



HERITAGE MUSEUM BUILDINGS UNDER CLIMATE STRESS: MAPPING DETERIORATION ACROSS URBAN AND COASTAL REGIONS

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Abstract

Heritage museum buildings in Malaysia increasingly face environmental stressors, such as high humidity, temperature changes, and heavy rainfall. Many are found in urban centres and coastal zones. Each location brings unique environmental challenges that influence the severity and type of deterioration. These cultural assets are susceptible, underscoring the need to understand how environmental conditions, especially those tied to geographic location, contribute to building degradation. Yet current maintenance often overlooks location-specific weaknesses, leading to poor conservation outcomes. This study compares environmental deterioration in heritage museum buildings across urban and coastal settings. Condition assessments were conducted at selected museums across multiple states and examined alongside regional temperature and humidity data. A spatial heat map generated in QGIS shows the distribution of deterioration by environmental exposure. The results show that coastal buildings face more moisture, dampness, and mould due to high humidity and salty air. Urban buildings, however, present localized problems like heat retention, pollution stains, and poor ventilation. The analysis demonstrates that environmental stressors, especially humidity and rain, work with location to shape building conditions. The study recommends climate-responsive, location-specific maintenance strategies to preserve heritage assets in the long term. These findings aim to help heritage managers and conservation stakeholders plan targeted interventions and optimise resources in tropical urban and coastal areas.

Keywords: Heritage Conservation, Climate-Responsive Maintenance, Building Deterioration, Tropical Heritage Buildings, Spatial Risk Mapping

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INTRODUCTION

Heritage museum buildings in Malaysia showcase the country's history and diverse architecture. They play important roles in education, tourism, and supporting national identity (Athirah & Harun, 2025; SER, 2020). However, preserving these buildings is becoming harder because Malaysia's tropical climate brings high humidity, heavy rain, and changing temperatures (Nur Fisya et al., 2025; Daengprathum et al., 2022; Hidalgo-Sánchez et al., 2022).

Environmental factors speed up the deterioration of heritage buildings, especially in coastal areas where salty air, moisture, and strong winds cause more biological growth, erosion, and material damage (Del Cisne et al., 2024; Hernández et al., 2023; Luo et al., 2023). The problem is made worse by weak environmental protections and uneven maintenance. Since Southeast Asia is very vulnerable to climate change and about 70% of Malaysia is coastal, heritage buildings face even greater risks (Dickerson, 2019).

Even with conservation efforts based on the National Heritage Act 2005 (Malaysia, 2005) and JWN guidelines, 61% of conservation work focuses on museum buildings, and 70% still have physical problems caused by environmental damage (Asyraf Mohd Bekeri et al., 2023; Hauashdh et al., 2020). Most current practices are reactive, fixing damage only when it becomes serious. This approach speeds up deterioration, raises repair costs, and puts the buildings' authenticity at risk (Azizan et al., 2020; Ferreira et al., 2021).

Most earlier studies have looked at restoration or documentation separately, without combining data on environment, building condition, and defects. This study fills that gap by analysing environmental stress, condition ratings, and defect patterns in Malaysian heritage museums. It uses spatial and statistical methods to help develop preventive maintenance strategies that respond to climate challenges.

LITERATURE REVIEW

As a heritage building, a museum is integral in upholding cultural identity. However, it is increasingly threatened by environmental stressors (Bülbül Bahtiyar & Dişli, 2022; Dişli & Kilit, 2024). Past studies identified several environmental factors, such as wind, rain, humidity, solar radiation, and salt-laden air, as key factors in material deterioration at heritage sites. These pressures exacerbate common defects, including dampness, cracking, coating delamination, and biological growth, especially in tropical and coastal regions such as Malaysia and Indonesia. (Arif et al., 2024; Daengprathum et al., 2022; Fadhilah Bahardin et al., 2022; Ortega-Morales et al., 2019; Zain et al., 2022).

