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Risk assessment of fungal formations in historic buildings based on dynamic thermo-hygrometric analysis

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ABSTRACT
Historical and cultural heritage must be preserved and protected from deterioration. In particular, the integrity of structures is threatened by inadequate maintenance, exceptional events (such as fires and floods), and exposure to increasing air pollution. In addition, indoor environments may provide favorable conditions for colonizing harmful agents. Fungal contamination and growth in buildings can lead to the deterioration of surfaces. Fungi need damp environments to germinate and grow, for example, in the presence of water condensation on surfaces. In this paper, an investigation is carried out to examine the conditions that favor the growth of different fungal species on building materials commonly used in historic buildings, such as brick masonry, limestone, and plaster. The analyzed climatic conditions refer to three locations, typical of Northern, Central, and Southern Europe, respectively. These conditions are obtained using the DesignBuilder software. A more detailed analysis of the walls is then performed with the WUFI software. The paper suggests solutions to reduce the risk of fungal growth and, therefore, to avoid phenomena that can damage the historical heritage.

Section: RESEARCH PAPER

Keywords: biodeterioration; fungal growth; dynamic hygrothermal analysis; condensation risk

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1. INTRODUCTION

Building biodeterioration can occur due to various agents and mechanisms, and the effects on colonized surfaces are various. The analysis of climatic conditions and material characterization play a decisive role in assessing the deterioration of the construction elements and identifying the most appropriate conservation measures. Several researchers have focused on investigating fungal species that proliferate in buildings [1], [2]. The study conducted by Guerra et al. [3] on a historic building in Porto Alegre (Brazil) led to the isolation of 60 fungal colonies that attack mortar coating. Generally, mold and moisture-related problems are reported in the literature among the main factors causing building pathologies. A systemic approach to the humidity problems in buildings was adopted by Pietrzyk [4], who provided a tool to perform a probabilistic risk/reliability analysis of building performance concerning fungal growth. As Andersen et al. [5] stated, nature and culture influence the fungal composition indoors, as they determine the ways and habits of window opening and, consequently, the permeability and exchanges between internal and external environments. A pilot study on Danish homes showed that a closed envelope protects against outside fungal spores but simultaneously entraps spores from fungi growing inside the building.

Moreover, even indoor environments perceived as good and dry might still have undiscovered dampness, resulting in fungal growth. This was demonstrated by the investigation conducted by Bastholm et al. [6], who found that fungal contamination can occur even in spaces with controlled conditions. That is the case of a Danish museum with controlled relative humidity below 60% that had xerophilic fungal formations on heritage artifacts throughout the repository. Furthermore, building materials can be pre-contaminated by fungal spores, as shown in a study by Andersen et al. [7] on gypsum wallboards. The results suggest that some fungal species are already incorporated in the materials, probably in the paper/carton layer or the gypsum core, before the panels reach the retailers or the building site. De Castro Silveira et al. [8] conducted a study in the humid temperate climate of Florianópolis (Brazil) to investigate the influence of thermal insulation and solar orientation of walls on mold growth in naturally ventilated residences using simulations. The impact of wind-driven rain on the spore germination was analyzed in [9]. Results showed that wind-driven rain loads tend to intensify mold growth on interior wall surfaces, especially at the edges of the walls, and to increase indoor relative humidity (RH) and energy consumption for heating.

Nowadays, advanced techniques can be employed to characterize the building materials and identify possible conservation and restoration measures, such as energy-dispersive X-ray fluorescence spectroscopy, powder X-ray diffractometry, and thermogravimetric analysis (TGA). In [10], colorimetric acquisition from a laser scanner and materic survey were used to observe alterations and irregularities within the masonry of a historic chapel. Forestieri e Álvarez de Buergo [11] used infrared thermography (IRT) to evaluate the water distribution in stone specimens made of calcarenite and sandstone under steady laboratory conditions for temperature and relative humidity. Based on the study's outcomes, IRT can be effectively used as a non-destructive technique to identify the stone's physical characteristics and the validity of conservation measures.

Moisture and temperature are the parameters affecting mold growth the most. In particular, the critical moisture level is the lowest relative humidity at which mold growth starts, and it varies for different species and materials [12]. Menneer et al. [13] explained that among the various factors influencing mold prediction models are fungal diffusion, fungal production, and available nutrients. However, most models only include the relative humidity levels and temperature. Based on the VTT model, mold indices were generated using air RH and temperature measurements from domestic environments.

As observed by [14], steady-state methods (such as Glaser) are unsuitable for predicting the long-term moisture response of a wall. Instead, numerical hygrothermal models simulating the coupled transport of heat and moisture over varying environmental conditions could provide the necessary data to evaluate the long-term heat and moisture performance of building elements and predict the risk of moisture damage [15]. Bruno and Bevilacqua [16] demonstrated that mass transportation phenomena influencing the transmission thermal losses in opaque envelope components depend on the built-in humidity level, material hygrometric properties, and climatic conditions. An overview of how the combined heat, air, and moisture modeling evolved is provided by Hens [17]. The author points out that although the theory is well established and the currently available software is quite complete, they are not always enough to explain and treat the damage cases encountered in practice. As several assumptions and simplifications are adopted in modeling, the risk assessment for a specific situation is loaded with uncertainty.

