

Diagnostic strategies for fungal damage in Lasem's tropical heritage buildings

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ARTICLE INFO	ABSTRACT
<i>Article history:</i> Received July 04, 2026 Received in revised form Aug. 04, 2026 Accepted August 17, 2026 Available online September 01, 2026 <i>Keywords:</i> Fungal Heritage building Hygrothermal Rising damp Sustainable settlement *Corresponding author: Maria Immaculata Ririk Winandari Department of Architecture, Faculty of Civil Engineering and Planning, Universitas Trisakti Jakarta, Indonesia Email: mi.ririk@trisakti.ac.id ORCID: https://orcid.org/0000-0002-1550-7109	<i>The deterioration of wall surfaces resulting from fungal proliferation in tropical heritage houses is governed by interconnected moisture-transfer processes operating within and around the building envelope. Consequently, engineering-based interventions are required to address persistent humidity-related problems. This study seeks to develop alternative strategies for reducing wall moisture by examining soil geology, drainage performance, and hygrothermal characteristics as interconnected determinants of building deterioration. The research was conducted in Karangturi, Lasem, an area characterized by a humid tropical coastal environment and a substantial concentration of heritage buildings. A mixed-methods research design was adopted, incorporating variables including soil texture and permeability, drainage conditions, air temperature, relative humidity, illuminance, air velocity, and wall-surface moisture. The findings demonstrate an association between soil characteristics and the occurrence of rising damp. Wall-surface moisture exhibited a pronounced asymmetrical distribution, suggesting vapor accumulation associated with insufficient air movement and localized air stagnation. These environmental conditions support the development of a moisture-vapor accumulation mechanism within the interior environment. The findings establish a diagnostic sequence in which fine-grained soils are associated with capillary moisture rise, subsequently contributing to an increased indoor vapor load. When this condition occurs simultaneously with stagnant airflow and relative humidity levels exceeding 80%, the potential for fungal proliferation increases substantially. An integrated, field-verifiable mitigation strategy can be implemented through adjustments to subsurface drainage, installation of capillary breaks, application of vapor-permeable lime plasters, and improvement of natural ventilation. The range of mechanisms identified through this study can provide a practical basis for guiding conservation decisions and environmental interventions within tropical heritage areas.</i>

Introduction

Heritage buildings, particularly those located in tropical coastal environments, face persistent deterioration of building materials as a consequence of damp wall conditions and recurrent fungal proliferation. These two interrelated problems can negatively influence occupant comfort while simultaneously creating substantial challenges for long-term conservation efforts (Yuk et al. 2024). The presence and continued development of fungi on building wall surfaces may compromise both the physical integrity and functional usability of heritage structures. Local climatic conditions and geological characteristics constitute important environmental drivers of this deterioration process (Astuti et al. 2024). Over time, such degradation may undermine the cultural significance of heritage buildings, whose values are deeply associated with collective memory, local identity, and cultural traditions (Ahmadi and HaghighatBin 2026). Lasem was selected as the research location because it represents a tropical coastal area containing numerous heritage buildings along the northern coast of Java. At present, the area is managed through a zone-based conservation framework that emphasizes sustainability as an important component of heritage-area management (Fahmi, Anggarini, and Hoque 2024; Putri 2024; Winandari et al. 2023).

Moisture represents one of the most immediate and influential factors contributing to biodeterioration. It is commonly introduced into building systems through groundwater, precipitation, and surface runoff. Once moisture enters or is transferred to the heritage building envelope, excessive moisture levels can accelerate biodeterioration by creating favorable conditions for fungal proliferation (Qiu et al. 2025). Such deterioration affects not only the aesthetic quality of building surfaces but also the physical properties and performance of building materials, thereby creating potential threats to structural integrity. Nevertheless, reactive approaches to biodeterioration remain common in tropical regions such as Indonesia. In contrast, contemporary discourse concerning built-heritage conservation increasingly emphasizes low-technology adaptation strategies, including approaches derived from vernacular knowledge. Such strategies are particularly relevant in areas

where limited resource availability constrains the implementation of sophisticated technological retrofits (Dabaieh, Zacharia, and Kazem 2026).