In urban areas, climatic fluctuations and pollution accelerate material deterioration and surface wear (Del Cisne et al., 2024). In contrast, coastal areas are subject to distinct damage mechanisms, including elevated humidity, salt

crystallization, and wind erosion (Hernández-Montes et al., 2023; Luo et al., 2023). Consequently, the location of a building—whether transitional, coastal, or urban—plays a significant role in the progression and nature of deterioration in historic structures.

In response to these risks, recent studies increasingly advocate for preventive maintenance of heritage buildings (Ferreira et al., 2021). Rather than addressing issues only after they arise, a risk-based preventive approach aligns maintenance priorities with building condition and environmental risk factors (Lucchi, 2020; Silva & Henriques, 2021). This strategy not only mitigates deterioration but also reduces long-term costs and conserves resources.

GIS-based maps, created with open-source spatial analysis tools such as QGIS, highlight the need to map deterioration patterns across heritage museum sites (Gabriele et al., 2023). QGIS helps identify high-risk areas and environmental stressors that drive material decay by combining building condition data with environmental factors such as temperature, humidity, and moisture (Guerri et al., 2023; Papakonstantinou, 2025). This spatial insight, together with environmental monitoring, improves understanding of and ability to observe preservation challenges (Graser et al., 2025; Maurya & Kumar, 2024).

Despite rising global awareness, preventive maintenance of heritage buildings in Southeast Asia remains inadequate. Research shows that policy limitations, a shortage of technical skills, and inconsistent funding block systematic preservation efforts in the region (Asyraf Mohd Bekeri et al., 2023). Thus, it is urgent to adapt international preventive models to local contexts, particularly in countries such as Malaysia that are vulnerable to climate change.

METHODOLOGY

This study used a mixed-methods approach to examine deterioration patterns and environmental stress impact on heritage museum buildings across different regions of Malaysia. A total of 13 heritage museum buildings, representing urban, coastal, and urban-coastal areas, were selected based on their location, regional exposure, and function. The framework in Figure 1 combines building condition assessments, environmental monitoring, and spatial analysis to create a clear understanding of how climate factors affect the severity of deterioration.

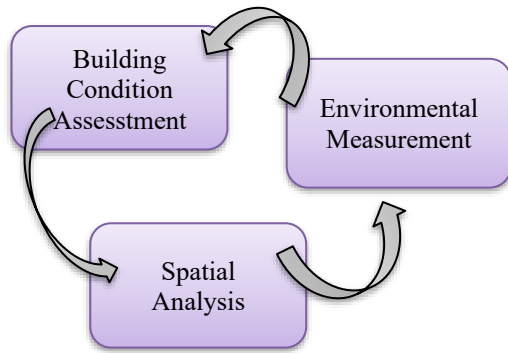


Figure 1: Methodological Framework

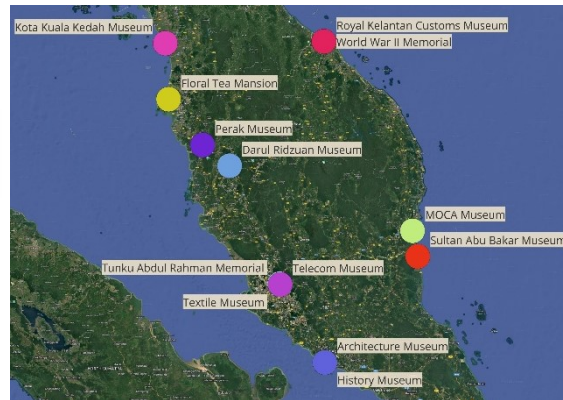


Figure 2: Spatial Distribution of Heritage Museums Buildings collected across Malaysia Peninsular.

Figure 2 and Table 1 show the spatial distribution of heritage museum buildings in several states in Malaysia, including Kuala Lumpur, Perak, Kedah, Penang, Kelantan, Pahang, and Malacca.

