A SYSTEMATIC REVIEW: UNDERSTANDING ENVIRONMENTAL DRIVING FACTORS OF HERITAGE BUILDING DEGRADATION

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ABSTRACT

As the realm responds to nature's will, environmental factors are often cited as threatening the heritage building's wholeness and genuine character. Evolution in this research field has discussed various fractions of elements into these factors. Inevitably, this Systematic Literature Review (SLR) aims to comprehensively understand the extent and nature of environment, such as humidity, temperature fluctuations, pollution, and biological growth, that influence heritage buildings' degradation. Focusing on scholarly articles between 2020 and 2024 from reputable databased of Scopus and ScienceDirect, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework and systematic review of the filtered articles, the study found the contributed insights of the key area. The findings are categorized around three main themes: (1) Environmental and Climatic Impacts, (2) Material-Specific Degradation Mechanisms in Heritage Buildings, and (3) Diagnostic and Preventive Technologies for Heritage Building Preservation. The review reveals that moisture and temperature as the main environmental factors causing material decay, show up the cracking, erosion, and biological growth. Air pollution hastens chemical degradation, whereas natural disasters cause immediate and widespread loss in structural integrity. This paper calls underlining interdisciplinary collaboration to respond to environmental challenges ensuring the structural integrity of heritage buildings for future generations.

Keywords: Heritage Building Defects, Degradation Factor, Environmental Impact, Heritage Building Preservation, Preventive Maintenance.

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1. INTRODUCTION

Past civilizations' history, architecture and traditions are revealed through heritage buildings, priceless ethnic treasures (D'Alpaos & Valluzzi, 2020; Santangelo et al., 2022; Vîlcea et al., 2023). Their preservation as a global priority importance justifies as these structures represent artistic and technical brilliance of their era (Bajno et al., 2021; Mouraz et al., 2023). However, reams of environmental factors constantly threaten the long lifespan of heritage buildings, accelerating structural and material degradation (Chen et al., 2023; A. J. Prieto et al., 2020; Shrestha et al., 2024).

The degradation such as cracks, and biological growth, weaken the structural's stability (Mascaro et al., 2022), compromising the loss of authenticity through original materials alteration (Orlenko et al., 2021), architectural modification (Liu et al., 2020), and aesthetic value diminishing (Dias et al., 2022). On this ground, heritage building stakeholders and practitioners, face challenges in sustaining the preservation work of vulnerable heritage buildings (Kayan & Ashraf, 2023; Norazman et al., 2023; Ruiz-Jaramillo et al., 2020).

To understand the situations, diagnostic method is important to identify the routes of degradation that oftenly missing during the conventional observation. Related to that, the merging of diagnostic technologies such as thermal scanning is essential to improve degradation identification at early stage and enable proactive conservation. By fill in the gap of knowledge, this study emphasized specific vulnerabilities of heritage building and potential prevention approach to delay the degradation. Therefore, this study aims to reconcile the gap of heritage building degradation environmental factors with the diagnostic method by exploring the environmental factors that influence the degradation, emphasizing diverse climates prone to stressors and identification of diagnostic methods focusing on finding the suitable preservation approach upon the degradation driven factors.

2. LITERATURE REVIEW

The studies on multichallenge of degrading heritage buildings, threatening their structural stability commonly brought by environmental stressors (de Oliveira et al., 2023; Mascaro et al., 2022). While previous studies have explored specific environmental stressors such as moisture intrusion (Michette et al., 2017), temperature fluctuations (Zarzo et al., 2021), and pollution(Esteban-Cantillo et al., 2024) that affect heritage buildings; this literature review explores the factors holistically to understand the relation of it. The moisture, pollutants, as well as temperature fluctuations cause salt crystallization (Desarnaud, 2024)and freeze-thaw cycles (Sahyoun et al., 2024) to affect bricks, stones substantially, and timber, influencing their physical and chemical impact(Khan & ., 2023), in addition to mechanical properties.

These environmental stressors compromise structural integrity (Cappai et al., 2024; Rossi & Bournas, 2023). Ali et al., (2024) showed that, importantly, increased water absorption in many coral stones in Stone Town Zanzibar results from the marine environment, exposing considerable coastal material weakness. Advocates urge revising restoration guidelines to use resilient materials (Cantatore & Fatiguso, 2021); these materials should match the look and function of other originals and improve environmental resilience. Targeted conservation strategies against climate change and land subsidence, such as sustainable materials and techniques, are zeroed in on by (Paupério et al., 2024; Zaccariello et al., 2024). Elnaggar et al., 2024) strongly suggest that Mediterranean museums implement necessary preventive conservation measures, such as advanced HVAC systems, UV filters, and exact indoor climate control, to combat environmental threats effectively.

The integration of environmental science, along with heritage conservation, is absolutely analytically important (Edvardsson et al., 2021; Rinaudo et al., 2023). Environmental sensors and data analytics play a truly major role in real-time monitoring of humidity, pollutants and other degradation factors, (Daengprathum et al., 2022; Hidalgo-Sánchez et al., 2022). Therefore, proactive strategies for minimizing extreme temperatures humidity fluctuations and pollution need cross-disciplinary collaboration.

Through figure 1, this review presents a theoretical framework including environmental stressors (B. Prieto et al., 2020), material vulnerability (Shan et al., 2022), along with adaptive capacity (Dilling et al., 2023; Vallury et al., 2022). Temperature, moisture, along with pollution, affect heritage materials' vulnerability, influenced by their physical as well as chemical properties (T. M. Ferreira & Santos, 2020; Trizio et al., 2022). Maintenance effectiveness along with material durability determine a system's meaningful adaptive capacity, reflecting its large resilience to environmental changes (Ghaderi et al., 2022; Kalantari & Tehrani, 2021). Many proactive conservation strategies must improve adaptive capacity and lessen the effect of meaningful environmental stressors on heritage buildings (Dyson et al., 2016).

