidden accumulation, local dampness, and microbial persistence emerge through the interaction of climate, envelope configuration, cooling, ventilation, pressure differences, and operation [28,29,33]. Effective moisture control therefore requires integrated building adaptation rather than fragmented countermeasures.

In hot-humid buildings, the key objective is not simply to prevent moisture entry, but to secure drying after wetting while avoiding moisture trapping. This perspective has implications for envelope design, material selection, ventilation strategy, cooling and dehumidification operation, and retrofit practice.

7.1. Envelope Design

Envelope design should address rain control, drainage, airtightness, vapor permeability, and drying pathways as an integrated system [28,29,33]. In addition to minimizing water entry through interfaces, penetrations, and openings, assemblies should be designed so that any moisture that does enter can drain and dry. This is especially important in hot-humid climates, where repeated small-scale wetting may accumulate if recovery is weak.

Cold-climate vapor-control logic should not be transferred directly without modification. Strong interior vapor retarders or low-permeance interior finishes may help suppress winter moisture migration in cold climates, but in hot-humid buildings they may restrict inward drying and increase the likelihood of moisture trapping [28,29,37,52]. Envelope design should therefore be based on realistic moisture-entry pathways and available drying directions rather than one-way assumptions about vapor control.

7.2. Material Selection

Material selection in hot-humid buildings should consider not only thermal or sorptive properties, but also long-term moisture retention, drying behavior, biological susceptibility, and the position of the material within the assembly. Materials with high moisture-buffering capacity may moderate short-term humidity fluctuations, yet under persistently humid conditions they may also retain moisture and sustain favorable conditions for microbial persistence if drying opportunities are limited.

Potentially suitable material strategies include vapor-open interior finishes where inward drying is required, drained and ventilated cladding systems, moisture-tolerant sheathing, exterior coatings with resistance to biological fouling, and assemblies that combine rain control with a clear drying path. Inorganic or moisture-tolerant materials may be advantageous in locations where intermittent wetting is expected, provided that surface condensation and retained dirt or nutrients are also controlled.

Conversely, potentially problematic strategies include low-permeance interior finishes that block inward drying, moisture-sensitive organic materials placed near cooled or poorly ventilated layers, impermeable coatings applied to surfaces that require drying, and assemblies in which absorptive materials are enclosed between vapor-resistant layers. Vinyl wall coverings, foil-faced layers, low-permeance paints, or highly absorptive organic boards may become risky when they are placed on the wrong side of the assembly or used without drainage, ventilation, or drying capacity.

These examples should not be interpreted as universal prescriptions. In hot-humid buildings, material suitability depends on climate exposure, wetting mechanism, drying direction, local temperature, airflow, maintenance, and the likelihood of biological contamination. The key design question is therefore not whether a material is intrinsically “safe,” but whether the material and its surrounding assembly can tolerate wetting and recover before moisture damage develops. Therefore, material selection should be evaluated at the assembly level rather than at the material level alone. A material that is moisture-tolerant in one configuration may become risky when combined with low-permeance layers, poor drainage, weak airflow, or a cooled adjacent surface.

7.3. Ventilation, HVAC, and Pressure Control

Ventilation and heating, ventilation, and air-conditioning (HVAC) operation in hot-humid climates must be evaluated together with latent-load control, pressure management, and envelope moisture safety [37,52]. Ventilation in hot-humid buildings has two roles. It is an air-quality strategy, but it can also become a pathway for moisture entry [10,28]. This caution is particularly important when outdoor-air introduction or unbalanced airflow increases latent moisture loading, especially in buildings affected by duct leakage or pressure-driven infiltration [9,28,29,37]. It is therefore not sufficient simply to provide the required ventilation rate. Designers must also consider outdoor-air humidity, moisture-entry pathways, and whether ventilation is coupled with latent-load control.

Moisture risk differs among HVAC configurations. In naturally ventilated or mixed-mode buildings, outdoor air exchange may support thermal comfort and dilution under favorable conditions, but it can increase indoor absolute humidity during high-dew-point periods. In split-air-conditioner systems, sensible cooling may be achieved locally while latent removal, air mixing, and concealed-space conditions remain insufficient. In ducted systems, duct leakage and pressure imbalance may draw humid outdoor air into attics, crawl spaces, wall cavities, or service zones, especially when the conditioned zone operates under negative pressure. Systems that introduce outdoor air without adequate dehumidification can increase latent load, whereas dedicated outdoor-air treatment or controlled dehumidification can reduce moisture accumulation if properly integrated with envelope airtightness and drainage. Ducts and air-handling components themselves may also become moisture-risk locations when humid air contacts cold duct surfaces, poorly insulated ducts, cooling coils, drain pans, or stagnant sections of the system. Condensation within or on HVAC components can support microbial accumulation if drainage, insulation, filtration, cleaning access, and maintenance are insufficient. Therefore, HVAC moisture control should include not only room conditions, but also duct insulation, condensate drainage, filtration, inspection access, and regular maintenance.