DATA COLLECTION

Data collection used three instruments:

- i) Visual Building Condition Assessment (BCA) based on PWD BCA/FCA guidelines, with a 5-level condition rating and a risk matrix;
- ii) Environmental measurements of temperature, humidity, and surface moisture, recorded at multiple locations with at least five readings per variable, averaged; and
- iii) Spatial and tabular data integration, combining GIS coordinates, regional classifications (urban, coastal, urban-coastal), and defect counts into a unified database for analysis.

Table 1 illustrates the geographical spread of heritage museums across Peninsular Malaysia, categorised into three regional contexts as follows:

Table 1: Spatial Distribution of Heritage Museums Buildings Regions Colour-coded

Colour	Area	Buildings	Characteristics
 Purple	Urban	Telekom Museum, Textile Museum, and TAR Residency Memorial in Kuala Lumpur, and the Perak Museum and Darul Ridzuan Museum in Perak.	Inland city centres; Exposure on urban heat and pollution due to traffics and active town activities.
 Green	Coastal	Kota Kuala Kedah Museum in Kedah and World War Museum or known as <i>Bank Kerapu</i> in Kelantan.	Near coastal edges; exposed to sea breeze, spray, humidity, and saline air
 Blue	Urban-Coastal	Teh Bunga Mansion in Penang, the Historical Museum and the Architectural Museum in Malacca, the Royal Kelantan Customs Museum in Kelantan, the MOCA Museum, and the Sultan Abu Bakar Museum in Pahang.	Towns combining both urban infrastructure and proximity to coastline; exposed to dual stressors

DATA ANALYSIS

The data were analysed in three stages:

- Descriptive Statistical Analysis: Defect frequencies, building condition ratings, and environmental readings were summarized to identify key deterioration patterns.
- Spatial Distribution Mapping: Using QGIS, thematic maps were generated to visualise the geographic distribution of high-risk buildings, environmental exposure zones, and defect intensities across regions.
- Correlation and Risk Mapping: The relationship between environmental stressors and building condition scores was assessed in Excel. Risk levels were visualised in QGIS using graduated symbols and colour coding. The urban-coastal comparison was conducted using side-by-side map frames and attribute table filtering, enabling triangulation of environmental, structural, and spatial factors for climate-responsive interpretation.

Descriptive Analysis

Descriptive statistics summarised condition ratings, defect frequencies, and environmental parameters across 13 heritage museums. Using a 1–5 scale, mean and range values established baseline deterioration trends.

Table 2: Descriptive Statistics Condition ratings by locations

Area	Count	Min	Max	Mean	Std Dev
Urban	5	3.45	3.84	3.62	0.164
Coastal	2	3.69	4.02	3.86	0.165
Urban Coastal	6	2.61	3.91	3.28	0.3925

Table 3: Descriptive Statistics Defects by locations

Area	Sum	Min	Max	Mean	Std Dev
Urban	640	78	163	128	29.3
Coastal	296	130	166	148	18
Urban Coastal	805	81	185	134	36.862

A descriptive summary in Table 2 indicates clear regional disparities in building condition. Coastal museums recorded the highest and most consistent condition ratings (Mean = 3.855; SD = 0.165), while urban museums showed stable but slightly lower performance (Mean = 3.622; SD = 0.164). Urban-coastal museums exhibited the lowest ratings and highest variability (Mean = 3.277; SD = 0.392), indicating compounded deterioration pressures from combined climatic and urban stressors.

String from that, Table 3 illustrates that urban-coastal zones had the highest total defects (805), followed by urban (640) and coastal (296). However, coastal museums recorded higher defects per site, suggesting severe localized deterioration.

Table 4: Descriptive Statistics Categories of Defects by locations

Area	Moisture-related surface damage (Sum)	Structural (Sum)	Coating deterioration (Sum)	Biodeterioration (Sum)
Urban	512	68	35	16
Coastal	277	11	6	2
Urban Coastal	507	172	143	49

Defect categorisation revealed moisture-related damage as the dominant issue across all regions, particularly in urban (512) and urban-coastal (507) zones. Structural defects were most prevalent in urban-coastal areas (172), while coating deterioration and biodeterioration were also concentrated in these zones, reflecting intensified environmental exposure as stated in table 4.