Cultural heritage objects and artworks (paintings, textiles, wooden objects, written documents, maps, audio-visual materials, stone objects, stained-glass windows, etc.) are made of materials that can be subjected to biodeterioration [18], [19], which can result in enormous and irreparable cultural losses [20]. For example, microbial attacks have been detected on the paintings of brick walls at old Chinese tombs [21]. Canvas paintings are also highly vulnerable to moisture exposure [22] [23]. Signs of deterioration on canvas oil paintings were observed in the historic building that houses the National Theater of Costa Rica. The damages were caused by microorganisms, among which a new species, expanding the list of fungi capable of inhabiting and damaging cultural heritage. Fazio et al. [24] have identified two fungal species responsible for the deterioration phenomena that affected the Jesuit South American polychrome wood sculpture at the Museum of Natural Sciences in La Plata, Buenos Aires province, Argentina. Fungal diversity was analyzed by Pinheiro et al. [25] at some archives and libraries in Portugal. Some species are known to be eroding and staining agents and can alter the paper's mechanical and structural characteristics. Mold contamination was also found in paper samples from the Ottoman Archives in Turkey [26]. Kosel and Ropret [27] gathered information on fungal isolates and their biological activity from the original materials of cinematographic films and historical photographs. Photographic emulsions and coatings, being organic and hygroscopic, serve as a readily available and rich source of nutrients. The effects of the fungi were also observed on old albumen prints taken from an Egyptian archive dating back to 1880-1890 [28], causing changes in color and darkening of the light areas. The identified fungal species could grow on the surface of the model Albumen silver print, causing damage to the binder and extending their growth to the paper fibers. Guiamet et al. [29] studied the phenomena of biofouling and biodeterioration of photos and maps preserved in the Historical Archive of the Museum of La Plata, Argentina, and in two repositories of the National Archive of the Republic of Cuba. The fungi degraded the cellulose and produced pigments and acids, altering the aesthetic of the documents and causing the biodeterioration of photographs [30]. Rakotonirainy et al. [31] sought to understand the origin of fungal development and the causes of mold growth problems in cinematographic films stored in plastic and metal containers at the French Film Archives. The authors discovered that the concentration of airborne fungi was relatively low, while fungal concentrations on the surfaces were up to four times greater than the limit.

Furthermore, fatigue damage due to relative humidity cycles [32] or uniform moisture content (or temperature) variation [33] can cause fracture mechanisms in paintings. Analyzing the wall paintings of the Samye Temple in Tibet, He et al. [34] discovered that the volume change caused by clay minerals in the adobe support and mud plaster layers, subject to humidity variations, combined with the impermeable acrylate coating, may have accelerated degradation. The difference in thermal and humidity expansion properties between the various materials of the stratigraphy can cause stress between the layers, decaying the wall paintings [35]. The deterioration risk for the polychrome clay sculptures of the Buddha at Baosheng Temple in Suzhou, China, was assessed by Sheng et al. [36]. Field environmental monitoring demonstrated that the sculptures' surface layer is in a state of dynamic absorption and evaporation, depending on the humidity of the surrounding air, directly affecting the risk of microbial growth.

Historic buildings and archaeological heritage are particularly vulnerable to the formation of fungal colonies [37]. This is because they are often unoccupied [38], and therefore, the indoor environmental conditions may not be controlled, creating favorable settings for the growth of fungi on the surfaces of the building elements. Olivito et al. [39] developed a process for generating an inventory of historical and cultural heritage buildings. The goal was to identify a prioritized list of criticalities in urban areas with higher vulnerability and to determine a safety threshold from a structural perspective.

Experience has proved that installing monitoring systems can help to control the constantly changing indoor environmental conditions according to the actual behavior of structures and materials. For example, Svatos et al. [40] developed a measurement system for diagnosing the technical and thermal features of wooden houses' envelope. In addition to air, temperature, and humidity sensors, four moisture guard intelligent sensors were placed in the exterior walls to allow early diagnosis of humidity in the structure. Lamonaca et al. [41] proposed a distributed measurement system to monitor a museum's environment by counting the Colony Forming Units and evaluating the pollution by fungal spores. Another example is provided by D'Alvia et al. [42], who used a wireless sensor network, minimally invasive, for environmental data acquisition in a museum. A distributed sensor network using the RS-232 protocol was developed by Giulietti et al. [43] to create a remote monitoring system based on electrical impedance measurements. Measurement nodes were installed into the structural elements to immediately identify the presence of contaminants or the formation of cracks. Finally, Lamonaca et al. [44] proposed upgrading the hardware interface architecture to synchronize the operations of standalone measurement instruments in the absence of networking, using phase delay compensation programming. A study conducted by Grøntoft [45] on sculptures in two Norwegian Medieval stone churches has highlighted the need for frequent and systematic recording of environmental parameters to protect artifacts of cultural heritage, such as painted wood. However, the author underlines that the lack of a budget for conservation inhibits such measures.

Fungal spores are everywhere, and even though their main passage into the indoor environment is through the outdoor air [46], spores can also be transported inside with the occupants' shoes and clothes, pets' fur, firewood, etc. Additionally, they can originate from food or spoiled food, potted plants [46], or be embedded in contaminated building materials [7].

Predicting the existence of fungal growth can be difficult since its appearance results from a complex and multivariate process. The most critical parameters affecting the development of mold are [47]-[54]:

- The hygrothermal conditions, i.e., temperature, air RH, and water availability of the substrate;
- The availability and quality of nutrients;
- The material's properties in relation to pH, chemical composition, water absorbing potential, etc.

It is generally accepted that indoor dampness and excess moisture are crucial to fungal germination and growth [1], [53], [55], while they have also been associated with adverse health symptoms among the occupants [1], [56]-[60]. Water condensation on the buildings' surfaces or construction should be prevented. Risk areas are external walls with insufficient insulation, thermal bridges, and generally, cold surfaces and spaces with restricted air movement or inadequate ventilation. For example, the common practice of internally insulating historic buildings can result in moisture accumulation in the wall structure and restrict its ability to dry out [2].

The necessary nutrients for mold growth can be easily encountered, as any source of carbohydrates and even dust or dirt reserves can be broken down into useful sugars and other compounds [50], [51]. Finally, the properties of different building materials dictate which species can germinate and proliferate on them. That is because each fungus has specific requirements for water availability, nutrients, pH level, temperature, etc. [47]. Studies have shown associations between specific materials serving as substrates and their common colonizers [61].

There is consensus for the optimal conditions of fungal growth about moisture availability and temperature, which are typically used for risk assessment of fungal growth. Generally, 75% of relative humidity is considered critical for the appearance of growth, while the ideal temperature ranges between 20-30°C [12], [53], [62] - [64]. Therefore, fungi can be divided based on their required moisture level into xerophilic, mesophilic, and hydrophilic, or into primary, secondary, and tertiary colonizers [1], [47], [52], [65], [66]. Primary colonizers (xerophilic fungi) require an Equilibrium Relative Humidity (ERH) smaller than 80%. Secondary colonizers (mesophilic fungi) need an 80-90% ERH. Tertiary colonizers (hydrophilic fungi can grow when ERH is higher than 90% [1].