Planned ventilation and uncontrolled leakage should be distinguished clearly. Planned ventilation can be designed, filtered, conditioned, and balanced, whereas leakage may deliver humid air directly to vulnerable hidden locations. Pressure control is also important because cooled indoor spaces operating under excessive negative pressure may draw moisture-laden outdoor air into wall cavities, attics, or service spaces. Ventilation and HVAC design should therefore not be considered independently. In hot-humid buildings, they must be integrated with airtightness, pressure balance, drainage, and dehumidification.

7.4. Cooling and Dehumidification Operation

Cooling in hot-humid climates should be understood not only as sensible heat removal, but also as moisture control. Even when indoor temperature is acceptable, local dampness and condensation risk may remain high if RH, dew point, or local surface cooling are not well managed [12,28]. Cooling strategy should therefore address both latent load and the distribution of surface temperatures.

Temperature-only control can be problematic in hot-humid buildings. Intermittent cooling may lower surface temperatures while leaving indoor or concealed-space humidity high, thereby increasing the risk of localized high surface RH after shutdown or during humid recovery periods. Oversized cooling equipment may also satisfy sensible load quickly without sufficient runtime for dehumidification. Conversely, continuous or controlled dehumidification can reduce latent load, but it must be coordinated with ventilation, envelope airtightness, and pressure balance to avoid drawing humid outdoor air into vulnerable assemblies.

Particularly important is the avoidance of localized low-temperature surfaces in poorly ventilated areas such as behind furniture, in closets, near floor edges, around ducts, or near supply outlets. In practical terms, this means that cooling and dehumidification should be coordinated, airflow should be sufficiently distributed, and control targets should include humidity-related variables such as indoor RH, dew point, or surface RH rather than temperature alone. Where feasible, operation should aim to avoid long periods of high indoor RH and to prevent high-dew-point outdoor air from reaching cooled hidden surfaces.

Passive measures that reduce cooling demand can also contribute to moisture safety. External shading, roof overhangs, solar-control glazing, reflective or ventilated roof assemblies, and reduction of internal heat gains can lower cooling intensity and reduce the occurrence of locally cold surfaces. However, such measures should be coordinated with ventilation and drying pathways, because reducing sensible cooling demand alone does not necessarily resolve latent moisture load.

7.5. Retrofit Implications

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Retrofit practice may intensify moisture risk if thermal upgrading changes the moisture balance of the building without adequate attention to drying pathways [28,29,33]. Added insulation, improved windows, tighter envelopes, or altered system operation may unintentionally create new locations of lowered surface temperature, changed vapor-resistance distribution, or concealed moisture stagnation.

Retrofit planning in hot-humid buildings should therefore evaluate rain exposure, drainage, leakage routes, concealed spaces, cooling operation, and realistic drying directions together. Higher thermal performance is not inherently problematic; the problem arises when improved thermal control is achieved without corresponding attention to moisture removal and recovery.

7.6. Key Adaptation Principles

Taken together, the discussion above suggests several key principles for hot-humid building adaptation. Moisture-entry pathways should be minimized, but avoidance of moisture trapping is equally important. Drying after wetting should be explicitly secured through drainage, permeability, airflow, or operational control. Ventilation should not be assumed to improve moisture safety automatically under high-dew-point conditions. Latent-load control must be treated as central rather than secondary. Concealed spaces and local low-airflow zones should be regarded as critical risk locations. For practical application, the key issues relevant to envelope design, retrofit, and building operation in hot-humid buildings are summarized in Table 3.

For practical assessment, these principles can be translated into a set of checkable diagnostic questions. First, where can moisture enter the assembly or space through rain, vapor diffusion, air leakage, capillary transport, or humid ventilation air? Second, where will the coldest surfaces or layers occur during cooling operation? Third, in which direction can the affected layer dry, and is that drying path blocked by low-permeance materials or stagnant cavities? Fourth, how long do surface RH, material moisture content, or concealed-space humidity remain above critical levels after wetting? Fifth, does the HVAC system remove latent load without creating excessive negative pressure or unintended humid-air pathways? These questions do not replace detailed hygrothermal simulation or field diagnosis, but they help translate the drying-deficit framework into design and retrofit decision-making.

