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Smart Heritage Management and Economic Sustainability Through AI and IoT: A Digital Strategy for Lawang Sewu in Indonesia

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ABSTRACT

Tropical heritage buildings are increasingly exposed to complex environmental threats such as high humidity, air pollution, and temperature volatility, all of which accelerate material degradation and undermine their cultural and economic value. Traditional conservation methods—often reactive and periodic—have proven inadequate in addressing these compounded risks. This study aims to develop a smart, economically sustainable framework for heritage management by integrating Artificial Intelligence (AI) and the Internet of Things (IoT) technologies. Using Lawang Sewu, a historic colonial-era building in Semarang, Indonesia, as a case study, the research employs a mixed-method approach combining a systematic literature review, bibliometric analysis, and thematic synthesis to assess technological trends, risk categories, and implementation gaps in tropical contexts. A seven-phase adaptive model is proposed, incorporating real-time environmental monitoring, predictive analytics, Heritage Building Information Modeling (H-BIM), and Digital Twin technologies to support proactive decision-making, optimize maintenance cycles, and reduce long-term conservation costs. The results reveal that AI-IoT convergence not only enhances environmental responsiveness but also protects tourism-based revenue streams and aligns with Sustainable Development Goals (SDGs), particularly SDG 11 and SDG 8. The proposed strategy positions heritage preservation as a digitally enabled economic investment, transforming static monuments into dynamic, climate-resilient assets. This research contributes a replicable model for policymakers, urban planners, and conservation professionals seeking to bridge cultural heritage management with digital innovation and sustainable economic development in tropical urban regions.

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1. INTRODUCTION

Tropical heritage buildings such as Lawang Sewu in Semarang, Indonesia, embody historical narratives and contribute significantly to urban identity and tourism-driven economies(Karnowahadi et al., 2021; Nurul, 2019). However, these structures face escalating risks from environmental stressors—notably air pollution, humidity, and temperature volatility—which accelerate decay and reduce their economic utility (Of, 2022;Murzyn-Kupisz, 2012). Traditional preservation methods, often reactive and resource-intensive, are insufficient in meeting the multidimensional risks posed by climate change and urbanization (ICCROM, 2025). This context underscores the need for a digitally enabled and economically sustainable framework that reframes heritage conservation as both a cultural and economic imperative (Maietti, 2023).

As suggested by Oliveira et al., materials of cultural heritage, such as limestone and brick, are particularly susceptible to chemical reactions caused by airborne pollutants, leading to corrosion, discoloration, and loss of structural integrity (Oliveira et al., 2021). The impacts of climate change, particularly variations in microclimate conditions, have further exacerbated these risks.

Several scholars like Broomandi et al. have noted that the presence of delicate particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs), and gases like SO_2 and NO_2 directly contribute to the deterioration of façade materials and are also a threat to the aesthetic as well as the functional integrity of historical buildings (Broomandi et al., 2022). These environmental threats are exacerbated in the tropical urban setting, where industrial development and emissions from motor vehicles continue to be poorly regulated. In Lawang Sewu, the high fenestrations and passive ventilation system of the building make it particularly susceptible to exterior air quality, thermal loads, and humidity fluctuations(Oliveira et al., 2021); (Mohd Dzulkifli et al., 2016).

Traditional preservation approaches to cultural heritage are typically based on physical examination, condition surveys, and repair upon damage. Waroonkun and Laohaviraphap indeed view these approaches as primarily reactive and only minimally able to forecast and deter environmental risk factors, resulting in inestimable losses(Fatorić & Seekamp, 2017); (Elfadaly et al., 2018). The increased complexity of degradation factors necessitates a shift in paradigm from recurring and manual systems to technology-enabled, data-driven systems that enable real-time decision-making(Fatorić & Seekamp, 2017); (Bertolin, 2019).