Indoor environmental conditions are quite distinct from outdoor settings [67], and therefore, indoor fungi are also specific for indoor spaces [5]. The fungal species that have most commonly been isolated from indoor surfaces are: *Aspergillus fumigatus*, *Aspergillus melleus*, *Aspergillus niger*, *Aspergillus versicolor*, *Cladosporium herbarum*, *Paecilomyces* spp., *Penicillium brevicompactum*, *Purpureocillium lilacinum*, *Stachybotrys chartarum*, *Trichoderma* spp. [68], [69], [70], [71]. Commonly encountered species in water-damaged buildings are: *Aspergillus* spp., *Aspergillus niger*, *Aspergillus versicolor*, *Acremonium* spp., *Chaetomium* spp., *Cladosporium* spp., *Cladosporium chartarum*, *Cladosporium sphaerospermum*, *Penicillium* spp., *Penicillium chrysogenum*, *Trichoderma* spp., and *Stachybotrys chartarum* [72], [73], [74], [75]. More specifically, *Aspergillus versicolor*, *Wallemia sebi*, *Paecilomyces variotii*, and some *Penicillium* species have low moisture requirements (xerophilic fungi). At the same time, *Trichoderma* spp., *Stachybotrys chartarum*, *Chaetomium globosum*, *Aspergillus fumigatus*, and actinomycetes require ERH above 90% to initiate growth (hydrophilic fungi) [1], [65], [76].

The present study aims to investigate biodeterioration in cultural heritage by analyzing which fungal species are commonly found in building materials used in historic buildings. The literature analysis reveals that research on the formation of fungi on building materials is relatively fragmented. Each study focuses on a specific case, analyzing individual materials under certain conditions. However, an overarching vision is missing. The proposed study seeks to fill this gap by providing a collection of fungal species that can grow on some of historic buildings' most common building materials. Knowledge of the identity of the microorganisms colonizing the materials facilitates the definition of conservation strategies to avoid damage and promote restoration. Prevention and control measures can be implemented more readily using the developed database. The occurrence of the indoor growth conditions is assessed regarding the typical climate of three localities, representative of Northern, Central, and Southern Europe. Following a preliminary analysis in [77], this work deepens the behavioral study of certain building materials concerning heat and humidity transfer. Finally, possible mitigation strategies are suggested to prevent degradation phenomena.

2. MATERIALS AND METHODS

2.1. Common construction materials in historic buildings and associated fungal species

The present study aims to assess the risk of fungal growth on the interior surfaces of historical buildings under normal operating conditions. The analysis will be carried out for some commonly encountered materials in historical buildings, namely brick masonry, limestone, and plaster finish (Figure 1). The main properties of the analyzed materials are summarized in Table 1.

Risk assessment of fungal contamination is a challenging process. Different investigations performed in the same space often result in distinct outcomes and sometimes even contradicting results. The sampling techniques and detection analysis used by the independent consultants or companies conducting the inspection significantly affect the study's outcome. There are no generally accepted guidelines on the procedure to be followed when performing an investigation, and therefore, it is hard to get reproducible results [78] -[80]. The decisions made before and during an inspection influence the species that can be isolated or whether they can even be detected. For example, the growth media and cultivation hygrothermal conditions will always favor certain species [47]. Bastholm et al. showed that when working with fungi, the investigator needs to know what to look for [6].

It would, therefore, be of great interest to highlight the critical conditions, areas, and materials in historic buildings to facilitate their identification at an early stage. This analysis can guide investigators and consultants during the decision-making process so they can successfully isolate the most relevant of the present species. On that note, a summary of the associated mycobiota of the examined materials is presented, creating a short database for future reference. These connections have been drawn from analyzing existing literature on field studies. Table 2 summarizes the frequently isolated fungal genera and species and their associations with the selected building materials.

2.2. Simulation assumptions

Hourly dynamic simulations were conducted using the DesignBuilder [88] and WUFI [89] software. The first was used to predict the evolution of internal environmental conditions of the building and evaluate the occurrence of condensation phenomena favorable to the growth of fungi. The second was used to perform a detailed analysis of the hygrothermal behavior of the single structures, particularly the external walls.

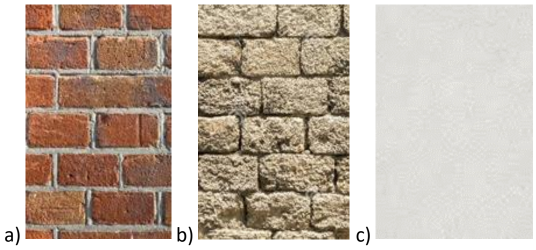

Figure 1. Analyzed building materials for historic buildings: a) brick masonry, b) limestone, c) plaster.

Table 2. Properties of the analyzed building materials.

Material	Conductivity, W/mK	Specific Heat, J/(kg · K)	Density, kg/m^3	Vapor diffusion resistance factor
Brick	0.84	800	1700	16
Limestone	1.40	1000	2000	50
Plaster	0.35	840	950	8.3

Table 1. Fungi associated with building materials.