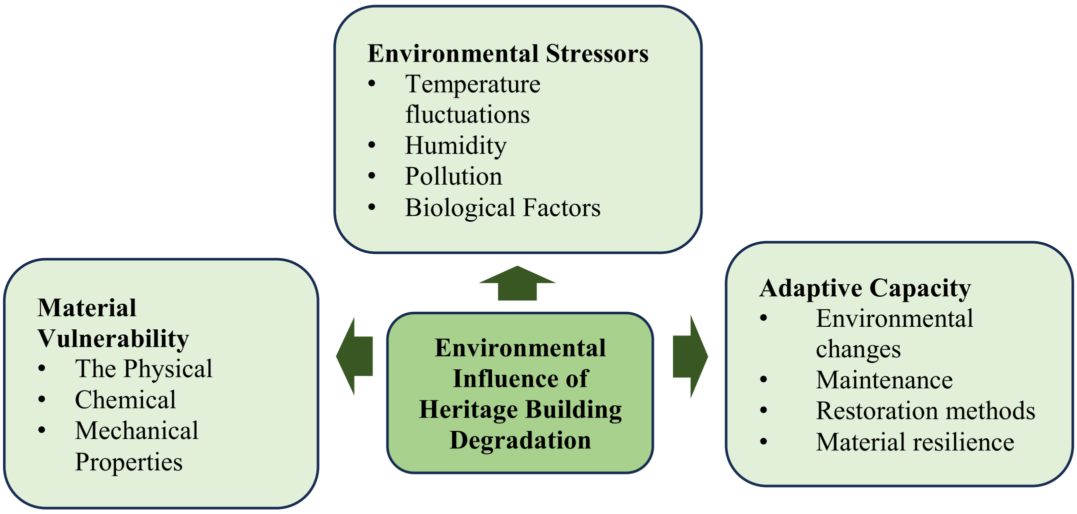

Figure 1: Theoretical Framework of Environmental Influence of Heritage Building Degradation

Preserving heritage buildings needs a multidisciplinary approach (Marra et al., 2021). This approach integrates scientific research(M. P. Ferreira & Granato, 2020) and technical innovations on building diagnostic (Cruz et al., 2022) to address environmental challenges. This review clearly draws attention to the analytically urgent need to develop truly thorough strategies, incorporating environmental monitoring, along with advanced diagnostics, as well as sustainable preservation practices, to safeguard our indispensable ethnic heritage for future generations.

3. MATERIAL AND METHODS

This study involved three (3) phase of methodology involved the Systematic Literature Review (SLR) Implementation, Data Abstraction and Thematic Analysis, and Quality Appraisal and Expert Assessment that will explain further. Transparency, thoroughness, as well as consistency in conducting systematic literature reviews are promoted by the widely recognized Preferred Reporting Items for Systematic Reviews, and Meta-Analyses (PRISMA) approach, a standard for many such reviews. Accuracy and rigor in analysis are improved by researchers' adherence to PRISMA guidelines, which provide clear instructions on systematically identifying, screening and including relevant studies in their review (Page et al., 2021).

This study utilized two reputable academic databases, Scopus and ScienceDirect, to ensure comprehensive coverage of peer-reviewed literature across various disciplines. Scopus provides a wide-ranging index of research publication, offering access to a relevant studies of heritage conservation, while ScienceDirect contributed by providing high-quality journal articles on architectural degradation and environmental influences. Although these databases offer broad coverage, potential limitations, such as content gaps specific to each platform, were considered.

3.1 Identification

An extensive collection of relevant literature has been gathered using key steps of the systematic review process. The key terms were identified initially and thoroughly, and related words were explored using dictionaries, thesauri, encyclopedias, and prior research. All relevant terms were identified carefully, and search strings were developed simultaneously in the Science Direct and Scopus databases. 186 publications concerning the study topic were retrieved from the two (2) databases during the initial systematic review phase.

Table 1: The search string

Scopus	TITLE-ABS-KEY(("heritage build*" OR "historical build*") AND (degradation OR defect) AND (factors OR causes)) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English")) **Date of Access: December 2024**
Science Direct	(("heritage build" OR "historical build") AND (degradation OR defect) AND (factors OR causes)) **Date of Access: December 2024**

3.2 Screening

Screeners evaluate many potential research items to guarantee that at least some adjust with the predefined RQs. Studies are selected based on their relevance to the topic "Understanding Environmental Driving Factors on Heritage Building Degradation". Many duplicate studies are then removed at this stage. Initially, 120 publications were excluded, leaving 50 papers for further evaluation based on specific inclusion and exclusion criteria (outlined in Table 2). The primary inclusion criterion focused on literature that provides practical recommendations, including reviews, meta-syntheses, meta-analyses, books, book series, chapters, and conference proceedings that have yet to be addressed in the most recent studies. The significant inclusion criteria focus on addressing the degradation of heritage buildings due to environmental factors, including case studies of heritage sites and studies proposing preventive conservation strategies, emphasizing interdisciplinary approaches. The review was limited to English-language publications from 2020 to 2024 to maintain the study's focus on recent developments. To ensure academic rigor, 10 publications were excluded due to duplication, non-peer-reviewed articles, and non-English published articles.

Table 2: The selection criterion is searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2020-2024	< 2020
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press

3.3 Eligibility

Initially, 50 articles were selected for review during the eligibility phase (step three). The title and main content of all 120 articles were carefully evaluated to confirm the satisfaction of the inclusion criteria and study objectives. Consequently, a total of 10 articles were conclusively excluded due to several important factors, including their irrelevance to the field of study, insignificantly vague titles, abstracts failing to adjust precisely with the study's objectives, as well as the complete lack of accessible full-text based on empirical evidence. A total of 40 articles were also carefully selected for the final, thorough review, thus creating the important core data set for this systematic review. A rigorously applied selection process guaranteed that only the most relevant data, along with high-quality studies, were precisely identified for the analysis of environmental influences on heritage building degradation.

3.4 Data Abstraction and Analysis

This study used integrative thematic analysis to extract insight of the forty (40) final publication selected through assertions or material relevant extraction, as shown clearly in Figure 2 and Figure 3. The authors and co-authors evaluated key studies on factors contributing to heritage building degradation, examining their methodologies and research findings before carefully developed key themes using the study's evidence. The thematic development involved to identify major and subthemes during and categorizing the key themes related to the study. Adding to that, the main studies systematically have been evaluated though collaboration of author and co-authors to analyze the methodologies and findings ensuring the consistencies. Five (5) analysis conducted involves content analysis to identify and categorizing key environmental factors and emerging patterns in heritage building degradation been identified through trend analysis to achieve research objectives (RO) 1. Before analyse the studies on risk mitigation and preventive conservation efforts the data has been through comparison analysis to evaluate different methodological approaches from different studies to achieve research objectives (RO) 2. Therefore, any inconsistencies or discrepancies in theme development were discussed to achieve the consensus.

3.5 Quality of Appraisal

Following the guidelines proposed by Kitchenham and Charters. (Kitchenham, 2007), after selecting Primary Studies (PSs), assessing the quality of the research they present and comparing them is necessary. As original research articles, PSs provides empirical data on heritage building degradation include case studies, experimental research, and field-based analyses.

Furthermore, to strengthen the clarity, integrity, reliability and validity of the selection process, expert assessment was included into this phase and consistent with theme development. Two experts involved are in heritage building conservation and architecture from higher education institution and one expert were involved with heritage building conservation industry, reviewed the final selection of studies, ensuring the relevancy and integrity of the study ensuring it aligned with the objectives. Discrepancies in theme development again were discussed collaboratively among authors and reviewers, ensuring a cohesive and well-structured thematic analysis. Adjustments were made based on expert feedback before finalizing the key research themes.