In the Lasem context, fungal growth continues to recur despite attempts to eliminate it through wall coatings and manual removal of mold. Consequently, mitigation measures designed to reduce excessive humidity are required to minimize or potentially eliminate recurring fungal proliferation. Two interconnected environmental systems are particularly relevant in Lasem: rising damp, which is influenced by soil type and permeability, and indoor airflow, which plays an important role in regulating relative humidity (RH). At the same time, salinity and the potential for seawater intrusion may further aggravate wall dampness and accelerate material deterioration (Marwanza et al. 2023). As reported by Li et al. (2020), inadequate air circulation can cause indoor RH to exceed 80%, a condition associated with visible fungal growth. The presence of persistent wall moisture within interior spaces indicates that long-term fungal control cannot be achieved through a single intervention. Instead, a comprehensive intervention strategy is necessary to interrupt the interconnected processes sustaining the deterioration cycle.

A range of previous studies has investigated factors associated with moisture in buildings (Yuk et al. 2024), material characteristic (Chen et al. 2024), environmental condition (Mubarak, Fitra Yuda, and Nuryana 2025), human activities (Sirror 2024), and fungal type in heritage buildings (Dán et al. 2024). Although numerous studies and technological innovations have addressed these issues, several research gaps remain and require further investigation.

The novelty of this research lies in its holistic framework, which integrates soil geology, drainage systems, and indoor microclimate conditions in relation to fungal growth. This paper aims to identify the relationships among soil type, drainage performance, and microclimatic conditions in contributing to fungal growth and subsequent damage to heritage buildings in Lasem. This objective was pursued by mechanistically assessing relevant risks, including groundwater absorption capacity, indoor temperature, daily RH patterns, and air velocity near wall surfaces. Diagnosis was undertaken through a mixed-methods approach. The resulting findings were then used to formulate intervention criteria concerning soil characteristics, drainage systems, wall materials,

and indoor air-movement strategies. Fungal growth on heritage-building walls in Lasem and the environmental factors contributing to this deterioration constitute the central focus of the research. Within this framework, Lasem is positioned as a potential model for area-based conservation in humid tropical coastal environments.

Methods

To identify the interconnected factors contributing to humidity and fungal-growth risks in Lasem's coastal heritage houses, this study adopted a mixed-methods research approach. Quantitative methods were employed to evaluate technical and environmental performance through field-based and laboratory measurements. Qualitative methods were subsequently used to interpret the quantitative findings through direct observation, interviews, and document analysis. The methodological framework integrated indoor

hygrothermal behavior, settlement-scale drainage assessment, and soil hydrogeology. The external moisture supply affecting building plinths was determined through hydrogeological assessment. Continuous monitoring of air temperature, RH (Yuan et al. 2023), V, and illumination (Lerma et al. 2021) as well as repeated measurements of wall-surface moisture (Kang et al. 2022), was undertaken to characterize indoor hygrothermal conditions. Settlement drainage was also investigated to identify external constraints affecting moisture conditions. Field observations were conducted in June 2025 and July 2025. Primary outcomes, including RH degree-hours, were reported separately to capture diurnal asymmetry in the environmental conditions.

Identification of soil-moisture factors was conducted by integrating soil sampling (see figure 1), geotechnical soil-index testing based on K-values in cm/s, and GIS-based zonation to identify areas susceptible to moisture-related problems. Descriptive and inferential statistical analyses were applied to establish relationships between soil geology and moisture conditions.



Figure 1. Samples of soil for the permeability test procedure

Temperature (°C), RH (%), air velocity (m/s), and illuminance (lux) were continuously measured (Cao et al. 2021). Measurements were focused on a room in which visible fungal growth was present (figure 2). Sensors were positioned within the occupied zone and near the selected wall surface, as illustrated in figure 3. Wall-surface humidity was recorded three times daily, namely in the morning, at midday, and at night.

RH values were calculated from the time-series measurements and reported separately for daytime (08:00 – 18:00) and nighttime (18:00 – 08:00) periods. For analytical interpretation, air velocity was classified into stagnant conditions ($=0 - 0.05$ m/s) and target conditions ($\geq 0.15 - 0.20$ m/s).