The application of Artificial Intelligence (AI) and the Internet of Things (IoT) has offered hopeful means for the conservation of heritage(Addabbo et al., 2019); (Mitro et al., 2022). Researchers such as Mishra and Lourenço, (2024) have presented the application of AI in automating crack detection, surface degradation, and water intrusion using deep learning and image processing techniques. Concurrently, researchers such as Marzouk and Atef, (2022)have applied IoT sensor networks to monitor indoor environmental parameters—temperature, CO_2 levels, and relative humidity—to facilitate dynamic environmental control of historic buildings. The intersection of these technologies enables predictive maintenance and warning systems, reducing the need for physical intervention and enhancing long-term sustainability(Mishra & Lourenço, 2024)

While these technologies have shown promise in other regions, their application in Southeast Asia remains limited due to contextual and infrastructural constraints. Despite notable progress in Europe and East Asia, AI- and IoT-based systems have not yet been widely employed in Southeast Asia. As pointed out by Hu and Assaad, (2024); (Franco et al., 2024) the norm is that most frameworks are created in temperate climates and less often adapted to suit tropical climatic conditions. Preservation of colonial heritage such as Lawang Sewu in Indonesia(Gbran & Sari, 2023), for example, usually faces constraints in terms of funding, technical capacity, and current environmental information(Croce et al., 2023a); (Bruno et al., 2023). Moreover, there is a lack of contextualized research that combines innovative conservation technologies with the unique climatic, material, and cultural characteristics of tropical urban heritage(Croce et al., 2023a); .

The current research fills this void by designing an integrated AI-IoT framework for the environmental and structural conservation of Lawang Sewu in Semarang, the rapidly emerging tropical city(Siccardi & Villa, 2022); (Karatzas et al., 2024). Three main goals guide the current research:

Investigate the evolving dynamics and identifiable patterns characterizing the integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in the field of cultural heritage conservation, with a focused lens on environmental monitoring and risk reduction strategies (Marzouk & Atef, 2022).

Identify the key determinants and methodological frameworks that underpin the application of AI and IoT in improving air quality control, monitoring structural integrity, and reinforcing the overall efficiency of heritage conservation efforts (Siccardi & Villa, 2022).

Develop a forward-looking conservation model that leverages cutting-edge digital innovations to enable adaptive, anticipatory responses to the shifting environmental conditions impacting heritage environments (Paschalidou et al., 2022).

Integrating digital platforms like H-BIM into heritage conservation practices, and Digital Twins (DT)(Hu & Assaad, 2024), this research proposes an adaptive and scalable model for tropical heritage conservation in a sustainable manner. The research highlights the potential of AI-IoT convergence not just for enhancing structural robustness but also for enabling inclusive, context-sensitive preservation policies for the fragile cultural heritage in Southeast Asia (Ali et al., 2021); (Alahi et al., 2023); (Nawaz & Babar, 2024); (Laohaviraphap & Waroonkun, 2024a).

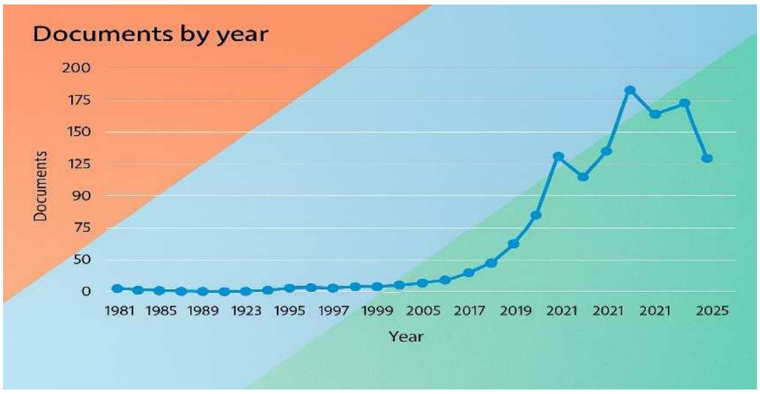


Figure 1. Annual Distribution of Publications in Scopus Using the Keywords “Heritage” and “Risk Assessment.