The application of Anas Abouzahra's Quality Assessment (QA) framework (Abouzahra et al., 2020), comprising five (5) QA criteria for our SLR. The scoring procedure for each criterion includes three possible ratings: "Yes" (Y) with a score of 1 if the criterion is fully met, "Partly" (P) with a score of 0.5 if the criterion is partially met but has some gaps or shortcomings, and "No" (N) with a score of 0 if the criterion is not met at all.

Table 3: Quality Assessment by the Experts

Quality Assessment	Expert 1	Expert 2	Expert 3	Total Mark
Is the purpose of the study clearly stated?	Y	Y	Y	3
Is the interest and the usefulness of the work presented?	Y	Y	Y	3
Is the study methodology established?	Y	Y	Y	3
Are the concepts of the approach clearly defined?	Y	Y	Y	3
Is the work compared and measured with other similar work?	Y	Y	Y	3

The Table 3 presents a QA process used to evaluate a study based on specific criteria. The experts assess the study using the listed criteria, with each criterion being scored as "Yes" (Y), "Partly" (P), or "No" (N). Here is a detailed explanation:

1. **Is the purpose of the study clearly stated?**
   - This criterion examines whether the study's objectives are clearly defined and well-articulated which is essential for establishing the research's direction and scope.
2. **Is the interest and usefulness of the work presented?**
   - This criterion assesses whether the study's significance and potential contributions are clearly explained. It evaluates the research's relevance and impact.
3. **Is the study methodology established?**
   - This criterion evaluates whether the research methodology is clearly defined and appropriate for achieving the study's objectives. A well-defined methodology is essential for ensuring the study's validity and reproducibility.
4. **Are the concepts of the approach clearly defined?**
   - This criterion examines whether the theoretical framework and key concepts are clearly defined and articulated. Clear definitions are crucial for understanding the study's approach.
5. **Is the work compared and measured with other similar work?**
   - This criterion assesses whether the study has been compared to existing research. Benchmarking against other studies helps position the work within the broader academic context and highlights its contributions.

The study is thoroughly evaluated by each expert individually, using these criteria; subsequently, all expert scores are completely summed for the final rating. All three experts' combined scores must importantly exceed 3.0 for the study to proceed. A specific quality standard selects many studies and only these studies qualify for further analysis.

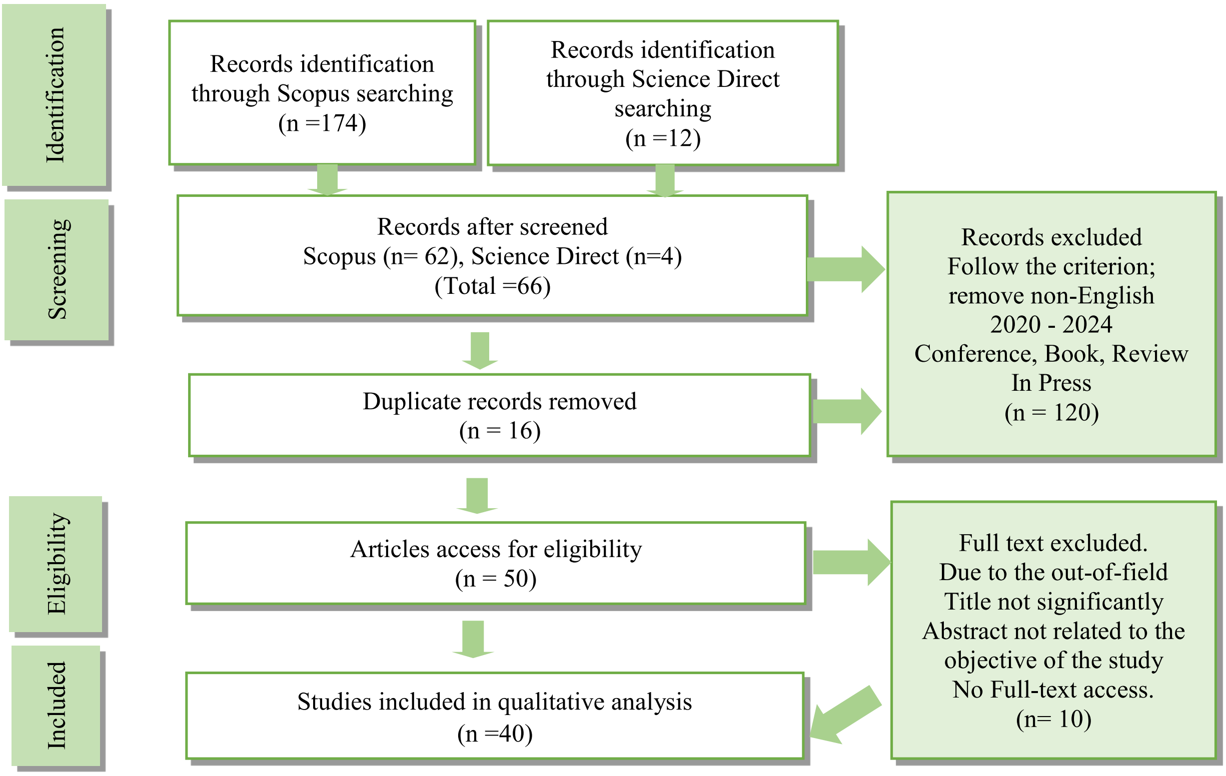

Figure 2: Flow Diagram of the Proposed Search Study

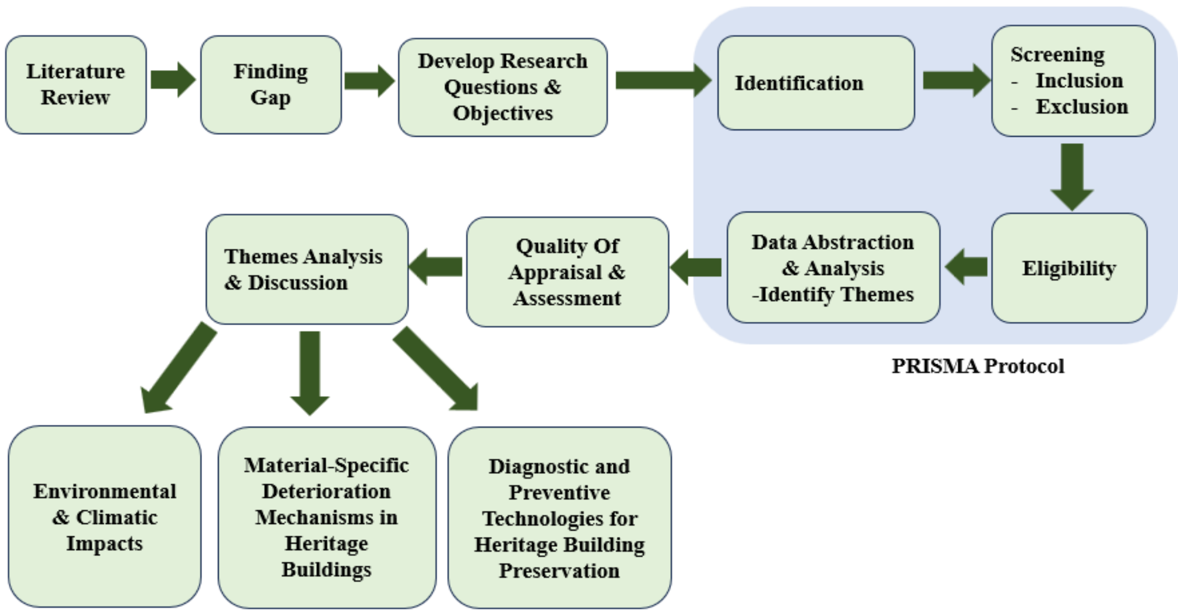

Figure 3: Flow of The Research Methodology

4. RESULTS AND DISCUSSION

Throughout the SLR process, this study refined three key themes to guarantee consistency. The findings discover three (3) key themes consists of environmental influences, material degradation and technical diagnostic methods which will be discussed in this section.