Figure 2. Microclimate observations on fungus-covered walls

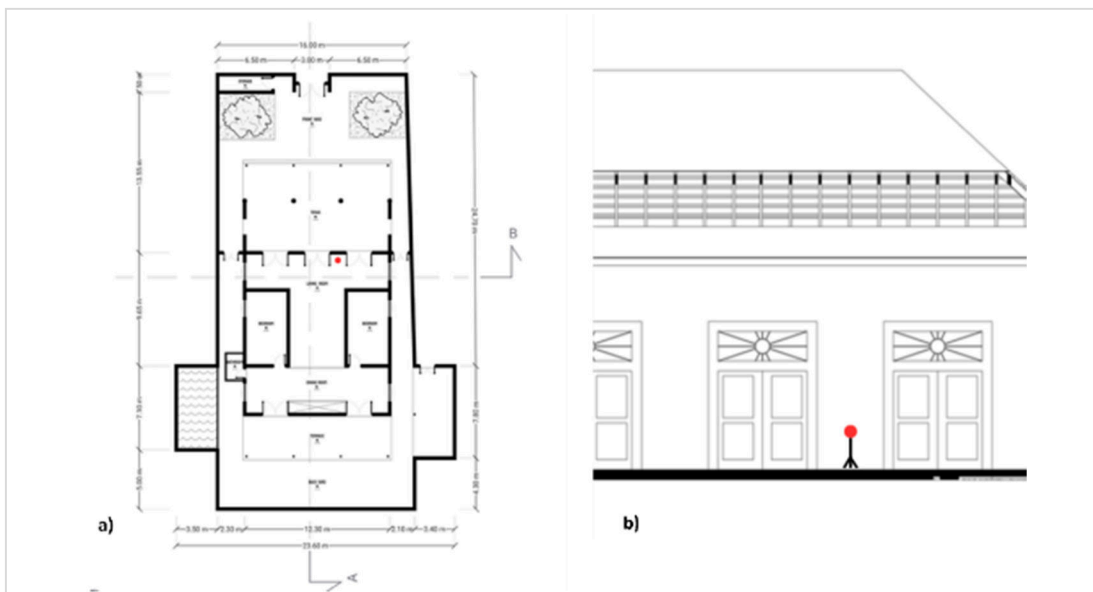


Figure 3. The sensor placement on the building plan (a) and elevation (b)

A combination of drainage-data collection and hydrological experiments was employed to evaluate the contribution of drainage systems to wetting at the base of heritage walls. Drainage-channel types, dimensions, and soil characteristics within the settlement drainage network were documented (figure 4). A rainfall design scenario was developed using secondary data collected during the preceding decade from

BBWS Pemali Juana, Semarang. The design discharge (Q_{design}) at local inlets was estimated using a hydrological procedure, whereas drainage-capacity discharge (Q_{cap}) was established through hydraulic analysis. Q_{cap} and Q_{design} were subsequently compared using Manning's capacity calculations (Garrote et al. 2021). A schematic drainage map was prepared to illustrate the principal flow routes.