Table 3. Key issues for design, retrofit, and operation.

Domain	Main risk	Moisture consequence	Practical response
Rain control / drainage	Repeated rain wetting	Exterior fouling; envelope moisture; delayed drying	Provide drainage, flashing, and drying paths
Airtightness / pressure	Humid air leakage	Hidden wetting; local high RH	Seal leakage paths; avoid negative pressure
Vapor resistance	Blocked drying direction	Summer condensation; moisture trapping	Check inward/outward drying potential
Material selection	Retentive or sensitive	Microbial persistence; deterioration	Use moisture-tolerant materials with drying capacity
Ventilation	Humid outdoor-air supply	Higher latent load; surface RH risk	Ventilate with humidity and pressure control
Cooling / dehumidification	Temperature-only control	Cold surfaces; high RH; condensation	Control latent load, dew point, and air distribution
Hidden spaces	Stagnant attics, voids, cavities	Concealed reservoirs of moisture and microbes	Provide access, drainage, drying, or conditioning
Operation / maintenance	Furniture, cleaning, use patterns	Persistence and exposure variability	Include operation and maintenance in design

Note: Practical responses should be selected according to climate exposure, assembly type, drying direction, HVAC system, and maintenance feasibility.

These principles suggest a broader adaptation shift: from temperate-climate moisture design centered on preventing winter condensation, toward hot-humid design centered on avoiding chronic accumulation, securing drying potential, and integrating envelope measures with operational moisture control. This shift does not imply reducing ventilation below health or code requirements. Rather, it means that ventilation in hot-humid buildings should be provided with humidity control, pressure balance, and latent-load management. In this sense, moisture control guidance for hot-humid buildings should be framed not only around rain exclusion and thermal efficiency, but also around pressure control, moisture release, and the avoidance of chronic moisture trapping during operation [37]. Figure 7 summarizes the broader shift in moisture-control logic required for design and retrofit in hot-humid buildings.

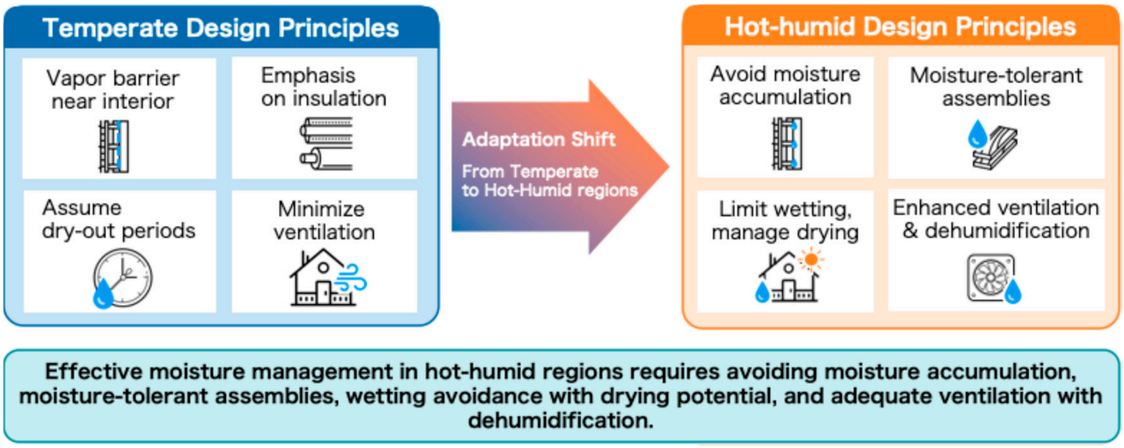

Figure 7. Schematic shift from temperate-climate moisture-control logic to hot-humid moisture-control logic, emphasizing humidity-controlled ventilation, latent-load control, pressure balance, and secured drying pathways.

8. Limitations and Future Research Needs

Despite the growing body of relevant work, important limitations remain in current research and assessment frameworks for moisture damage in hot-humid buildings. Climate research, envelope modelling, moisture-risk indicators, microbiological measurements, and practical building design have largely progressed in parallel rather than as an integrated field [28,29,37,46,52]. Yet the essence of moisture damage in hot-humid buildings lies precisely in the coupling among these domains. Future research should therefore move beyond general recognition of humid-climate risk and focus on methods that can quantify drying deficit, identify localized vulnerability, validate risk indicators, and translate findings into design and operational decisions.