4.1 Background of Selected Study

This section provides important background analysis on 40 selected studies, concentrating on key themes needing a thorough comprehension of environmental, material and technical factors affecting heritage structure durability. It uses diverse diagnostic techniques, material evaluations and preservation strategies, drawing attention to the important cross-disciplinary approaches needed for heritage building challenges of preservation. The table 4 below showed the selection of article based on the themes.

Table 4: Background of selected study

No	Authors	Title	Year	Themes	Summary of key findings
1	(Diz-Mellado et al., 2021)	Non-destructive testing (NDT) and Finite Element Method (FEM) integrated procedure for heritage diagnosis: The Seville Cathedral case study	2021	Diagnostic and Preventive Technologies for Heritage Building Preservation	NDT and FEM identified structural failures causing Seville Cathedral's degradation.
2	(Janssens et al., 2023)	Hygrothermal Risk Assessment Tool for Masonry Walls in a Changing Climate	2024	Environmental and Climatic Impact	Hygrothermal risk tool predicts moisture-related damage in heritage building retrofits
3	(Karimi, Mishra, et al., 2024)	Deep Learning-based Automated Tile Defect Detection System for Portuguese Cultural Heritage Buildings	2024	Diagnostic and Preventive Technologies for Heritage Building Preservation	Deep learning detects tile degradation, achieving 97% accuracy in classification.
4	(Hernández-Montes et al., 2023)	Prediction Model for the Evolution of the Degradation of Bricks in Heritage Buildings in Venice Caused by Climate Change	2023	Environmental and Climatic Impact	New tool estimates masonry degradation rates under variable climate conditions.
5	(F. Carvalho et al., 2023)	Decay Products of Historical Cements from the Palace of Knossos, Crete, Greece	2023	Material-Specific Degradation Mechanisms in Heritage Buildings	Black crusts contain gypsum; salt efflorescence primarily consists of thenardite.
6	(Tokarski et al., 2022a)	The Impact of Biochar Used in Repairs to Historical Buildings on Public Health	2022	Diagnostic and Preventive Technologies for Heritage Building Preservation	Biochar reduces mold growth in historic buildings, improving air quality.
7	(Ma et al., 2024)	Water-related Degradation Risk Assessment for Sustainable Conservation of Heritage Buildings in the Forbidden City, China	2024	Environmental and Climatic Impact	Water-related risks threaten
8	(Cadelano et al., 2023)	Method for Quantitative Assessment of Moisture Content of Porous Building Materials Based on Measurement of Thermal Inertia with Active Infrared Thermography †	2023	Diagnostic and Preventive Technologies for Heritage Building Preservation	Infrared thermography accurately measures masonry moisture using thermal inertia.
9	(İnce, 2021)	Relationship Between Capillary Water Absorption Value, Capillary Water Absorption Speed, and Capillary Rise Height in Pyroclastic Rocks	2021	Material-Specific Degradation Mechanisms in Heritage Buildings	New equation predicts capillary rise in pyroclastic rocks using matrix properties.
10	(Tichy et al., 2023)	Pretty in pink? Complementary Strategies for Analysing Pink Biofilms on Historical Buildings	2023	Diagnostic and Preventive Technologies for Heritage Building Preservation	Salt composition influences microbiomes in heritage buildings with pink biofilms.
11	(Shrestha et al., 2024)	Cultural Heritage Degradation in the Historical Town 'Thimi'	2024	Environmental and Climatic Impact	Heritage threatened by social, economic, and environmental challenges.
12	(Yıldız et al., 2024)	Investigation And Characterization of Black Crusts on Limestone at Historical Buildings in the Cities Of İstanbul And Edirne (Turkey)	2024	Material-Specific Degradation Mechanisms in Heritage Buildings	Black crust on limestone forms via sulfation, accelerating surface degradation.

No	Authors	Title	Year	Themes	Summary of key findings
13	(Coletti et al., 2023a)	Degradation Effects on Bricks Masonry in the Venice Lagoon Cultural Heritage: Study of the Main Façade of the Santa Maria dei Servi Church (14th Century)	2023	Material-Specific Degradation Mechanisms in Heritage Buildings	Salt crystallization and firing inconsistencies accelerate masonry degradation in Venice.
14	(Khalil et al., 2022)	Weathering of Monumental Islamic Marble In Egypt: A Contribution to Heritage Studies	2022	Environmental and Climatic Impact	Severe environmental factors caused marble degradation in historic Cairo buildings.
15	(Comite et al., 2021a)	The Impact of Atmospheric Pollution on Outdoor Cultural Heritage: An Analytic Methodology for the Characterization of the Carbonaceous Fraction in Black Crusts Present on Stone Surfaces	2021	Diagnostic and Preventive Technologies for Heritage Building Preservation	New method quantifies black crust components on polluted historical monuments.
16	(Pawłowicz et al., 2024)	Reverse Engineering as a Non-Invasive Examining Method of the Water Tower Masonry Structure Condition	2024	Diagnostic and Preventive Technologies for Heritage Building Preservation	Laser scanning and reverse engineering accurately assess historic building conditions.
17	(Ullauri et al., 2024)	Incidence of Environmental Factors on Travertine Façade of Heritage Buildings in the Historic Center of Cuenca-Ecuador. A Test Scenario Through Digital Imagen Processing	2024	Environmental and Climatic Impact	False-NDVI effectively assesses environmental degradation of Cuenca's travertine facades.
18	(Menéndez et al., 2022)	Bayesian Assessment of Surface Recession Patterns in Brick Buildings with Critical Factors Identification	2022	Diagnostic and Preventive Technologies for Heritage Building Preservation	Bayesian analysis identifies masonry wall degradation patterns using photogrammetry data.
19	(Doğan, 2023)	Reasons for Degradation of Historical Buildings and the Significance of Memory in the Adaptive Reuse Process of Architectural Heritage: Case Study of Saint Vincent de Paul School in Istanbul	2023	Material-Specific Degradation Mechanisms in Heritage Buildings	Unsupervised and expert-led interventions impact heritage building degradation and adaptation.
20	(Austigard & Mattsson, 2020)	Monitoring Climate Change Related Biodegradation of Protected Historic Buildings	2020	Environmental and Climatic Impact	MBM panels monitor climate impact on biodegradation in heritage buildings.
21	(d'Ambrosio Alfano et al., 2023)	Moisture In Historical Buildings from Causes to the Application of Specific Diagnostic Methodologies	2023	Diagnostic and Preventive Technologies for Heritage Building Preservation	Moisture accelerates heritage building decay; diagnostic methods aid conservation efforts
22	(Vogel et al., 2020)	Moisture Regime of Historical Sandstone Masonry — A Numerical Study	2020	Diagnostic and Preventive Technologies for Heritage Building Preservation	Open drainage system effectively reduces rising damp in historic masonry walls.
23	(Berardengo et al., 2023a)	Short-Training Damage Detection Method for Axially Loaded Beams Subject to Seasonal Thermal Variations	2023	Diagnostic and Preventive Technologies for Heritage Building Preservation	PCA-based damage index improves structural monitoring by filtering environmental effects.
24	(Miran & Husein, 2024)	Evaluating Degradation Causes and Defect Patterns in Heritage Buildings: A Comprehensive Analytical Approach	2024	Diagnostic and Preventive Technologies for Heritage Building Preservation	Moisture damage, interconnected degradation, and material incompatibility through FHM20 Moisture Meter