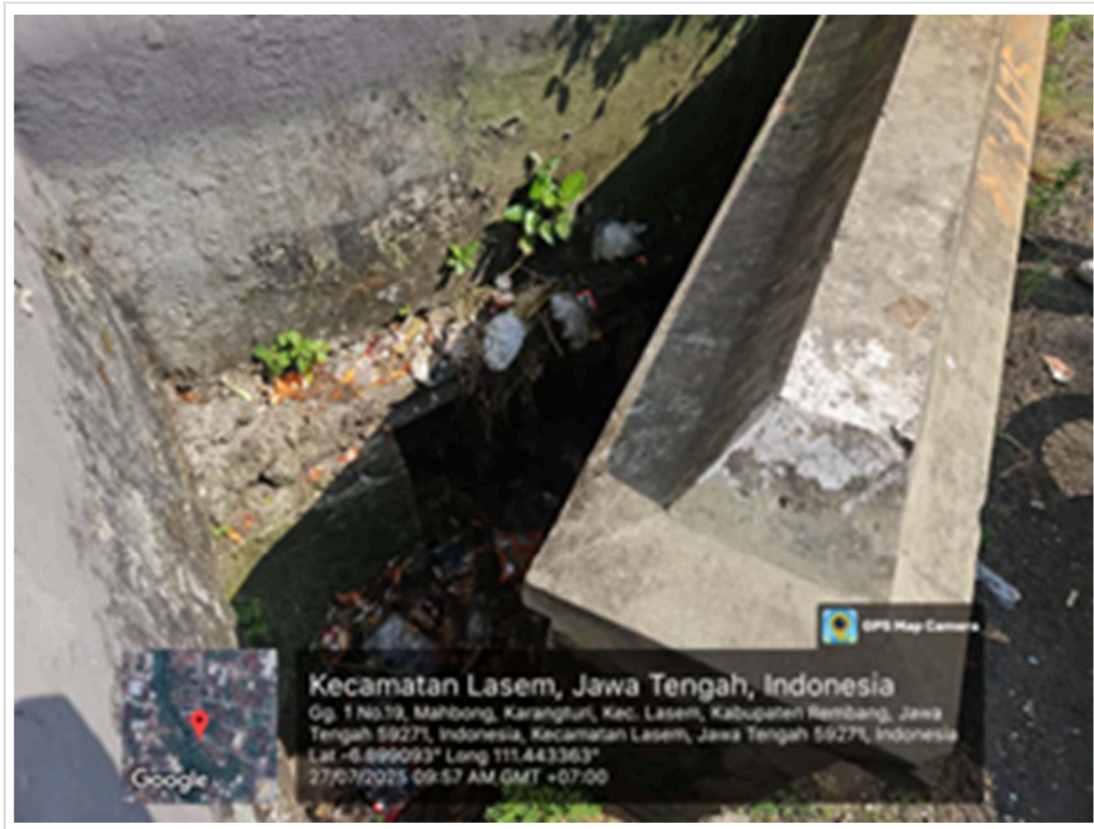


Figure 4. Drainage condition in Karangturi Settlement

Regression analysis was applied to determine the strength of relationships among the measured variables, including RH, temperature, illuminance, and air velocity (V). Bivariate analysis was used to compare environmental conditions between the first and second measurement sessions. Building moisture conditions were associated with the lot-scale drainage-capacity deficit ($Q_{cap} < Q_{design}$) and indoor RH load. The resulting analysis was used to evaluate environmental conditions that could represent potential risks for fungal proliferation.

Results and discussion

Soil characteristics and rising damp

The soil characteristics of Karangturi comprise fine-sand alluvium with relatively greater drainage capacity and silt-clay alluvium (see [figure 5](#)). These soil types exhibit low-to-medium permeability and can retain moisture near building foundations for extended periods, with

K-values ranging from 0.00293 to 0.000928 cm/s. The predominance of low-permeability soil sediments represents one of the principal risk factors for capillary moisture intrusion into heritage structures. Strong capillary suction generated by fine soil pores, together with prolonged water retention, constitutes an important moisture-retention mechanism ([Qu et al. 2024](#); [Hussary et al. 2022](#)).

Recent investigations of rising damp in heritage sites provide strong support for the physical mechanism identified in Lasem. Groundwater sources and porous masonry can maintain continuous hydraulic connectivity because particular soil textures generate greater matric potential than coarser-grained materials ([Bai et al. 2025](#)). This phenomenon becomes particularly evident where seasonally shallow groundwater tables intersect the foundation zone, as occurs in Karangturi. The site's stratigraphy indicates that although coarser underlying layers may interrupt capillary continuity, the persistence of groundwater within fine-grained soil layers contributes to chronic wetness ([Qu et al. 2024](#)).