Table 5: Descriptive Statistics Humidity Readings by locations

Environmental Parameter	Location	Sum	Min	Max	Mean	SD
Moisture (%)	Urban	107.26	17.5	27.1	21.44	3.52
	Coastal	79.30	35.6	43.7	39.22	4.05
	Urban Coastal	132.16	15.0	29.0	22.03	4.31
Temperature (°C)	Urban	140.92	25.3	30.0	28.18	2.22
	Coastal	54.00	26.0	38.0	27.00	6.00
	Urban Coastal	166.74	26.0	28.87	27.79	1.02
Humidity (%RH)	Urban	327.50	62.0	70.7	65.50	4.29
	Coastal	165.00	82.0	83.0	82.20	0.50
	Urban Coastal	449.00	68.0	82.0	74.83	4.52

Tables 5 illustrate that the environmental readings reinforce these findings. Coastal zones recorded the highest moisture (Mean = 39.22%) and humidity (Mean = 82.2%), while urban and urban-coastal zones showed moderate moisture (~21–22%) but higher defect occurrence, indicating accumulated exposure and material vulnerability. Urban areas recorded the highest temperature (Mean = 28.18°C), while coastal zones showed lower variability due to marine influence.

Overall, urban-coastal environments emerge as the most vulnerable typology, driven by a combination of environmental stressors.

Comparative Analysis

Comparative analysis indicates that urban (512) and urban-coastal (507) zones recorded the highest moisture-related surface defects, consistent with moderate moisture levels (21.44% and 22.03%). In contrast, coastal areas, despite higher moisture (29.33%), showed fewer defects (277), possibly due to better ventilation, material behaviour, or smaller building scale. Structural defects were most significant in urban-coastal zones (172) under moderate humidity (74.83%). In contrast, coastal zones recorded minimal structural issues (11) despite higher humidity (82.2%), suggesting deterioration is driven by combined environmental exposure and maintenance limitations rather than humidity alone.

Urban-coastal areas also exhibited the highest coating deterioration (143) and biodeterioration (49), reflecting intensified environmental stress from interactions among temperature, humidity, and moisture. Overall, urban-coastal environments are the most vulnerable, experiencing compounded deterioration effects.

Table 6: Comparison Statistics Condition and Environmental Readings by Regions

Location	Average Total Defects	Average Condition Rating	Average Moisture	Average Temperature	Average Humidity
Urban	640	3.622	21.44	28.18	65.5
Coastal	296	3.855	39.22	27	82.2
Urban Coastal	805	3.27667	22.03	27.79	74.83

Comparative analysis (Table 8) confirms that urban-coastal zones are the most vulnerable, with the highest defect levels and elevated humidity despite moderate condition ratings. Coastal zones, though fewer in number, exhibit higher moisture and humidity, indicating significant exposure risk, while urban areas experience thermal stress but comparatively less severe deterioration.

Spatial And Correlation Mapping

In addition to descriptive and comparative analyses, the data have also been analysed through spatial and correlation mapping using 3 different approaches, including spatial and environmental risk mapping and correlation mapping analysis, as follows:

a) Spatial and Environmental Risk Mapping Analysis

Spatial mapping using QGIS was applied to analyse total defects, identify environmental hotspots, and classify deterioration risks based on combined environmental factors, including moisture, temperature, and humidity.