No	Authors	Title	Year	Themes	Summary of key findings
25	(Li et al., 2021a)	Cross Validation of Hygrothermal Properties of Historical Chinese Blue Bricks with Isothermal Sorption Experiments	2021	Material-Specific Degradation Mechanisms in Heritage Buildings	Historical Chinese blue bricks absorb more moisture, impacting heritage conservation strategies.
26	(Abdullah et al., 2023)	Numerical Simulation and Diagnosis Geotechnical Parameters of Historical Buildings in Najran City, Kingdom of Saudi Arabia	2023	Environmental and Climatic Impact	Clay dissolution, salt crystallization, and climate accelerate Najran heritage degradation risks.
27	(Muradov et al., 2022)	Non-destructive System for In-wall Moisture Assessment of Cultural Heritage Buildings	2022	Diagnostic and Preventive Technologies for Heritage Building Preservation	Microwave spectroscopy improves moisture assessment, surpassing surface-limited traditional methods.
28	(Coskun et al., 2024)	The Effect of Structural Retrofitting and Ventilation Scenarios on The Indoor Microclimate of a Historical Library: The Necip Pasa Library, Turkiye	2024	Diagnostic and Preventive Technologies for Heritage Building Preservation	Mechanical ventilation reduces chemical degradation risk; structural retrofitting has minimal impact.
29	(Daengprathum et al., 2022)	Estimation of Effects of Air Pollution on the Corrosion of Historical Buildings in Bangkok	2022	Environmental and Climatic Impact	Air pollution accelerates corrosion in Bangkok's heritage; preventive measures needed.
30	(Ponce-Antón et al., 2024)	Investigation on 19th Century Fired Bricks and Lime Plaster for The Conservation of Historical Building Materials: A Case Study of the Church of Sant Rafael (Barcelona, Spain)	2024	Material-Specific Degradation Mechanisms in Heritage Buildings	Masonry degradation linked to microporosity, rising damp, and gypsum weathering in church.
31	(Velastegui-Cáceres et al., 2024a)	Implementation of Laser Scanning and HBIM Technology for the Structural Evaluation of Built Heritage in Ecuador	2024	Diagnostic and Preventive Technologies for Heritage Building Preservation	HBIM and FEM identify structural vulnerabilities for heritage seismic risk assessment.
32	(Silva et al., 2022)	Effects of Atmospheric Pollutants on Human Health and Degradation of Medieval Historical Architecture (North Africa, Tunisia)	2022	Environmental and Climatic Impact	Air pollution accelerates medieval heritage decay; harmful particles threaten human health.
33	(A. J. Prieto et al., 2020a)	On the Impacts of Climate Change on the Functional Degradation of Heritage Buildings in South Chile	2020	Environmental and Climatic Impact	Climate change may improve heritage buildings' functionality; AI aids maintenance prioritization.
34	(Zain et al., 2022a)	Physical Elements of Heritage Buildings: Study of the Kadariah Palace in Pontianak City, West Kalimantan	2022	Material-Specific Degradation Mechanisms in Heritage Buildings	Kadariah Palace's belian timber deteriorates from biological and environmental damage factors.
35	(Pérez-Portugal et al., 2023)	Calibration of UAV Flight Parameters to Inspect the Degradation of Heritage Façades Using Orthogonal Arrays	2023	Diagnostic and Preventive Technologies for Heritage Building Preservation	Optimized UAV methodology enhances heritage façade inspections through efficient photogrammetry.
36	(Zhang et al., 2024)	Experimental Study on the Degradation Mechanisms of Physical and Mechanical Properties of Red Sandstone After Thermal-Acid Coupling Treatment	2024	Material-Specific Degradation Mechanisms in Heritage Buildings	Thermo-acid exposure weakens sandstone, increasing porosity, cracks, and structural degradation.
37	(Karimi, Valibeig, et al., 2024)	Degradation Detection in Historical Buildings with Different Materials Based on Novel Deep Learning Methods with Focusing on Isfahan Historical Bridges	2024	Diagnostic and Preventive Technologies for Heritage Building Preservation	Deep learning detects historic bridge defects with 96% accuracy for preservation.

No	Authors	Title	Year	Themes	Summary of key findings
38	(Hernández et al., 2023)	Comparative Study of Degradation in Built Heritage in a Coastal Area: Barbanza Peninsula (Galicia, NW Spain)	2023	Environmental and Climatic Impact	Salt and humidity influence granite decay; coastal areas show better preservation.
39	(Arif et al., 2024)	Biological Degradation of Timber Components of Balla Lompoa Ri Galesong in South Sulawesi, Indonesia	2024	Material-Specific Degradation Mechanisms in Heritage Buildings	Biological degradation damages timber heritage; termites and fungi pose major threats.
40	(Elnahas et al., 2022)	Gas Chromatography-Mass Spectrometry and Scanning Electron Microscopy with Energy-Dispersive Radiograph Analysis of Biodeteriorative Metabolites Produced by Aspergillus Species	2022	Material-Specific Degradation Mechanisms in Heritage Buildings	Fungal species cause masonry degradation through hyphal penetration and acid production.