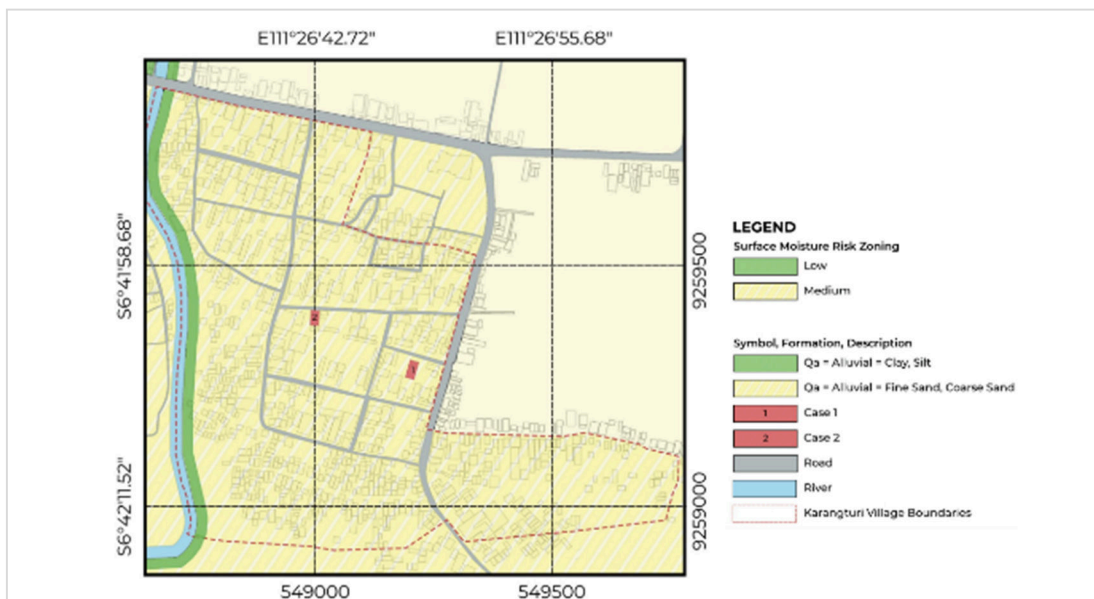


Figure 5. Soil moisture risk map in Karangturi settlement, Lasem

At the settlement scale, the soil characteristics and relatively flat geomorphology of Karangturi correspond closely with the observed risk of fungal growth. Saline intrusion can increase pore-water salinity within coastal aquifers, thereby accelerating deterioration of wall plaster while simultaneously trapping moisture within building assemblies. Groundwater levels exert a stronger influence than rainfall intensity (Qu et al. 2024). Conversely, the combined influence of groundwater levels, rainfall intensity, and disrupted drainage in Karangturi contributes to prolonged soil-moisture retention.

The statistical characteristics observed in Karangturi indicate that reducing moisture within heritage structures requires source-control strategies centered on maintaining drainage continuity. Systematic improvements to drainage infrastructure and the installation of capillary breaks at wall bases should therefore be considered to interrupt capillary moisture movement through low-permeability soils. Vapor-permeable lime/pozzolan plasters are recommended to facilitate the safe drying of salt-affected building fabric. A summary process model describing heritage-building deterioration corresponds with causal patterns involving soil permeability and wall moisture. The Karangturi case demonstrates that effective conservation diagnosis requires the integration of multiple spatial and environmental scales. Soil-type

mapping at the settlement scale, combined with climatic monitoring at the wall scale, is necessary to evaluate the progression of material degradation.

The interior microclimate

An important dimension of heritage-building deterioration is revealed by the interior microclimate data collected in Karangturi, particularly the mediating role of air movement in active fungal colonization. Measurements from both cases (figure 6) indicated elevated humidity, temperatures ranging from 27°C to 31.4°C, and very low illumination levels. Persistent air velocities of 0 m/s in unventilated rooms, behind furniture, and within corners indicate a fundamental reduction in the building's capacity to regulate its passive environmental conditions (Zhang et al. 2026). The interior humidity dynamics, which would ordinarily be influenced by natural air exchange, are substantially altered under these stagnant conditions, producing a self-reinforcing environmental cycle favorable to fungal growth. These combinations of humidity and temperature provide conditions that accelerate fungal proliferation (Tringa, Kavroudakis, and Tolika 2024).

According to microclimate research concerning cultural heritage environments, the boundary layer adjacent to a wall becomes increasingly saturated when water vapor

evaporates from damp wall surfaces into air masses characterized by limited movement. This process allows moisture to accumulate within both the interior air and the building structure (Frasca et al. 2020). The measurements demonstrated a rapid change in humidity, with RH increasing during nighttime and decreasing during daytime periods ($R^2 = 0.65$; $p < 0.0001$). The Karangturi data indicate that RH exceeded the 80% threshold during both daytime and nighttime periods (figure 6a). Such environmental conditions are highly favorable for fungal proliferation (Saraiva et al. 2025).