Fungi Genus	Fungi Species	REF.
PLASTER		
Acremonium	spp.	[61] [47] [81]
Alternaria	spp.	[61] [82] [83]
Aspergillus	*niger*	[82]
Aspergillus	*sydowii*	[84]
Aspergillus	*versicolor*	[84]
Cladosporium	*allicinum*	[5]
Cladosporium	*cladosporioides*	[82]
Cladosporium	*sphaerospermum complex*	[5]
Geosmithia	sp.	[83]
Lecanicillium	*kalimantanense*	[81]
Mucor	*globosus*	[82]
Parengyodontium	*album*	[81]
Penicillium	sp.	[61]
Penicillium	*brevicompactum*	[82]
Penicillium	*chrysogenum*	[81] [84]
Penicillium	*corylophilum*	[84]
Penicillium	*palitans*	[84]
Penicillium	*sumatrense*	[83]
Purpureocillium	*lilacinum*	[81]
Sarocladium	*kiliense*	[81]
Sporothrix	sp.	[61]
Wallemia	spp.	[5]
BRICK WALL		
Acremonium	*strictum*	[85]
Aspergillus	*fumigatus*	[85]
Aspergillus	*sydowii*	[84]
Aspergillus	*versicolor*	[84]
Cladosporium	*cladosporioides*	[85]
Penicillium	*chrysogenum*	[84]
Penicillium	*corylophilum*	[84]
Penicillium	*palitans*	[84]
Wallemia	spp.	[5]
LIMESTONE		
Acremonium	spp.	[81] [47]
Aeminium	*ludgeri*	[86]
Aspergillus	*glaucus*	[86]
Aspergillus	*sydowii*	[84]
Aspergillus	*versicolor*	[84] [87]
Aspergillus	*westerdijkiae*	[86]
Cladosporium	*cladosporioides*	[87]
Cladosporium	*langeronii*	[81]
Cladosporium	*sphaerospermum*	[87]
Cladosporium	*tenuissimum*	[87]
Epicoccum	*nigrum*	[87]
Lecanicillium	*kalimantanense*	[81]
Parengyodontium	*album*	[87]
Penicillium	*brevicompactum*	[86] [87]
Penicillium	*chrysogenum*	[83] [84] [86]
Penicillium	*corylophilum*	[84]
Penicillium	*crustosum*	[87]
Penicillium	*glabrum*	[83] [87]
Penicillium	*palitans*	[84]
Pseudogymnoascus	*pannorum*	[81]
Sarocladium	*kiliense*	[81]
Stachybotrys	*chartarum*	[83]
Talaromyces	spp.	[83]
Verticillium	*zaregamsianum*	[81]

In DesignBuilder, a test model consisting of a block of dimensions 6mx6m, with 30 cm thick walls, was considered. The south wall includes a windowed area with a 25% WWR (Window–to–Wall Ratio). In particular, the analysis was focused on the external walls, for which different materials were examined (brick masonry, limestone, plaster finish).

The building was simulated for two hypotheses. In the first case, an occupancy schedule from 8:00 to 18:00 was assumed, and the building was equipped with a heating and cooling system operating at the same time interval. The set point temperature is fixed at 20 °C for heating and 26 °C for cooling. In the second case, the simulation was conducted in free-floating conditions, assuming that the building is not occupied and not equipped with heating and cooling systems. Cultural heritage historic buildings often do not have the structural and functional characteristics to be regularly used but are kept as archaeological assets, not permanently occupied. In these cases, their conservation is even more challenging, as the necessary indoor environmental conditions to avoid the damage of the construction elements and materials are not maintained. An infiltration rate of 0.5 air change rate per hour (ach) is considered in both cases. Regarding the external conditions, the model was simulated in three locations representative of the climatic conditions of Northern, Central, and Southern Europe: Helsinki (60.169857, 24.938379), Berlin (52.520008, 13.404954), and Rome (41.902782, 12.496365). Based on the Köppen-Geiger world map climate classification [90], Helsinki belongs to the category “Dfb,” corresponding to a humid continental climate with warm summer; Berlin falls within the zone “Cfb,” including temperate oceanic climate with cold winter and warm summer, without dry season; Rome is labeled as “Csa,” Mediterranean climate with hot and dry summer. Hourly weather files from the EnergyPlus database [91] were employed. The main climatic parameters of the external conditions for the selected locations are shown in Table 3. Table 4 summarizes the analyzed case studies and the related codes.

The different cases have been coded in order to facilitate reading and understanding. The first letter indicates the material: “B” stands for “Brick,” “L” for “Limestone,” and “P” for “Plaster.” The second letter refers to the analyzed location: “R” for “Rome,” “B” for “Berlin,” and “H” for “Helsinki.” Finally, the plus/minus symbol at the end of the code indicates the presence (+) or absence (-) of occupants and heating/cooling systems. For example, the case study coded BR(+) marks the Brick building (B), located in Rome (R), in the scenario with occupants and a heating/cooling system (+). The LH(-) case study indicates the construction in Limestone (L), located in Helsinki (H), in the absence of occupation and systems (-). Eighteen case studies were analyzed in total, described in Table 4.

As for the calculation assumptions in WUFI software, each exterior wall has been remodeled using the same materials used in DesignBuilder. For the external climatic conditions, the same climatic files were used as for DesignBuilder, while for the internal climate, the conditions dictated by the EN 15026 standard [92] were set, with air temperature varying between 20 and 25 °C and relative humidity ranging between 35 and 65 %.

Table 3. Climatic conditions for the analyzed locations.

Location	$T_{\max}$, °C	$T_{\min}$, °C	Average annual RH, %	Wind speed, m/s
Helsinki	28.7	-21.4	79.2	3.8
Berlin	32.7	-8.8	73.5	4.2
Rome	31.1	-4.1	76.7	2.8

Table 4. Case study definition.

Case study	Material			Location			Heat/Cool. system and Occupancy	
	Brick	Limestone	Plaster	Rome	Berlin	Helsinki	Yes	No
BR(+)	v			v			v	
BR(-)	v			v				v
BB(+)	v				v		v	
BB(-)	v				v			v
BH(+)	v					v	v	
BH(-)	v					v		v
LR(+)		v		v			v	
LR(-)		v		v				v
LB(+)		v			v		v	
LB(-)		v			v			v
LH(+)		v				v	v	
LH(-)		v				v		v
PR(+)			v	v			v	
PR(-)			v	v				v
PB(+)			v		v		v	
PB(-)			v		v			v
PH(+)			v			v	v	
PH(-)			v			v		v

3. RESULTS AND DISCUSSION

Simulation results from DesignBuilder were analyzed in terms of internal conditions, characterized by zone temperature and relative humidity, and the risk of condensation on the internal surface of the vertical walls for the different orientations (North, South, East, and West). Critical conditions emerged for all the analyzed cases, with greater intensity for the unoccupied building without heating and cooling systems. The graph in Figure 2 shows the percentage of occurrence (calculated based on the