4.2 Environmental and Climatic Impact

Environmental stressor and climate are significantly influencing heritage buildings vulnerability with a various exposure and degradation level. Although temperature fluctuations, moisture infiltration, and air pollutions are mainly recognized as key factors, their effects on heritage buildings are diversify across regional and climatic zones. This theme examines the environmental stressors on heritage buildings in tropical, coastal, urban, and four-season climates to provide a better understanding of their impacts on heritage buildings globally as shown in Table 5.

Table 5: Environmental Factors and Climatic Condition Impact on Heritage Building Degradation

Climatic Condition	Environmental Factor	Type of Defect	Impact on Building Materials	Relevant Studies
Four-Season Climate	Freeze-thaw cycles	Cracking, spalling, & delamination	Expansion stress damages bricks & stones	A. J. Prieto et al. (2020b), Luo et al. (2023)
	Seasonal wetting-drying cycles	Surface erosion & material weakening	Pore expansion, structural instability	Abdullah et al. (2023), Janssens et al. (2023)
	Thermal stress (summer-winter contrast)	Microcracking & façade detachment	Loss of bonding strength, fragmentation	Hernández et al. (2023), Luo et al. (2023)
Tropical Climate	High humidity & moisture infiltration	Biological colonization (fungi, algae, lichen)	Surface staining, weakening of organic materials	Ma et al.(2024), Shrestha et al.(2024)
	Heavy rainfall	Capillary rising damp	Salt efflorescence, material decay	Abdullah et al. (2023), Zain et al. (2022a)
	Acid rain & pollution	Chemical weathering	Surface erosion, mineral loss	Khalil et al.(2022)
Coastal Climate	Salt-laden air	Salt crystallization & exfoliation	Surface flaking, microcracking	Hernández et al. (2023), Luo et al. (2023)
	High humidity & wind erosion	Mechanical abrasion	Loss of façade materials, uneven wear	Ullauri et al. (2024)
	Tidal water intrusion	Subsurface salt accumulation	Material expansion and spalling	Hernández et al. (2023), Ma et al. (2024)
Urban Climate	Air pollution (SO_2, NO_2, PM10)	Black crust formation & corrosion	Loss of decorative elements, gypsum formation	Daengprathum et al. (2022), Silva et al. (2022)
	Heavy traffic vibration	Structural cracks & joint failure	Destabilization of masonry structures	Ullauri et al. (2024)
	Urban heat island effect	Thermal expansion & shrinkage	Microcracking, weakening of mortar joints	Khalil et al.(2022)

4.2.1 Four-Season Climates

Heritage building in four-season climates regions facing the challenge on freeze-thaw cycles and temperature fluctuations experience which prone to mechanical damage, crack and spalling. Study in South Chile (A. J. Prieto et al., 2020a) found the increase of temperature and decrease condensation and rainfall in their climate, possibly reducing the risk of water-related degradation factor. In contrast, (Hernández-Montes et al., 2023) flag up that the masonry degradation exacerbated by the freeze-thaw cycles especially in humid climate. The same finding in Northen Europe and North America (Janssens et al., 2024) affirms the cause of material shrinkage and expansion by temperature fluctuation led to cracks, spalling and delamination. While, in Najran City (Abdullah et al., 2023), seasonal wetting-drying cycle increased the erosion and instability of the heritage building structural integrity.

4.2.2 Tropical Climates

Meanwhile, Heritage buildings in tropical climates face degradation due to high humidity, perpetual rainfall, and biodegradation, caused the moistures exacerbates capillary rising damp and salt crystallization that driving to structural weakening, surface flaking, efflorescence, and microcracking in masonry buildings accelerating material decay. In Thailand, airborne pollutants and acid rain further deteriorate stone and marble materials (Daengprathum et al., 2022), while thermal expansion from high temperatures worsens long-term degradation.

Whilst, timber structures are highly vulnerable to biological colonization by fungi, termites, and timber-boring insects, as discovered in South Sulawesi (Arif et al., 2024) and West Kalimantan, Indonesia (Zain et al., 2022a) causes internal damage, while fungi contribute to surface discoloration and material weakening. In addition, air pollution in Bangkok accelerates corrosion of copper and Portland limestone, forming gypsum crusts and salt deposits due to rising SO_2, NO_2, and PM10 levels (Daengprathum et al., 2022).

4.2.3 Coastal Area Climate

Exposure of heritage building to coastal environment makes it vulnerable towards wind erosion, high humidity and salt crystallization. (Del Cisne et al., n.d.; Hernández et al., 2023; Luo et al., 2023). Some of the building adjacent to coastal area such as Barbanza Peninsula, Spain (Hernández et al., 2023), Venice, Italy (Luo et al., 2023) and Cuanca, Ecuador (Del Cisne et al., n.d.) experience that higher rates of decay due to salt weathering that polluted the airborne penetrate, induces the crust formation, exfoliate, crack and impacting the structural integrity.

4.2.4 Urban Area Climate

In compare with urban environment, heritage building urban settings facing higher risk on the air pollution, traffic emissions, and anthropogenic stressors. The existence of particles of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter (PM10) in building in Bangkok (Daengprathum et al., 2022), Tunisia (Silva et al., 2022), Egypt (Khalil et al., 2022) and (Del Cisne et al.,2024) aggravated the corrosion of copper, and heavy metals led to black crust formation, mineral loss and acceleration of limestone and marble degradation. The higher rates of decay on exposed area comparing to protected areas find the air pollution adjacent to traffic polluted the environment (Del Cisne et al., n.d.)

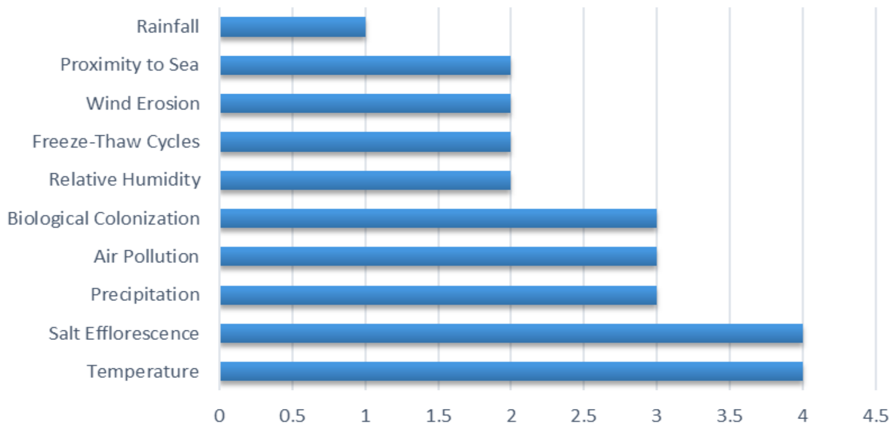

Figure 4: Discovery of Heritage Building Degradation by Environmental Factors

As per discussion above, temperature, salt efflorescence, pollution and moisture are the most important environmental factors affecting heritage buildings across climatic zone, as Figure 4 depicts. This section aligns with Research Objective 1 (RO1) on the exploration of environmental driving factors on heritage building degradation which compliment with the climatic variability (Hossain & Paul, 2019), water dynamics (Ma et al., 2024), air pollution (Esteban-Cantillo et al., 2024), and location-specific stressors (Kale et al., 2023) accelerate heritage building degradation. Warmer, wetter climates drive rapid biodegradation (Austigard & Mattsson, 2020), while freeze-thaw cycles (Sahyoun et al., 2024) and humidity fluctuations (Califano et al., 2022) worsen erosion, especially in porous structures (Esteban-Cantillo et al., 2024). This study highlights the need for region-specific conservation, including humidity control, protective coatings, pollution mitigation, and climate-adaptive materials for sustainable heritage preservation (Mohamed El Abd, 2023).