Illuminance measurements (figure 6b) indicate that both rooms remained under dim conditions, with maximum increases of approximately 18 lux and measured values below 3 lux. These conditions support the observation that the combination of warm temperatures, high humidity, and darkness creates an environment conducive to mold growth (Frasca et al. 2020).

Air movement generated through cross-ventilation can contribute to reducing indoor humidity (Patil 2026; Nugroho et al. 2026; Hamdy et al. 2023). Conditions associated with salt crystallization within building walls can also be reduced through air-exchange interventions (Frasca et al. 2020) and thermal inertia (Tringa, Kavroudakis, and Tolika 2024). Conversely, the combination of limited air movement, elevated humidity, and low illumination remains highly favorable to fungal development.

Moisture originating from the soil, characterized by K-values ranging from 0.00293 to 0.000928 cm/s, represents a continuous moisture source that can sustain fungal growth. This moisture facilitates persistent penetration into porous wall materials. Where moisture accumulates because of inadequate ventilation and unfavorable soil characteristics, the resulting environmental conditions can promote continued fungal colonization (Saraiva et al. 2025).

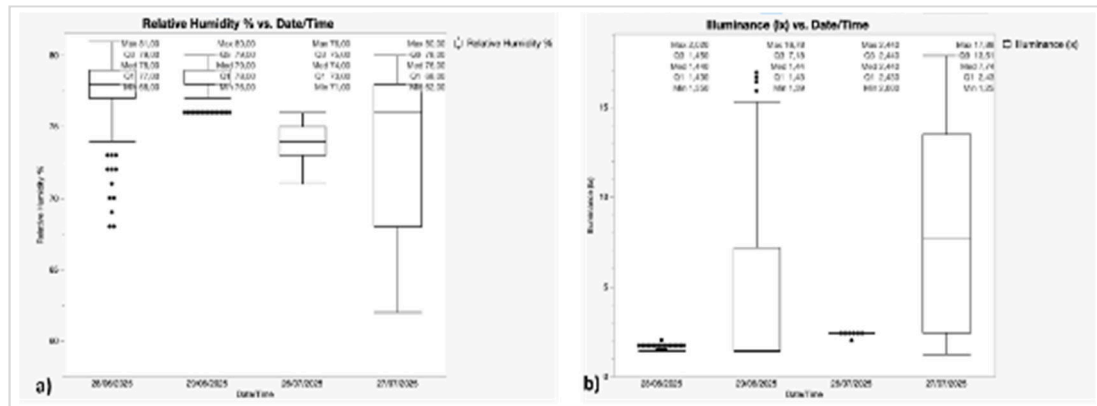


Figure 6. Humidity levels condition (a) and illumination (b)

Ventilation and lighting interventions can be introduced to reduce indoor humidity and improve environmental conditions. In the Karangturi cases, passive ventilation strategies can be implemented while giving priority to the conservation of heritage values. Ventilation management can reduce excessive humidity without compromising the physical integrity of the historic building structure (Zhang et al. 2026). The redesign of cross-ventilation pathways at appropriate locations, together with careful organization of interior spaces, can help maintain continuous airflow. The persistent darkness commonly observed in heritage buildings can likewise be addressed by improving indoor

lighting levels in ways that may inhibit fungal proliferation (Frasca et al. 2020).

The Karangturi case reinforces fundamental conservation principles by demonstrating that fungal deterioration operates as a complex and interconnected system. Soil moisture and the building's interior environmental conditions jointly influence the rate of material weathering. Integrated diagnostic procedures, extending from soil-type mapping to detailed microclimate monitoring, are therefore necessary to distinguish triggering factors from direct causes of deterioration. For heritage settlements located on fine-grained coastal sediments, building preservation should prioritize the restoration and management of the environmental setting that

surrounds and interacts with the historic building fabric.