Literature Review

Environmental Vulnerability of Tropical Heritage Buildings

Tropical heritage structures, particularly those located in Southeast Asia, face acute environmental challenges stemming from high humidity, fluctuating temperatures, and rising urban air pollution. These factors have been identified as key drivers of accelerated material decay, leading to aesthetic, structural, and cultural degradation(Poston, 2025& Poston, 2025). Limestone, brick, and timber—commonly used in colonial-era constructions—are particularly vulnerable to airborne pollutants such as SO_2, NO_2, and PM2.5, which react chemically with building surfaces and compromise structural integrity (Poston, 2025). Studies have also emphasized the compounding effect of biological growth and seasonal thermal cycles on façade deterioration, especially in high-humidity contexts (Poston, 2025 & Akyol and Avcı, 2023).

Despite these well-documented risks, preservation in tropical regions remains dominated by traditional, reactive conservation methods. These include periodic inspection, manual repairs, and limited environmental diagnostics, which are insufficient for addressing the complex and dynamic degradation factors prevalent in urban tropical climates (Poston, 2025). This has created a growing consensus around the need for predictive, real-time conservation frameworks that move beyond post-damage intervention (Poston, 2025; DataCalculus, 2024).

Emergence of Smart Technologies in Heritage Conservation

Recent advancements in Artificial Intelligence (AI) and the Internet of Things (IoT) have catalyzed a shift toward intelligent heritage management systems. AI applications in the field include image-based crack detection, surface anomaly recognition, and environmental pattern prediction using convolutional neural networks and deep learning architectures(Hamishebahar et al., 2022; Tabernik, D., Šela, S., Skvarč, J., 2024; Vina, 2024). Simultaneously, IoT-based monitoring systems—comprising sensor networks for temperature, humidity, CO_2, and particulate matter—have demonstrated success in facilitating dynamic environmental control and preventive maintenance (Yordanov, 2025).

Although these technologies have shown considerable promise in temperate regions such as Europe and East Asia, their application in Southeast Asia remains limited. Most smart conservation frameworks have been developed and validated in regions with robust technological infrastructure, ample funding, and stable climates (Buenafe et al., 202 ; SMART, 2025 ; Ocón, 2022). This geographic bias has created a disparity in digital heritage preservation capacity, leaving tropical regions underrepresented in both academic literature and practical implementation (Team, 2022).

Gaps in Contextualized Research and Policy Integration

Bibliometric analyses of Scopus-indexed publications between 2015 and 2025 reveal a stark underrepresentation of Southeast Asian countries in climate-responsive heritage research. Countries like Italy, Spain, and Romania dominate scholarly output, while Indonesia and other tropical nations remain on the periphery of global conservation discourse (Team, 2022 ; Ocón, 2020). The lack of localized studies that integrate AI-IoT technologies with the specific climatic, cultural, and economic conditions of the tropics has left a critical gap in the development of scalable, context-sensitive frameworks (Laohaviraphap and Waroonkun, 2024 ; Merciu, Petrişor and Merciu, 2021).

Moreover, existing literature rarely addresses the economic dimensions of heritage conservation. While the technical benefits of smart monitoring systems are widely acknowledged, few studies explore their role in enhancing long-term cost efficiency, reducing emergency maintenance spending, or sustaining cultural-tourism revenue streams—especially in resource-constrained cities (Merciu, Petrişor and Merciu, 2021; Grigore, 2017; Murzyn-Kupisz, 2012).

Contribution of This Study

To address these deficiencies, this study introduces an integrated framework that combines AI and IoT with Heritage Building Information Modeling (H-BIM) and Digital Twin (DT) technologies for the proactive conservation of tropical heritage assets. The framework is designed to operate under conditions of limited infrastructure and funding, aligning with Sustainable Development Goals (SDGs) related to sustainable cities (SDG 11) and economic resilience (SDG 8). By focusing on Lawang Sewu in Semarang, Indonesia, the research provides an empirically grounded, transferable model that bridges the technical, climatic, and economic dimensions of smart heritage management.