i. Spatial Distribution of Total Defects

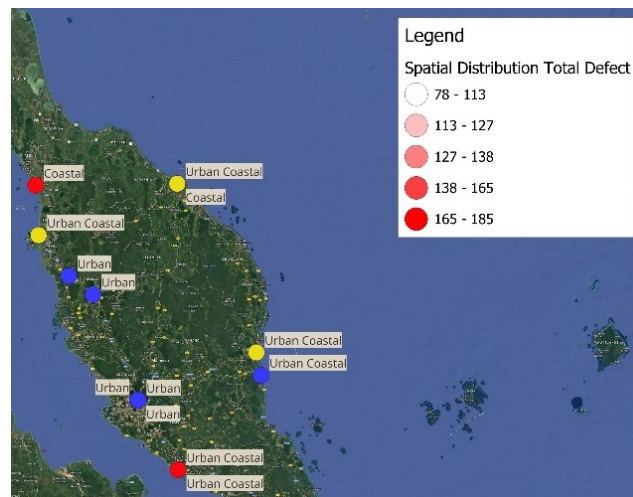


Figure 3: Spatial Distribution of Total Defects

Figure 3 shows defect distribution across museums, with the highest counts (165–185) concentrated in urban-coastal sites such as the Telekom Museum and the Architectural Museum. Lower defect counts (78–113) occur in less exposed locations. This pattern indicates that urban-coastal museums experience greater deterioration due to combined environmental and human-induced stressors.

ii. Heatmap of Deterioration Intensity

Figure 4 identifies deterioration hotspots in the Klang Valley, Melaka, and coastal corridors, indicating that urban pressure, environmental exposure, and visitor activity contribute to clustered, high-intensity building deterioration.

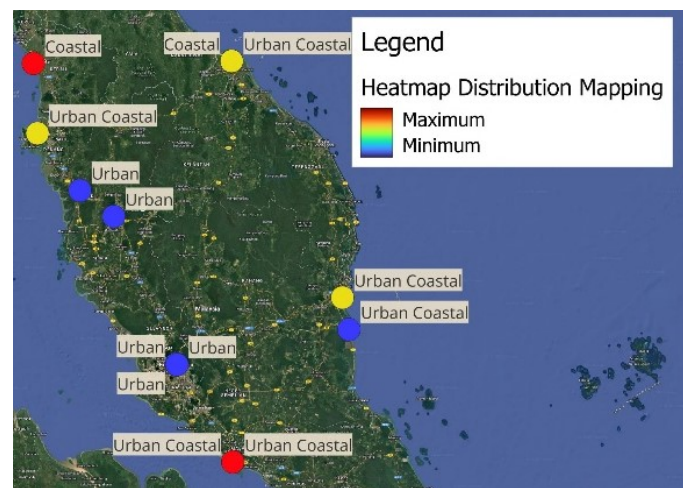


Figure 4: Spatial Distribution of Heatmap Deterioration Intensity

iii. Environmental-Based Deterioration Risk Classification

Table 7: Comparison Statistics Condition and Environmental Readings by Regions

Risk Level	Average Moisture	Average Temperature	Average Humidity
Low	20.37	26.75	65.92
Moderate	26.9	28.15	77.67
High	29.62	28.58	78.25

Table 9 shows high-risk buildings have elevated moisture (29.62%), humidity (78.25%), and temperature (28.58°C), indicating stronger environmental stress and deterioration risk. Figure 8 maps these risks, highlighting high-risk zones in Penang, Melaka, and southern coastal regions,

where tropical climate exposure intensifies deterioration, compounded by limited preventive maintenance practices. While moderate-risk museums are mainly located in central areas, low-risk sites tend to be inland or at higher elevations, like Perak and Kelantan.