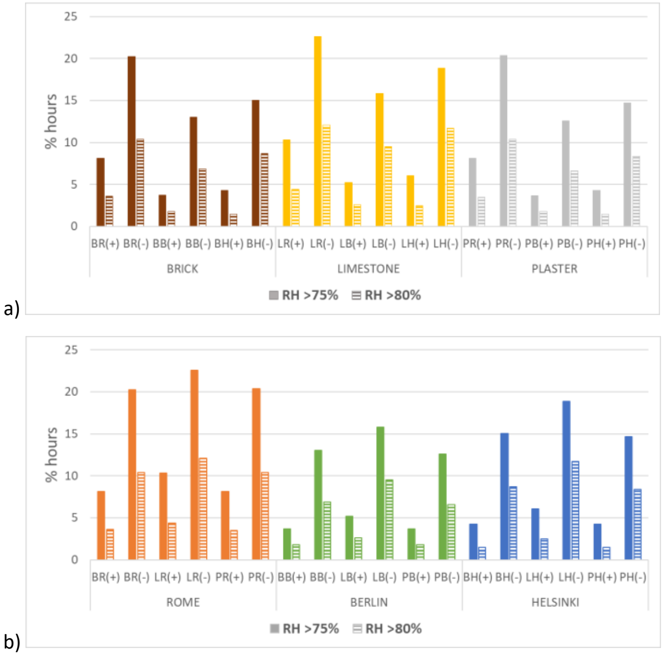

Figure 2. Percentage of hours over the total (based on simulation steps) in which RH values are equal to or higher than 75% and 80%, grouped by: a) material and b) location.

hourly simulation intervals) in which a relative humidity equal to or higher than 75% and 80% is recorded, grouped based on the building material (Figure 2a) and the location (Figure 2b).

It is worth noting that relative humidity not only reaches high values but is also maintained for long periods, favoring moisture condensation and, thus, the germination of fungal spores.

For example, the graphs in Figure 3, Figure 4, and Figure 5 depict the surface temperature of the north-facing wall and relative humidity of the air for the case studies LR(-), LB(-), and LH(-), related to the building with external walls with limestone, not occupied and not equipped with heating/cooling systems, for the three analyzed locations.

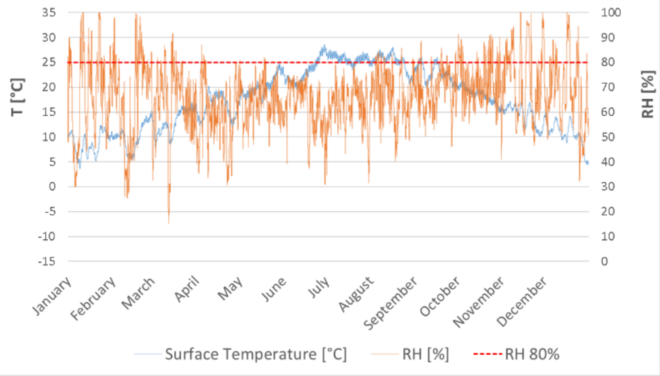

Figure 3. Surface temperature (north-facing wall) and relative humidity of the air for LR(-) (Limestone, Rome, no occupancy and no heating/cooling systems).

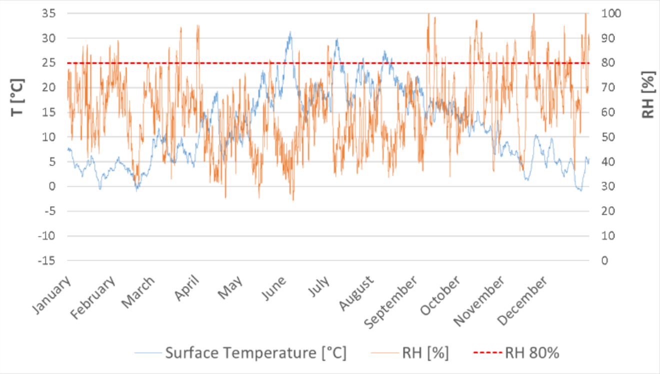

Figure 4. Surface temperature (north-facing wall) and relative humidity of the air for LB(-) (Limestone, Berlin, no occupancy and no heating/cooling systems).

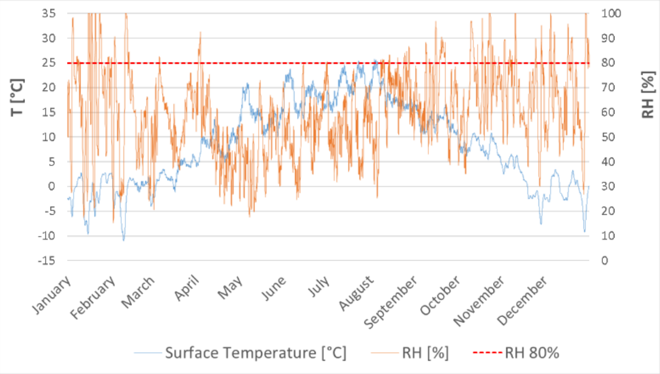

Figure 5. Surface temperature (north-facing wall) and relative humidity of the air for LH(-) (Limestone, Helsinki, no occupancy and no heating/cooling systems).

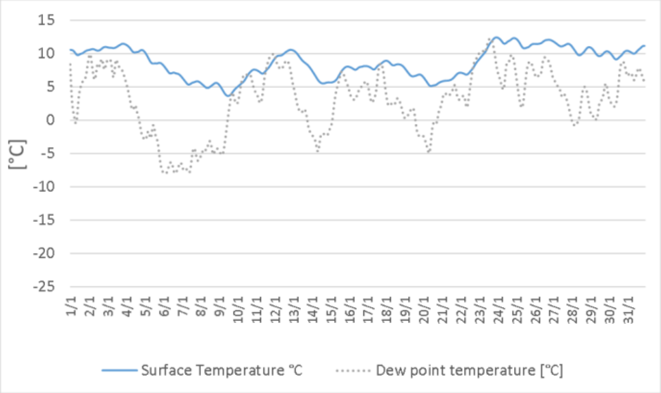

Figure 6. Surface and dew point temperature trend for the north-facing wall for LR(-) during January.