If your research article is quantitative and should have hypotheses development, you have to present in this section. The hypotheses development should clarify the works of previous studies before stating your hypotheses statements. State clearly the hypotheses statements and take you position either positive or negative if you examine the relationship among variables.

2. METHOD

To achieve the study's objectives, we adopted a Systematic Literature Review (SLR) methodology, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. A specific review process was established, incorporating rigorous inclusion and exclusion criteria, as well as a careful selection of search terms, to provide a comprehensive and impartial assessment of international practices in the preservation of tropical heritage buildings(Page et al., 2021). The PRISMA methodology provided a rational, concrete, and methodical way through which it was feasible to conduct an overall evaluation of technological interventions in cultural heritage conservation, especially those leveraging AI and IoT-driven systems (Addabbo et al., 2019).

Search Strategy and Database Selection

The first step of the review was conducted through searches in three established scholarly databases, namely Scopus, ScienceDirect, and Web of Science (WoS). However, upon cross-checking at the screening stage, all applicable records obtained from WoS and ScienceDirect were identified as being indexed in Scopus as well.

Consequently, Scopus was selected as the primary search platform. This was done to eliminate redundancy and maintain a high-quality, focused scope of work. Scopus has over 39,000 titles and is ideal for interdisciplinary research that includes environmental science, engineering, architecture, and cultural heritage—fields of the utmost relevance to this research. In addition, Scopus provides advanced functionalities in citation tracking, author network mapping, and institution-level research output, all of which facilitate the identification of top trends and top contributors to the field (Arachchige et al., 2021); (Zhu & Liu, 2020).

Due to its extensive coverage, precision in citation linking, and support for cross-disciplinary thematic content, Scopus was deemed the most appropriate source from which to draw a systematic review of AI-IoT-based solutions for safeguarding tropical heritage assets.

Eligibility Criteria and Study Selection Process

To keep the review on its research path—i.e., the protection of tropical heritage through digital solutions—a pre-stated set of eligibility criteria was utilized (see Table 1). The filtering was done on scholarly articles in the departments of Architecture, Engineering, Environmental Science, and Social Sciences. The articles were included only if they talked about "heritage buildings" with one other concept, such as "tropical climate," humidity," "air quality," "AI," or "IoT." Boolean logical operators were used to specify such pairs as "heritage building" AND "tropical climate" or "IoT" AND "predictive maintenance."

Only English-language journal articles from 2015–2025 were included to ensure that the data was consistent and current and peer-reviewed evidence was available. Non-English publications were excluded to eliminate the issue of translation ambiguity that might influence interpretation or analysis.

Table 1. Eligibility Criteria for SLR

Type of Criterion	Inclusion	Elimination
Research Field	Architecture, Environmental Science, Engineering, Social Sciences	Articles outside the scope of these fields
Source Database	Indexed in Scopus	Sources not included in Scopus
Topical Focus	Topics including tropical heritage, humidity, temperature, air pollution, AI, IoT	Topics lacking relevance to heritage or smart technology
Publication Date	2015–2025	Publications outside this time window
Article Type	Peer-reviewed academic articles	Grey literature, reports, proceedings, or editorials
Language	English	Non-English texts

The search strategy targeted the TITLE, ABSTRACT, and KEYWORDS fields to ensure the retrieval of thematically relevant literatur, ensuring that search terms were found in the title, abstract, or keywords. This literature review addresses priority subjects, including tropical climate risks, microclimate regulation, the use of AI in diagnostic applications for heritage, and IoT-based monitoring infrastructures.

The selected decade (2015–2025) encompasses recent developments in digital innovation for heritage preservation, driven mainly by climate-focused policy benchmarks such as the SDGs and the Paris Agreement. This time frame ensures that the review is current and pertinent to modern academic and policy issues (United Nations, 2024).