4.3 Material-Specific Degradation Mechanisms in Heritage Buildings

As the topic above show the impact of environment and climatic on the building and material conditions. This section provides deeper understanding of RO1 on how different materials reacts towards various environmental stressor.

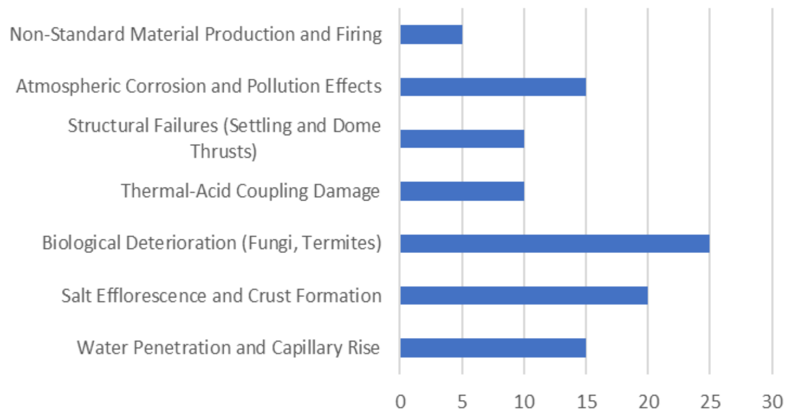

Figure 5: Frequency of Articles Studies on Materials

From the selected papers frequency of material studies that impact the heritage building degradation has been highlighted in Figure 5 showed biological degradation as the leading cause of heritage building deterioration, followed by salt efflorescence, water penetration, and atmospheric corrosion. Environmental pollutants and moisture-related mechanisms drive secondary product formation, accelerating material decay. Airborne pollutants, particularly gypsum and carbonaceous matter, contribute to black crust formation, as observed in historical cement at the Palace of Knossos (A. Carvalho & Camacho, 2023) lead to surface weathering and material loss.

4.3.1 Stone and Brick Deterioration Under Environmental Stressors

While these environmental stressors continuing impact materials across region, vulnerable stone and masonry exhibit various of moisture absorption rate that has been found in Chinese blue bricks (Li et al., 2021b) susceptible to freeze-thaw cycles and structural weakening and drying-wetting cycles and acidic exposure in red sandstone degradation (Zhang et al., 2024) dissolve essential mineral such feldspar and calcite, leading to material softening and structural instability. While masonry identified tidal exchange, capillary rise, and condensation-evaporation cycles (Coletti et al., 2023b) and the exposure to atmospheric pollutants, sulfur dioxide (SO_2), and nitrogen oxides (NO_x) (A. Carvalho & Camacho, 2023) compounds react with humidity accelerating chemical weathering and structural degradation leading to formation of black crusts, salt efflorescence, exfoliation, and crumbling led to structural weakening.

The pore structures increase water absorption and rise the capillary as the studies in pyroclastic rocks in Cappadocia, Turkey (İnce, 2021) and fired masonry and lime plaster from the Church of Sant Rafael in Barcelona (Ponce-Antón et al., 2024b) discovered that rocks with high porosity showed higher matrix content absorb more moisture making them prone to rising damp, gypsum formation, and salt crystallization. It demonstrates the significance of water penetration via capillary action in pyroclastic rocks, noting a strong correlation between pore characteristics and the rate of capillary rise, which accelerates material degradation.

4.3.2 Biological Deterioration of Timber Heritage Structures

As compared to stone and masonry, timber heritage building are more vulnerable towards structural weakening due to termite infestations (Elnahas et al., 2022) that hollowing the pillars, ceiling, floors and roof structures as found in the studies in Balla Lompoa Ri Galesong in South Sulawesi, Indonesia (Arif et al., 2024) and Kadariah Palace in Pontianak, West Kalimantan (Zain et al., 2022b) . The biodegradation agents such as subterranean termites (Microcerotermes serrula), drytimber termites (Cryptotermes), and powder-post beetles (Arif et al., 2024) and fungal biodegradation (Pinheiro et al., 2019) in Egyptian heritage buildings (Elnahas et al., 2022) accelerate the material decomposition penetrate the timber pores leading to material disintegration and degradation as Aspergillus species produce organic acids and hydrocarbons capability of weakening internal structures.

Table 6: Environmental Factors and Climatic Condition Impact on Heritage Building Degradation

Material Type	Degradation Mechanism	Specific Degradation Process	References
Stone & Masonry	Freeze-thaw cycles	Water infiltrates pores, freezes, expands, and fractures the structure	(Li et al., 2021b)
	Drying-wetting cycles & acid exposure	Acid dissolves feldspar and calcite minerals, weakening bonds	(Zhang et al., 2024)
	Salt crystallization	Evaporation deposits salts within pores, exerting pressure	(Coletti et al., 2023b)
	Black crust formation	Sulfur and nitrogen oxides react with stone, forming gypsum layers	(A. Carvalho & Camacho, 2023)
Timber Structures	Termite infestation	Termites burrow through wood, consuming cellulose and weakening structural integrity	(Arif et al., 2024; Elnahas et al., 2022)
	Fungal biodegradation	Fungal hyphae penetrate wood pores, producing enzymes that break down lignin and cellulose	(Elnahas et al., 2022; Pinheiro et al., 2019)
	Organic acid corrosion (Aspergillus fungi)	Fungal metabolic byproducts dissolve minerals and degrade organic materials	(Elnahas et al., 2022)
Decorative Timber Elements	High moisture absorption & fungal colonization	Waterlogged wood becomes a substrate for fungi, causing decay	(Zain et al., 2022b)

This refined table 6 provides a detailed breakdown of how each material types degrades, linking, specific decay mechanisms and effects. The vulnerable of roof, staircase, and decorative timber structures exhibited advanced degradation due tropical and humid climates necessitates preventive conservation strategies, including environmental monitoring, moisture control, and biological treatment methods to mitigate biodegradation risks.

4.4 Diagnostic and Preventive Technologies for Heritage Building Preservation

Heritage building diagnostic is important in determining targeted conservation strategies toward specific degradation factors. Therefore, aligned with RO2, this topic focuses on preservation that should be relies on advanced diagnostic such as Non-Destructive Thermography (NDT) to assess degradation and preventive technologies such as material innovation to guide the conservation efforts.