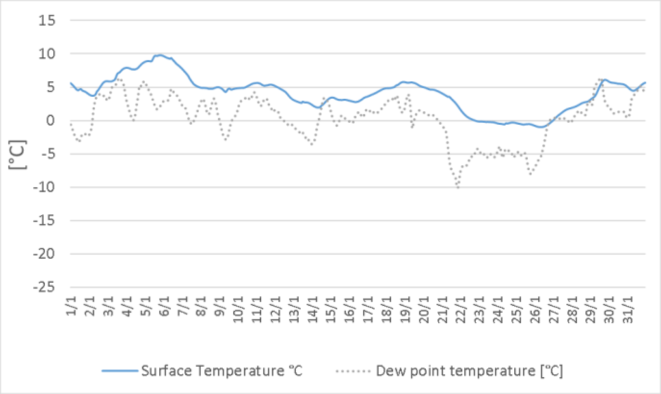

Figure 7. Surface and dew point temperature trend for the north-facing wall for LB(-) during December.

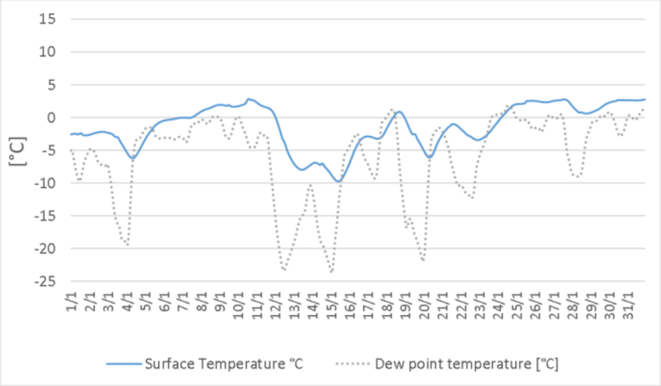

Figure 8. Surface and dew point temperature trend for the north-facing wall for LH(-) during January.

The graphs in Figure 6, Figure 7, and Figure 8 illustrate the trend of the monthly surface temperature of the wall facing north, compared to the dew point temperature curve, for the three analyzed locations. The construction is in limestone, the building is unoccupied, and there are no heating and cooling systems. For the considered period (a winter month), the surface temperature drops several times below the dew point, resulting in condensation.

As seen from Table 5, the risk of condensation is present in all the simulated cases. The abacus highlights the months in which condensation occurs at least in one simulation interval. It should be noted that condensation generally occurs on all the walls (N, S, E, and W). However, the risk is generally greater for north-facing walls.

Table 5. Occurrence of condensation for the analyzed case studies.

	January	February	March	April	May	June	July	August	September	October	November	December
BR(+)										🟩	🟩	
BR(-)	🟩	🟩									🟩	🟩
BB(+)									🟩	🟩		🟩
BB(-)									🟩		🟩	🟩
BH(+)	🟩	🟩									🟩	🟩
BH(-)	🟩	🟩								🟩	🟩	🟩
LR(+)	🟩	🟩								🟩	🟩	🟩
LR(-)	🟩	🟩									🟩	🟩
LB(+)							🟩		🟩	🟩	🟩	🟩
LB(-)			🟩	🟩					🟩		🟩	🟩
LH(+)	🟩	🟩							🟩	🟩	🟩	🟩
LH(-)	🟩	🟩							🟩	🟩	🟩	🟩
PR(+)										🟩	🟩	
PR(-)	🟩	🟩									🟩	🟩
PB(+)									🟩	🟩		🟩
PB(-)									🟩		🟩	🟩
PH(+)	🟩	🟩									🟩	
PH(-)	🟩	🟩								🟩	🟩	🟩

The dynamic hygrothermal simulations carried out using the software WUFI have provided further information on the heat and humidity transfer through the building envelope. The transient hygrothermal response was assessed for the different wall assemblies subject to various climates.

The humidity level in the structures is not constant but varies over time. Naturally, the moisture content level varies according to the material's physical properties, determining its hygroscopic characteristics. The profiles illustrated in Figure 9, for the external north-facing wall in Berlin, reveal that limestone can absorb more humidity. In fact, it shows that its humidity content varies between 6.37 and 7.30 kg/m², followed by plaster (4.92-5.87 kg/m²), and finally, by brick masonry (1.82-3.28 kg/m²).

In addition to the intrinsic characteristics of the material, the humidity content also varies significantly according to the climatic conditions to which the structure is exposed. The graphs in Figure 10, Figure 11, and Figure 12 show the moisture content profiles in the layers created for the simulated construction materials (brick, limestone, and plaster) for the north wall of the three locations. The results show that the same material, subjected to different climatic conditions, can absorb a variable quantity of humidity.

Figure 9. Moisture content within the various building materials under the climatic conditions of Berlin.

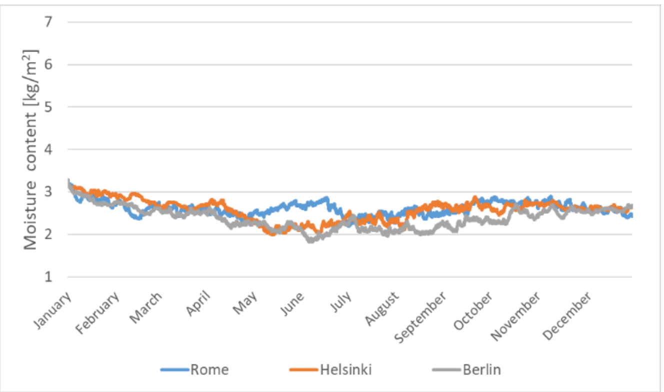

Figure 10. Moisture content within the “Brick” layer for the 3 locations (north-facing wall).