Subsequently, the search results were refined using Scopus' built-in filtering tools (LIMIT-TO function), narrowing the scope to peer-reviewed journal articles ('ar'), English-language publications, and subject areas including Engineering ('ENGI'), Environmental Science ('ENVI'), and Social Sciences ('SOCI').

After this search process, 583 documents were obtained from Scopus in the first instance, as follows:

- 316 articles retrieved using the query “heritage building” AND “tropical climate”
- 82 articles retrieved using “heritage building” AND “humidity”
- 118 articles retrieved using “heritage building” AND “temperature”
- 52 articles retrieved using “heritage building” AND “Artificial Intelligence (AI)”
- 23 articles retrieved using “heritage building” AND “Internet of Things (IoT)”

504 articles remained after removing 79 duplicates through EndNote version 21 (Bramer et al., 2016). During this step, 287 papers were removed because they were not relevant enough (e.g., seismic or fire safety but not climatic or environmental hazard studies). The remaining 217 articles were considered for review in full text. Of these, 125 were ruled out due to a lack of interaction with tropical heritage topics or insufficient technological depth in AI/IoT integration. A total of 91 articles were retained for closer examination.

Table 2. Thematic Search Strategies and Document Retrieval Summary

Thematic Area	Number of Retrieved Articles (N)	Search Strategy and Database Parameters (Scopus)
Risk Evaluation in Heritage Sites	316	Relevant publications were identified by applying a query targeting the presence of terms related to “heritage,” “buildings,” “risk,” and “assessment” within titles, abstracts, or

		keywords. The time span was limited to 2015–2025, and filters were applied to include only English-language, peer-reviewed articles from Engineering, Environmental Science, and Social Science fields.
Effects of Urban Atmospheric Pollutants	82	A refined search was conducted focusing on documents containing keywords associated with heritage structures and urban air pollution. The same time range and subject-area restrictions were used to capture interdisciplinary studies on air quality's impact on built heritage.
Climate-Related Fragility of Heritage Structures	118	Research addressing climate-driven risks to heritage buildings—especially in tropical and subtropical climates—was retrieved using a thematic query involving terms for heritage, buildings, climate, and risk, applied to titles, abstracts, and keyword fields.
Smart Heritage Applications Using AI Tools	52	Studies exploring artificial intelligence in the context of heritage conservation were extracted using a search phrase combining terms such as “heritage,” “buildings,” and “artificial intelligence,” targeting research on diagnostic models, automated monitoring, and preservation technologies.
Real-Time Monitoring with IoT Systems	23	The search targeted academic literature that intersects heritage structures with Internet of Things (IoT) technologies, using a combination of keywords related to real-time data acquisition, sensor networks, and digital monitoring systems, filtered by language, time period, and relevant academic domains.
Total Number of Relevant Records	591	—

Analytical Strategy and Synthesis Process

The analysis phase followed a mixed-methods framework, incorporating both Bibliometrix software and qualitative thematic synthesis. Wei and Jiang,(2023)was employed for its ability to process large-scale bibliographic data and generate useful visual outputs such as thematic maps, author networks, and country-level publication distributions (Aria & Cuccurullo, 2017).

These visual analyses enabled the identification of major research clusters, regional focuses, and key figures shaping the field of tropical heritage conservation through AI and IoT. Descriptive metrics such as publication frequency and geographical trends were analyzed to contextualize the academic landscape.

This was complemented by a qualitative synthesis approach, grounded in Braun and Clarke’s (2006) thematic coding methodology. The selected articles were analyzed to extract insights into:
The evolution of AI techniques in heritage diagnostics,

- The application of IoT for real-time environmental sensing,
- Integrated strategies for predictive and adaptive conservation.

Particular attention was given to case studies from the Global South and tropical regions, including urban environments such as Semarang, Indonesia, where Lawang Sewu serves as a salient example of a tropical heritage asset facing environmental stressors.