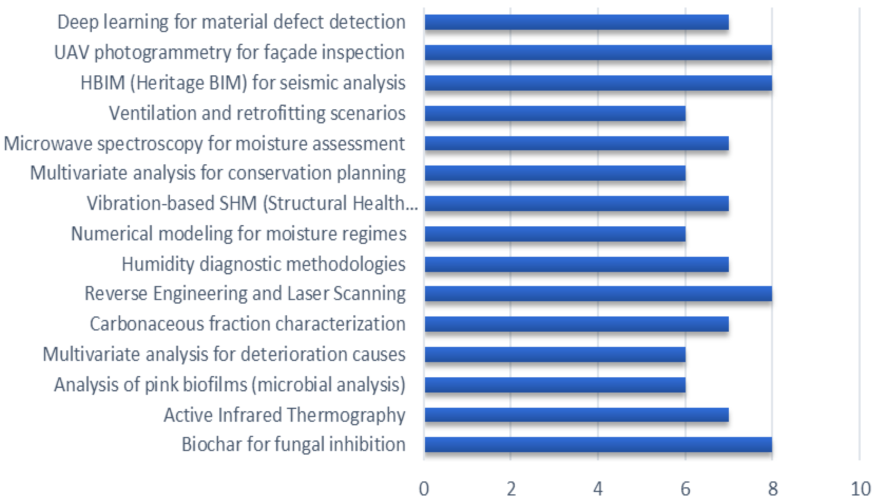

Figure 6: Frequency of studies on Heritage Building Diagnostic and Preventive Technologies

Figure 6 presents the frequency of studies on advanced diagnostic and preservation methods for heritage buildings, revealing equal distribution across technologies such as HBIM, UAV photogrammetry, and infrared thermography. Well-known as a critical factor in the degradation of heritage buildings, moisture necessitates innovative diagnostic and preventive measures (Diz-Mellado et al., 2021).

4.4.1 Moisture Assessment and Environmental Monitoring

In detecting in-wall moisture assessment, studies introduced a microwave spectroscopy-based system showing higher accuracy than traditional pin-type meters in detecting deep-seated water infiltration (Muradov et al., 2022) and active infrared thermographic procedure that quantifies water content in porous materials using thermal inertia calculations (Cadelano et al., 2023; d'Ambrosio Alfano et al., 2023)(Miran & Husein, 2024b) to help detecting surfaces with water evaporation resulting in temperature reduction. The existence of moisture level has been shown in their case study the Royal Palace of Naples (d'Ambrosio Alfano et al., 2023) and laboratories study exceeding 30% in some of wall sections. While, study by (Miran & Husein, 2024b) in Erbil City, Iraq identified the sources of it from roof water leakage and rising damp.

4.4.2 Non-Destructive Testing and Structural Modeling

These known as non-destructive testing (NDT) suggestedly to be integrate with Finite Element Method (FEM) simulations in assessing the weakness of heritage building structural system. The instruments such as Infrared Thermography (IRT), Ground Penetrating Radar (GPR), and Digital Image Processing (DIP) (Diz-Mellado et al., 2021) and laser scanning and Historic Building Information Modelling (HBIM) (Pawłowicz et al., 2024; Velastegui-Cáceres et al., 2024b) found in identifying foundation settlement and dome thrust forces in the assessment of the Tabernacle Chapel of Seville Cathedral with the FEM simulations found the high-stress points (Diz-Mellado et al., 2021), underscoring the necessity of foundation reinforcement and structural bracing. While, Balbanera Church in Ecuador using Finite Element Analysis (FEA) in diagnosing mechanical degradation in heritage buildings(Velastegui-Cáceres et al., 2024b) besides the prediction of surface degradation through a Bayesian probabilistic modelling (Menéndez et al., 2022).

4.4.3 Deep Learning-Based Deterioration Detection

Recently, in AI technologies, studies found the beneficial models that provide automated and real-time detection of material degradation Deep Learning-Based Degradation Detection. The accuracy of 96.58% through in detecting degradation Inception-ResNet-v2 (Karimi, Valibeig, et al., 2024) and 72% using YOLO(Karimi, Mishra, et al., 2024) deep learning models enhance the possible role of AI in heritage building assessment and monitoring while minimizing human error.

Despite the advancement diagnostic technologies, heritage building also been monitoring through a revolutions of remote sensing such as UAV Photogrammetry(Pérez-Portugal et al., 2023), and Reverse Engineering (Pawłowicz et al., 2024). This non-invasive geospatial analysis optimized and improving large-scale monitoring and map structural deformations effectiveness.

4.4.4 Structural Retrofitting and Climate Control

Several prevention technologies found in the studies that can be categorized as structural retrofitting and climate control also Atmospheric Pollution and Biofilm Control. Since retrofitting alone insufficient in enhancing structural stability due to chemical degradation risk reduction only up to 1% , Coskun et al., 2024) as found in the Necip Pasa Library in Türkiye examination, suggest the integration of retrofitting with other climate control system such as mechanical ventilation facilitating with real-time monitoring through Principal Component Analysis (PCA)-based damage detection method to differentiate seasonal temperature-induced changes from actual structural degradation for better prevention (Berardengo et al., 2023b). While, atmospheric pollution and biofilm can be control through anti-pollution coatings (Comite et al., 2021b), desalination treatments and microbial inhibition techniques(Tichy et al., 2023) or application of biochar-infused mortars (Tokarski et al., 2022b) and their ability to reduce microbial contamination by 70-100%, while also regulating indoor humidity focusing on eco-friendly conservation material.

In overall, the integration of diagnostic and prevention technologies is ideal in facilitating heritage building monitoring and preservation efficacy.

5. CONCLUSION

This study systematically reviewed and addressed the objectives to identify the driving of environmental on heritage building degradation and to evaluate advances diagnostic and monitoring tools for better preservation strategies. The findings support that climate condition, moisture infiltration, pollution, and biological colonization as a major factor to degradation across various climatic zones of tropical, coastal, urban, and four-season climates. Provides by the data-driven solution of long-term preservation studies, the integration of Moisture Assessment and Environmental Monitoring, Non-Destructive Testing and Structural Modeling and Deep Learning-Based Degradation Detection through AI modelling, UAV Photogrammetry, and Reverse Engineering enhances heritage building assessment. Attributed from that, the advancement of technologies also picks up on the prevention technologies through Structural Retrofitting and Climate Control and Atmospheric Pollution and Biofilm Control initiates the proactive preservation efforts mitigating degradation risks. The potential of future research should focus on integrating AI-based diagnostics, enhancing real-time environmental monitoring with eco materials for adaptive preservation for degradation prevention. This study bridging the scientific approach with technical practices, lays the foundation for betterment of heritage building resilient, prolonging the integrity amid the environmental challenges.

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