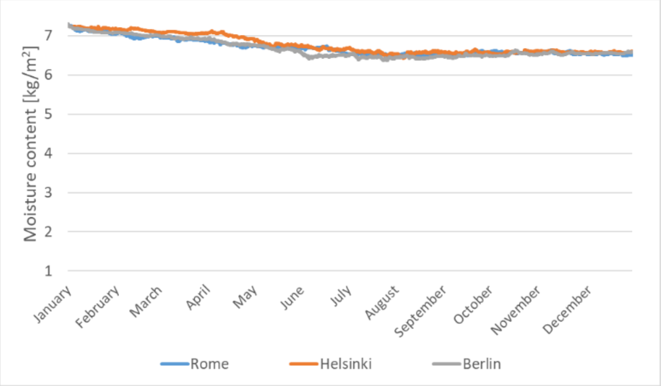

Figure 11. Moisture content within the “Limestone” layer for the 3 locations (north-facing wall)

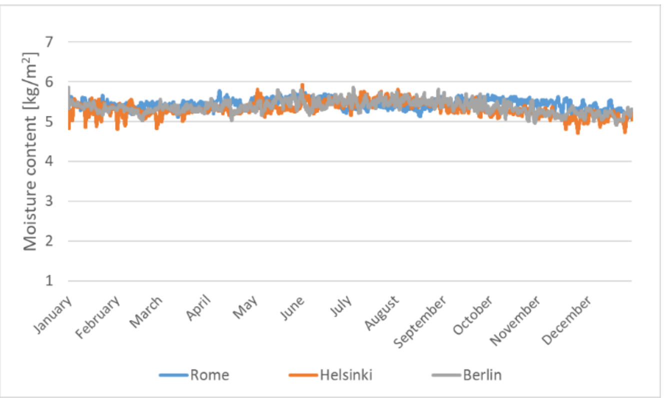

Figure 12. Moisture content within the “Plaster” layer for the 3 locations (north-facing wall)

The results show that the moisture content in the structure affects the thermal transmittance, which tends to increase as the humidity content in the layer increases. Consequently, the thermal transmittance, in real operating conditions, will vary dynamically according to the humidity content. Higher transmittance values lead to an increase in heat loss, with a consequent reduction of indoor air temperature and the surface temperature distribution, thus increasing the condensation risk.

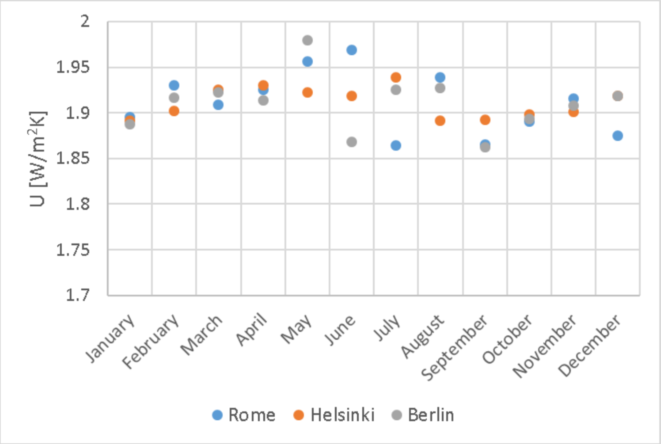

Figure 13. Transient values of the thermal transmittance of the external wall (Brick) for different locations.

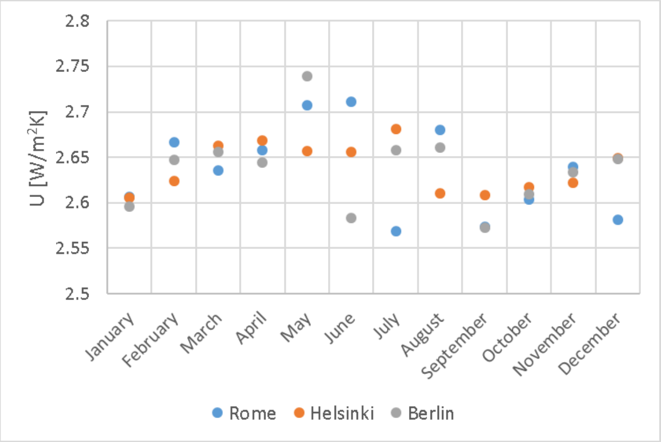

Figure 14. Transient values of the thermal transmittance of the external wall (Limestone) for different locations.

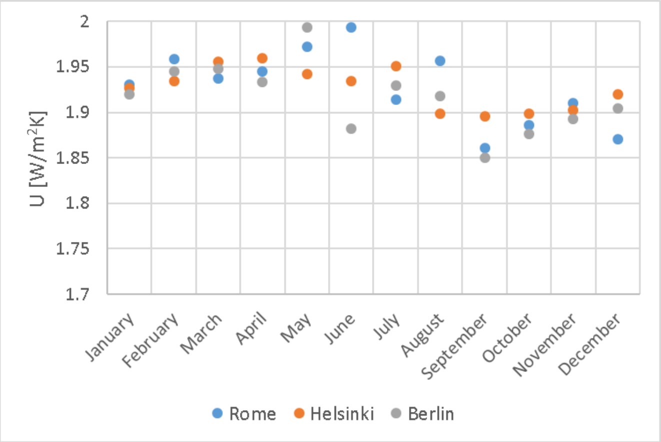

Figure 15. Transient values of the thermal transmittance of the external wall (with internal finish in plaster) for different locations.

Figure 13, Figure 14, and Figure 15 show the transient values for the thermal transmittance of walls for the different building materials and locations. Based on the analysis results, the thermal transmittance may increase to approximately 12% due to the increase in humidity.

The simulations' outcomes show the occurrence risk of favorable conditions for fungal growth on the inner surface of building materials. Different solutions can be suggested to prevent or mitigate this risk, and they can be classified as passive measures, active measures, and chemical treatments.

Passive strategies aim to maintain the external walls at a higher temperature to avoid cold surfaces and, thus, the condensation of water vapor. To this end, the most suitable solution would be to apply a thermal insulation layer, preferably on the external side, to keep the entire wall at a higher temperature. In the case of historic buildings, though, this type of intervention could collide with limitations about altering the facades that can compromise the historical and artistic value of the building. In order to maintain the aesthetic value of the buildings intact and preserve their peculiarities over time while improving the thermal transmittance of the envelope, a solution could be to apply specific thermo-plasters with low thermal conductivity on the building's external surfaces. Thanks to the use of fibrous insulation, organic or inorganic, and natural limes, these materials maintain similar thermo-hygrometric characteristics to traditional masonry and, therefore, can be perfectly compatible. Moreover, their breathability and high permeability allow the balancing of indoor humidity, thus avoiding the formation of condensation and mold. The latest research developments in this area have made available highly performing materials that can provide appropriate levels of thermal insulation, just a few centimeters thick. Furthermore, products based on natural materials (such as cork) are becoming widespread, allowing interventions in compliance with environmentally sustainable requirements.