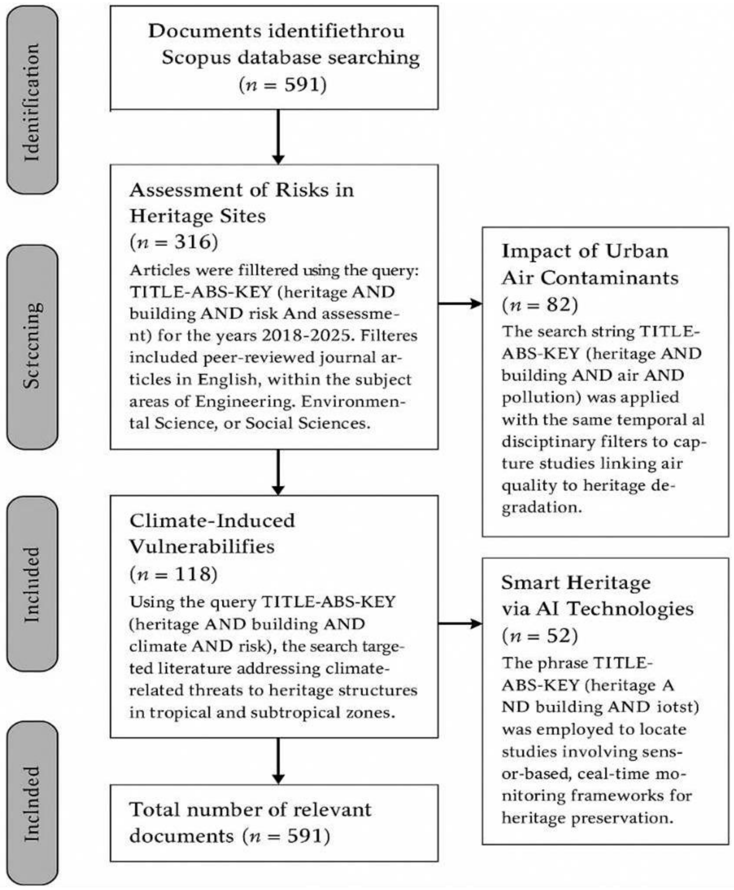


Figure 2. PRISMA 2020 Flow Diagram outlines the multi-step filtering process used to refine the dataset from 583 initial articles to the final 91 included studies.

In addition to environmental diagnostics, the methodology also accounts for economic dimensions of heritage conservation by reviewing literature that measures cost-benefit impacts of AI-IoT interventions, particularly in terms of reducing emergency maintenance costs, sustaining tourism income, and enabling efficient infrastructure investment. This dual focus on technology and economic performance ensures that the resulting model serves both cultural and financial sustainability objectives.

Through this combined bibliometric and interpretive methodology, the review achieved a multidimensional understanding of how intelligent technologies are advancing climate-responsive heritage preservation in tropical settings. The results inform the development of a context-specific digital conservation framework suitable for sites such as Lawang Sewu.

3. RESULTS AND DISCUSSION

Results

3.1. Analysis Using Bibliometrix

3.1.1. Keyword Network Mapping of the Identified Research Gaps (Hollesen, 2022); (Bucur et al., 2015); (Abu-allaban & El-khalili, 2014); (Mohd Dzulkifli et al., 2016); (Bienvenido-Huertas et al., 2021); (Addabbo et al., 2019); (Bruno et al., 2023); (Abdul Hamid et al., 2020); (Živković & Džikić, 2015). The co-occurrence visualization of keywords (Figure 3), created with Bibliometrix, illustrates the interconnectivity between prevailing themes in the 91 selected research papers particularly in the area of wise conservation of tropical heritage buildings. Mapping the themes identifies clusters focused on environmental stressors, material degradation, and technological interventions. While dominant clusters do have topics such as climate exposure, humidity, air quality, and structural deterioration of heritage property, the network also uncovers glaring gaps—most notably the lack of convergence between cutting-edge technologies such as AI and IoT on the one hand and environmental risk factors on the other hand, in tropical architectural conservation.