8.1. Building-Relevant Drying-Deficit Metrics

A first priority is the development of practical drying-deficit metrics. In this review, drying deficit was defined as an imbalance between cumulative moisture supply and cumulative drying capacity over a specified time window. Future work should translate this concept into measurable indicators that can be applied to field monitoring, hygrothermal simulation, and design comparison. Candidate metrics include drying time after rainfall or condensation, cumulative hours above critical surface RH, duration of high material moisture content, vapor-pressure deficit during recovery periods, nighttime recovery potential, and the ratio between wetting duration and drying duration.

Such metrics should be evaluated at multiple levels: climate, envelope component, local surface, concealed space, and occupied zone. A single climate index is unlikely to represent all relevant mechanisms. For example, high outdoor dew point may indicate weak exterior drying, whereas surface RH behind furniture may indicate local indoor microclimate risk. Future studies should therefore clarify which drying-deficit proxies are most useful for exterior surfaces, wall assemblies, semi-enclosed spaces, and indoor surface contamination.

8.2. Climate Inputs and Moisture-Critical Weather Years

Many current assessments still rely on representative weather years or simplified indoor boundary conditions. In hot-humid buildings, however, moisture risk depends not only on air temperature and mean RH, but also on dew-point temperature, high-humidity duration, rainfall sequence, nighttime recovery, and drying time after wetting [1–3,26]. Future work should therefore focus on translating climate datasets into building-relevant moisture-severity variables rather than relying only on conventional general-purpose weather descriptors.

This need is closely related to the selection of hygrothermal reference years and moisture-critical weather files for simulation. Conventional weather files do not necessarily represent sequences that are critical for mold growth, rain wetting, or drying failure. Future studies should compare present and future climate files in terms of dew-point exceedance, vapor-pressure deficit, wind-driven rain, nighttime drying potential, and wetting–drying sequences. This would help connect climate change information to building-level outcomes such as longer drying times, higher surface RH, and increased risk of concealed moisture accumulation [47,53].

8.3. Envelope Models, Spatial Locality, and Transient Effects

Representative-section hygrothermal analysis is useful, but real moisture damage often appears at localized interfaces, behind furniture, in concealed spaces, near penetrations, around ducts, or at thermal bridges. Future models therefore need more realistic representation of boundary conditions, material properties, airflow paths, local geometries, and operational patterns, as well as better methods for identifying where general heat and moisture transport processes become localized risk in real buildings [9,10,32,41,46].

Particular attention should be paid to spatial and transient effects. Moisture risk in hot-humid buildings may be controlled by short periods of cooling, intermittent air-conditioning, rain followed by weak drying, local airflow stagnation, or pressure-driven humid-air leakage. Future modelling should therefore evaluate not only peak moisture content or condensation occurrence, but also drying time, cumulative high-RH exposure, repeated wetting–drying cycles, and persistence of moisture near cooled layers. Coupling HAM simulations with airflow analysis or simplified pressure-network models would also help clarify how leakage, duct operation, and ventilation imbalance create local moisture accumulation.

8.4. Hot-Humid Validation of Risk Indices

Although the Fungal Index, VTT Mold Index, IBP-type approaches, MRD, DR-SIM, and probabilistic methods remain useful, their outputs represent different concepts and may become less discriminating under chronic humidity [11–18,21,48]. Future work should therefore focus not only on proposing new indices, but also on validating existing indices under hot-humid and persistently humid conditions.

A priority is the creation of datasets in which the same temperature and RH histories are evaluated using multiple indices and compared with observed material condition, visible mold, culture counts, qPCR, sequencing, and airborne measurements. Such datasets would clarify whether index saturation reflects model limitation, genuine chronic hazard, or a lack of discriminatory variables. They would also help determine whether hot-humid assessment requires modified thresholds, longer aggregation windows, recovery-sensitive metrics, or new indices explicitly designed for chronic humidity and weak drying.

8.5. Coupled Hygrothermal and Microbial Field Studies

Integrated field studies that measure physical conditions, microbial accumulation, and exposure-related metrics together remain limited [22,23,25]. Future research should better synchronize surface temperature, surface RH, material moisture content, wetness duration, DNA, culture-based counts, community structure, airborne particles, and occupant or operational data on common spatial and temporal scales.

This is particularly important because hygrothermal hazard and microbial load do not necessarily respond on the same time scale. Temperature and RH can change within minutes or hours, whereas microbial DNA, spores, fragments, and residues may reflect cumulative exposure over weeks or longer. Future studies should therefore include repeated sampling and long-term monitoring at deposition-prone surfaces, concealed spaces, HVAC components, and occupied-zone air. Such studies are essential for testing how drying deficit, local microclimate, microbial persistence, and exposure potential are connected.