Active measures include implementing ventilation strategies to regulate indoor humidity levels. Ventilation can be activated in two cases: for high occupancy or when the specific internal humidity X (gv/Kga) exceeds the external humidity level. However, the installation of ventilation systems could be incompatible with the protection constraints for archaeological heritage. Therefore, a less invasive intervention could be a decentralized ventilation unit. These devices are able to ensure adequate air exchange and are designed to optimize architectural integration, as they have a minimal visual impact. Furthermore, they can be easily controlled through smart, IoT-based technologies, allowing control logic implementation to maintain the desired internal conditions. An alternative solution, which can be adopted when the building's geometric configuration allows it, is that of "displacement ventilation." Based on the principle of natural air buoyancy, this technique introduces fresh, clean air at floor level, pushing the warm air and contaminants upwards to be extracted at ceiling level. This system could also be managed through automation and intelligent control.

Chemical treatments are substances used to eliminate fungal formations and prevent or reduce the onset of bio-colonization and biodegradation. For example, Ding et al. [93] investigated the use of low-pressure plasma etching to remove microbial biofilm from building limestones. This innovative technique was found especially effective in cleaning microbial contaminations. Furthermore, plasma etching is able to decompose and eliminate the sugar-containing compounds on the limestones, which is the primary nutrient for microbial reproduction, thus inhibiting microbial growth.

Organic biocides are commonly used to reduce the bio-colonization of construction materials. It is possible to prolong the recolonization period by combining the application of organic and inorganic active elements. Ruffolo et al. [94] developed a new product based on pure or doped titanium dioxide nanoparticles (TiO_2), which was tested on the southeast wall of Villa dei Papiri covered with plaster in the archaeological site of Herculaneum, Naples (Italy). Ślosarczyk et al. [95] investigated the efficacy of metal and metal oxide nanoparticles, such as silver, titanium dioxide, or zinc oxide, in improving the resistance of building materials (e.g., brick, limestone, mortar) to biological damage by offering antimicrobial activities. These nanostructures can enter the cells of microorganisms and alter their behavior, leading to inactivation. TiO_2 nanomaterials and their composites can be used in anti-biofouling coatings thanks to their antialgal, antifungal, and antibacterial properties for different materials (limestone, marble, brick, wood, glass, cementitious surfaces, and others) [96]. Pastor et al. [97] worked on optimizing several complexes of the biocide carbendazim with clays for its potential use as antimicrobial additives in restoration mortars. Brick surfaces can be coated with zinc and silver nanoparticles to achieve hydropic, photocatalytic, and antibacterial properties [98]. This treatment inhibits a broad spectrum of microorganisms, such as viruses, fungi, and bacteria. Finally, a composite coating was prepared by Wang et al. [99] to enhance the resistance of ancient bricks to atmospheric agents, bacteria, and algae.

The protection of historical and cultural heritage plays a crucial role in modern society. Working groups have been dedicated to defining the tools to evaluate the needs and impacts of conservation, collecting all types of knowledge, even tacit knowledge [100]. Preventive conservation is a proactive approach to avoid or minimize damage and deterioration to cultural heritage and artifacts [101], while it is also practical from a cost perspective [102].

Of course, conservation measures vary depending on the object of protection, for example, sites, buildings, art collections, etc. [103]. Various international organizations operate in this sector. They have a fundamental importance in providing recommendations and guidelines for cultural heritage conservation, particularly concerning environmental conditions. Some of the leading organizations are the “International Council of Museums” (ICOM), which provides guidelines for various aspects of museum management, including conservation practices and environmental conditions; the “International Centre for the Study of the Preservation and Restoration of Cultural Property” (ICCROM), which focuses on conservation and restoration, offering expertise and resources to professionals in the field; the “International Council on Monuments and Sites” (ICOMOS) that is dedicated to the conservation and protection of cultural heritage sites; the “Getty Conservation Institute” (GCI), addressing various aspects of conservation, including environmental management and the impact of climate on cultural heritage; the “Canadian Conservation Institute (CCI)” which is known for its work on environmental issues affecting cultural heritage, such as the impact of humidity. Regarding environmental recommendations, the organizations generally emphasize maintaining stable and controlled conditions, particularly for humidity and temperature, to prevent damage to cultural artifacts. Some of the key recommendations include the following:

- Temperature and Relative Humidity Control: Keeping stable temperature and relative humidity levels to prevent fluctuations that can lead to condensation, mold growth, and other forms of biodeterioration.
- Light Control: Protecting artworks from excessive exposure to light, particularly UV radiation, to prevent fading and other light-induced damage.
- Air Quality: Ensuring good air quality to prevent pollutants and contaminants that can adversely affect cultural materials.
- Storage and Display Guidelines: Providing recommendations for appropriate storage and display conditions for various types of artifacts.

The findings from this study can significantly contribute to establishing criteria and guidelines for safeguarding and preserving historical heritage against biodeterioration.

4. CONCLUSIONS

This study has provided a reference database of fungal genera and species associated with some commonly used materials in historical buildings. In typically uninsulated envelopes such as those analyzed, the study showed the formation of condensation according to the boundary conditions. In particular, the analysis highlights that high relative humidity conditions are generated when heating and cooling systems are not present. However, condensation occurred in different percentages in all the examined cases. This demonstrates the challenge of preserving historic buildings, as the occurrence of condensation creates a high risk for fungal growth. Regarding the studied materials, limestone is the most vulnerable to condensation.

Three solutions have been suggested to prevent fungal development in buildings. Passive measures, based on thermal insulation, to keep the structures' surface temperature higher than the surrounding air. Active measures, to lower the relative humidity levels in indoor environments. Finally, chemical treatments, involving the use of particular substances capable of removing the fungal colonies from the material's surface and preventing germination. The identified measures can be used separately or in combination and are applicable in compliance with the constraints to which historical and archaeological heritage buildings are usually subject.

The present study has some limitations. The analysis was conducted on an ideal building model, for which specific calculation assumptions were adopted. Furthermore, the weather files used in the simulation do not include data for pouring rain, which can affect the moisture content in the structures, modifying heat and mass transport results. Future studies should aim to model an existing building in actual usage conditions and to perform simulations considering rainfall data.

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