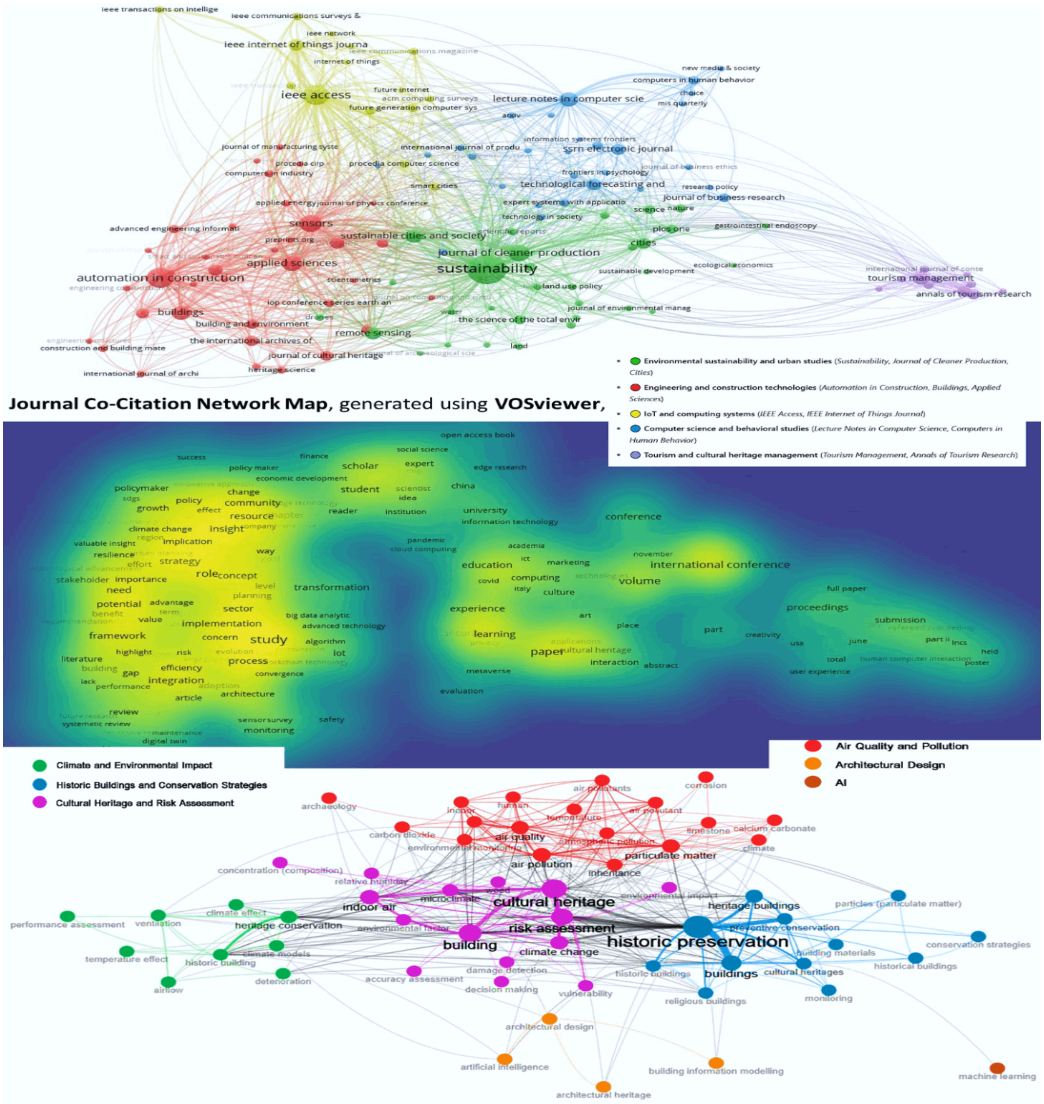


Figure 3. Keyword Co-occurrence Network Map from Bibliometrix, Journal Co-Citation Network Map, generated using VOSviewer,

Through structural density and thematic disjunctions within core concepts, the network suggests the need for additional research, immediately connecting technological intelligence with environmental diagnostics in heritage contexts. These findings suggest a potential for interdisciplinary approaches to close the gap between conservation science and on-site environmental investigation.