Figure 5: Deterioration Risk Mapping Based on Environmental Condition

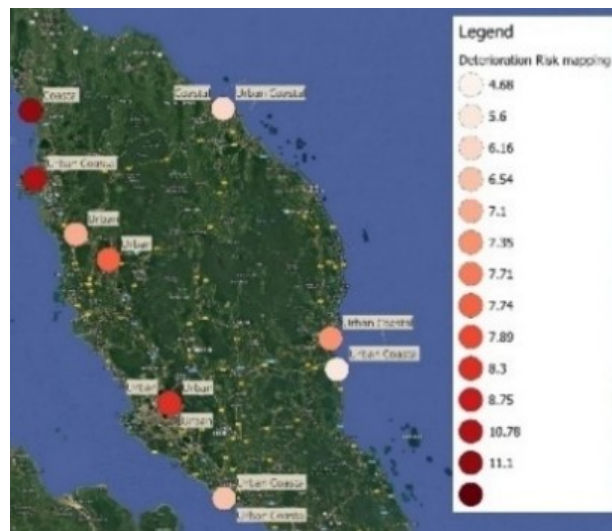


Figure 6: Deterioration Mapping based on Risk Score

Figure 6 presents a graded risk index map for deterioration. It is based on weighted inputs, including condition ratings, total defect scores, and

environmental measurements. Sites such as Telecom Museum (11.3) and Architecture Museum (10.76) have the highest risk scores. Their moisture and humidity readings are also elevated. This visualisation underscores the importance of spatial profiling for prioritising conservation efforts.

a) Correlation Analysis

The study analysed relationships across all museums using Pearson correlation and QGIS mapping. Despite geographic variation, this combined approach reveals overall links between temperature, humidity, moisture, and building condition, providing a clearer understanding of how environmental stress accumulates and influences deterioration patterns across different locations.

i. Pearson Correlation Matrix Interpretation

Table 8: Correlation Matrix Between Environmental Parameters and Building Deterioration

	Total Defect	Condition Rating	Risk Level	Temperature	Humidity	Moisture
Total Defect	-					
Condition Rating	-0.103	-				
Risk Level	0.090	0.89	-			
Temperature	-0.177	0.062	0.125	--		
Humidity	0.150	-0.109	-0.028	-0.600	-	
Moisture	0.116	0.563	0.656	-0.075	0.529	-

Table 10 shows a strong correlation between condition rating and risk level ($r = 0.891$), indicating that poorer conditions lead to higher risk. Moisture has moderate to strong correlations with condition ($r = 0.562$) and risk ($r = 0.656$), confirming it as a key deterioration driver. Humidity correlates with moisture ($r = 0.529$), reinforcing their combined effects. Temperature shows a weak negative correlation with defects ($r = -0.177$), indicating limited influence. Overall, moisture is the most significant environmental factor driving deterioration in Malaysian heritage museum buildings.

ii. Spatial Correlation Mapping (QGIS)

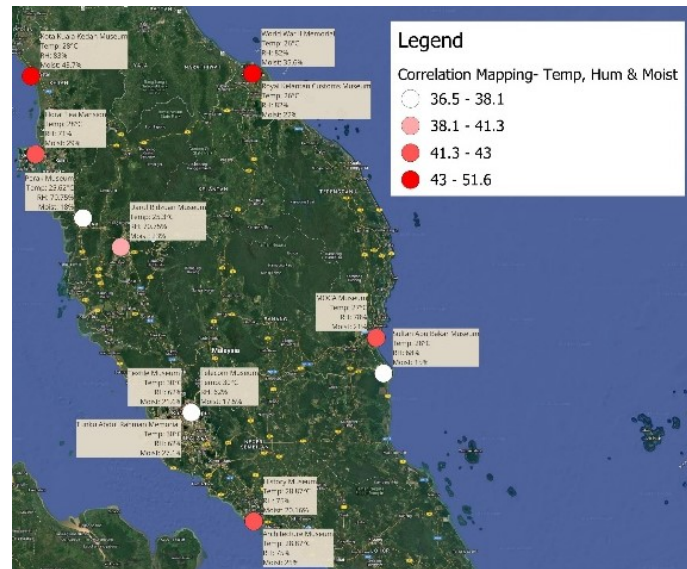


Figure 7: Deterioration Risk Mapping Based on Environmental Condition

A spatial correlation map (Figure 7) visualises the impacts of environmental stressors using average temperature, humidity, and moisture readings for each selected museum location. A composite environmental score was calculated as the mean of the three variables for each building. Based on overall environmental exposure, the score was categorised into quintiles to rank buildings spatially. The ranges are as follows:

- White (36.5–38.1) – Low environmental correlation
- Light Pink (38.1–41.3) – Mild influence
- Medium Pink (41.3–43) – Moderate stress
- Dark Pink (43–51.6) – High correlation with deterioration trends

Spatial mapping shows coastal and urban-coastal museums fall within medium to high environmental stress zones, indicating greater vulnerability, while inland sites experience lower stress. The correlation range (36.5–51.6) was divided into equal intervals to ensure consistent classification and reduce bias, supporting identification of priority conservation areas. This approach provides a macro-level understanding of environmental impacts across diverse locations. However, aggregated analysis may obscure localised conditions, particularly in unique coastal or highland settings. QGIS mapping complements statistical results by revealing site-specific stress patterns. Future research should expand

sample sizes to enable regional subgroup analysis and improve understanding of localised deterioration risks.

RESULTS AND DISCUSSION

Environmental Stress as A Deterioration Multiplier

The correlations and spatial analysis indicate that temperature, humidity, and moisture are associated with the risk of building deterioration. Humidity and moisture are interrelated, especially in urban coastal areas, where higher levels increase the risk to buildings. Therefore, this study contributes to the broader discussion of climate-related material degradation, for example, demonstrating that timber and masonry structures are vulnerable to recurring cycles of wet and dry conditions, biological growth, and surface damage. The consistent pattern of moderate to high environmental correlation values in these areas enhances the need for specific strategies to fit the maintenance protocols into the environmental conditions of each location instead of using generic conservation measures.

Spatial And Climatic Typologies Influence Performance

Building deterioration is not only about exposure, as shown by site differences within urban, coastal, and urban-coastal areas, but also depends on environmental and climate changes. As an example, building condition ratings in urban coastal areas are lower, with more defects, and have higher environmental readings than those in urban areas, indicating that the transitional zones are exposed to dual environmental stressors and require specialized conservation planning. This should include both inland heat management and marine exposure control.

Maintenance Gaps and Adaptive Shortcomings

Although building condition ratings and total defect counts did not strongly correlate with environmental factors in a linear way, their indirect influence through risk levels and moisture accumulation highlights the complexity of heritage conservation under climate stress. The weak correlations also show that maintenance practices vary. This underscores the need to shift from reactive maintenance to preventive conservation and maintenance, particularly for buildings with frequent recurring defects. Maintenance interventions should be seen not as separate technical tasks but as part of a broader strategy for climate resilience.

Implications For Heritage Conservation Policy and Planning

The study underscores a growing need to adapt the heritage museum building to a climate-sensitive approach that eases maintenance as a preventive measure, especially in tropical regions. Current national policies should enhance for

locational vulnerability or include climatic stress mapping in conservation priority setting. The findings from this study, especially the spatial risk patterns, are potentially useful to government conservation units and local authorities in designing region-specific conservation guidelines, allocating resources based on deterioration risk mapping, and prioritising heritage museum building conservation. This approach allows stakeholders to visualise deterioration patterns and manage risk structures before they cause critical damage.

CONCLUSION

This study examines deterioration patterns and environmental vulnerabilities of heritage museum buildings in tropical Peninsular Malaysia. Integrating condition ratings, environmental measurements, and spatial analysis, the findings identify humidity, temperature, and moisture as key drivers of defects such as biological growth, cracking, and material decay. QGIS mapping reveals greater vulnerability in coastal and urban-coastal areas due to compounded environmental exposure, with strong correlations between climate conditions and building performance. The study highlights the need for climate-responsive preventive maintenance strategies to address gaps in current practice. It underscores an urgent shift from reactive conservation to proactive, risk-informed approaches to enhance resilience and safeguard heritage assets for future generations.

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