8.6. Translation into Design, Retrofit, and Operation Guidance

Finally, future work should translate integrated research findings into practical guidance for design, retrofit, and operation. Many current approaches still assume standardized operation, whereas real moisture risk depends strongly on window opening, cooling pattern, ventilation timing, pressure balance, furniture placement, cleaning, maintenance, and dehumidification practice. Future assessment frameworks should therefore move from static specification-based evaluation toward integrated performance-based evaluation that includes design, systems, and operation together.

Priority topics include vapor-control strategies suitable for inward and outward drying, and moisture-safe retrofit of existing envelopes. Other priorities include HVAC configurations that provide latent-load control without excessive negative pressure, practical monitoring methods for concealed spaces, and maintenance strategies for surfaces prone to biofouling or dust accumulation. Rather than producing universal prescriptions, future guidance should identify decision pathways: where moisture enters, where cold surfaces occur, how drying can occur, how long high-RH conditions persist, and how operation modifies these processes.

Taken together, these research needs indicate that the next stage of hot-humid moisture research should not be defined merely by adding detail within separate subfields. Rather, it should focus on building integrated and testable frameworks that connect climatic change, drying deficit, envelope behavior, hazard indicators, microbial response, exposure pathways, and building adaptation.

9. Conclusions

This review has examined representative moisture-damage scenarios, climatic drivers, building-envelope mechanisms, risk indices, microbial implications, and design and operation issues in hot-humid buildings and in regions shifting toward more persistently humid conditions.

The first major conclusion is that moisture damage in hot-humid buildings should be understood not simply as an isolated defect or a discrete condensation event, but as the manifestation of drying deficit. Exterior biological contamination, summer condensation within envelope assemblies, local indoor dampness, moisture stagnation in concealed spaces, and material deterioration may differ in appearance, but all arise from the same underlying imbalance between moisture loading and insufficient recovery after wetting [1–3,28,30–33,45].

The second major conclusion is that this problem cannot be explained by climate alone. Moisture damage in contemporary hot-humid buildings is shaped jointly by changing climatic conditions and by weakened compatibility between buildings and climate resulting from modernization, cooling dependence, altered envelope composition, and changing living practices [3,5–8].

The third major conclusion is that existing moisture and mold risk indices remain useful, but their interpretation requires caution under hot-humid conditions. FI, the VTT Mold Index, IBP-type approaches, MRD, and DR-SIM all provide valuable information on hazardous environmental conditions, yet many become less discriminating when humidity is chronically high and drying is persistently weak [11–19].

The fourth major conclusion is that hygrothermal hazard, microbial load, community structure, and exposure represent different but connected layers of the moisture-damage process. Hygrothermal indices describe environmental suitability, microbial measurements describe accumulation and persistence, and airborne transport is more directly linked to exposure [22–25]. These layers should therefore be interpreted together rather than reduced to a single metric.

The fifth major conclusion is that effective adaptation in hot-humid buildings requires integrated strategies that combine envelope design, drainage, airtightness, ventilation, pressure control, cooling, dehumidification, and operation. Moisture control in such climates should be redefined not simply as moisture exclusion, but as the management of moisture entry, drying, and recovery under persistently humid boundary conditions [30,31,40]. These strategies should address not only mold prevention, but also durability, insulation performance, and service-life preservation.

The practical significance of this review lies in supporting envelope design, retrofit decision-making, and moisture-aware building operation in hot-humid climates. Overall, moisture damage in hot-humid buildings should be understood as a coupled problem linking climate-driven humidification, envelope moisture accumulation, interpretive limits of existing risk indicators, microbial implications, and building adaptation. Global warming is increasing atmospheric moisture loading. At the same time, population exposure, urbanization, building modernization, and air-conditioning use continue to expand. As a result, summer condensation and moisture damage in hot-humid buildings are likely to become increasingly important for building durability, energy performance, and indoor environmental quality. This topic should therefore be treated as an urgent and developing research area. Integrated frameworks are needed to connect climate inputs, building physics, microbial processes, exposure relevance, and operational control within a common understanding of drying deficit.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Research streams relevant to moisture damage in hot-humid buildings and the positioning of this review; Table S2: Major climatic indicators relevant to moisture damage in hot-humid buildings; Table S3: Comparison between physical indicators and microbial measurements in hot-humid buildings; Table S4: Reported regional examples of moisture-damage mechanisms in hot-humid and humidifying climates.

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