Integrated intervention strategy

Interior microclimate data from Karangturi further demonstrate the important role of air movement in active fungal colonization. Measurements from both cases (figure 6) indicated elevated humidity, temperatures ranging from 27°C to 31.4°C, and very low illumination levels. Persistent air velocities of 0 m/s indicate a fundamental limitation in the building's capacity to regulate its passive environmental conditions (Zhang et al. 2026). These combinations of elevated humidity and temperature accelerate fungal growth (Tringa, Kavroudakis, and Tolika 2024).

Interventions designed to disrupt the fungal-growth system in heritage buildings are most likely to be effective when they address several points of the moisture pathway simultaneously. In Karangturi, the principal interacting conditions include low soil permeability, stagnant indoor air, and persistent RH levels above 80%. Comprehensive interventions may incorporate environmental-engineering measures such as chemical injection, plinth ventilation, breathable plaster, and drainage improvements (Koca, Uğural, and Yaman 2024). This integrated strategy is consistent with the fundamental principles of cultural-heritage conservation.

Injection techniques based on silane, siloxane, and resin represent potential approaches for controlling moisture and associated fungal problems. However, their long-term effectiveness may be influenced by brick characteristics and pre-existing salt contamination (Koca, Uğural, and Yaman 2024). Conditions in Karangturi indicate the potential presence of salt-affected building materials as a consequence of saltwater intrusion in coastal environments. According to (Št'astný et al. 2023), changes in pore size caused by salt accumulation can reduce the effectiveness of injection treatments. Therefore, chemical injection applications in Karangturi should first undergo site-specific testing before being adopted as a general intervention strategy.

Plinth ventilation can modify the soil-wall boundary layer while preserving the authenticity of the heritage building (Zhang et al. 2026). Interrupting the movement of water through the plinth can reduce the upward transfer of moisture into the wall, thereby contributing to lower indoor humidity levels.

Another appropriate strategy for Karangturi involves replacing cement-based plaster with vapor-permeable lime-pozzolan plaster. Breathable plaster can reduce the duration of moisture retention within wall materials, facilitating more rapid evaporation and consequently reducing conditions favorable to mold growth. Fungal colonization occurs less frequently on lime-coated surfaces than on cement-coated materials (Tringa, Kavroudakis, and Tolika 2024).

Four principal steps can be implemented to manage heritage buildings in Karangturi. First, improving drainage represents the least disruptive and potentially fastest measure for reducing the moisture supply at its source. Second, replacing existing impermeable plaster with breathable plaster can be undertaken concurrently to improve the wall's drying capacity. Third, in locations where air stagnation persists despite the implementation of other measures, base or plinth ventilation can be introduced carefully and selectively. Fourth, chemical injection should only be performed after confirming that moisture and salts will not become trapped behind an impermeable barrier. For heritage communities worldwide confronting comparable deterioration problems in fine-grained coastal sediments, this staged and integrated approach provides a potentially transferable conservation model.

Conclusions

This study identified relationships among soil type, drainage conditions, and microclimatic characteristics in relation to fungal growth on heritage-building walls in Karangturi, Lasem. The dampness responsible for initiating fungal proliferation is associated with capillary moisture rise through lime-plastered brick walls. This moisture supply is influenced by fine-sand and clay-silt soils with K-values ranging from 0.00293 to 0.000928 cm/s. These conditions are further intensified by water-vapor accumulation resulting from indoor air stagnation ($v = 0$ m/s), which raises RH beyond the critical 80% threshold favorable to fungal growth. Wall moisture and microclimate-mediated water-vapor accumulation are therefore essential components of the environmental conditions supporting fungal proliferation. These circumstances facilitate interactions among multiple triggering variables

and reveal an underlying vulnerability model for heritage-building deterioration. By extending the analysis of the built environment to humid tropical contexts characterized by substantially higher thermal and moisture loads, the Karangturi findings frame heritage deterioration as a systemic rather than isolated problem. Accordingly, this study proposes a comprehensive strategy as an alternative means of mitigating fungal damage in tropical heritage buildings. Treatment of fungal-related deterioration can involve the installation of capillary flow breakers, repair and improvement of drainage systems, application of vapor-permeable lime plaster, and regulation of indoor ventilation.

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Maria Immaculata Ririk Winandari contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.
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