Thematic clusters are:

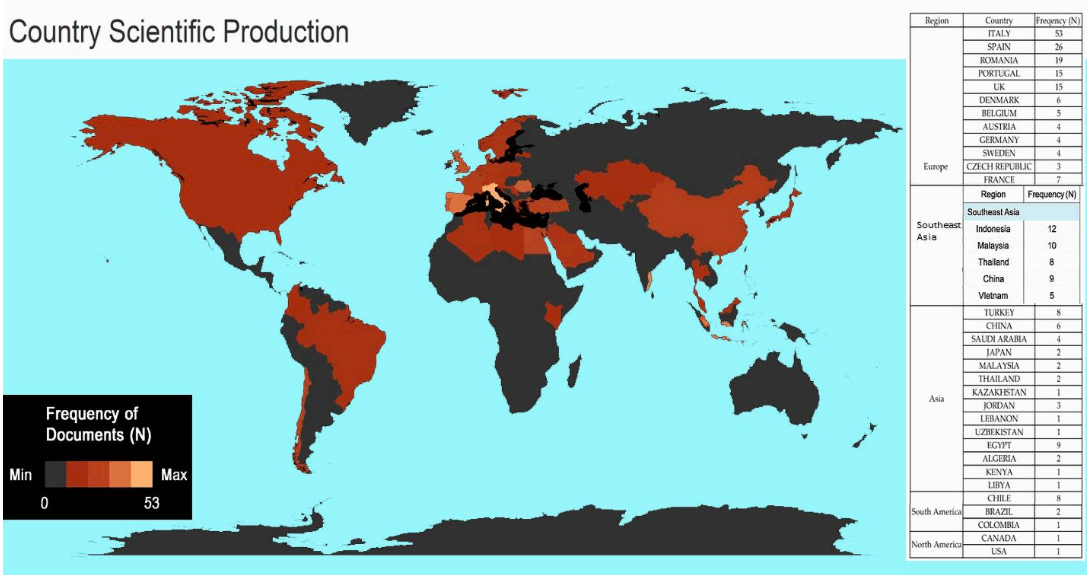
1. Tropical Climate Impacts and Microclimatic Behavior (Green cluster): The group focuses on keywords like “humidity,” “high temperature,” “transport of moisture,” and “passive cooling.” These are indicative of issues related to the direct impact of the tropical climate on building envelopes and heritage materials.
2. Cultural Heritage Risk Management (Purple cluster): The descriptors “heritage structures,” “environmental stress,” “degradation,” and “response of the material” represent risk severity evaluation and serve as a warning to prevent irreversibility.
3. \\tUrban Contaminants and Air Pollution (Red cluster): With a concentration of pollutants like PM2.5, SO2, and VOCs, this cluster addresses the role of urban atmospheric chemistry in the speeding up of degradation of sensitive architectural surfaces.
4. Preventive Conservation and Structural Monitoring (Blue cluster): Concepts such as “predictive maintenance,” “biomaterial sensitivity,” and “control of dampness” emerge here, highlighting the growing interest in active heritage conservation through continuous monitoring.
5. Digital Technologies and Computational Modeling (Orange and Brown clusters): Phrases such as “AI-based diagnostics,” “intelligent sensors,” “H-BIM,” and “digital twin” indicate the integration of digital methods into heritage observation and management.

While interest in environmental impact and digital technology is growing, a wide gap persists between environmental indicators (green/red clusters) and real-time sensing or AI-based reaction systems (orange/brown clusters). The relatively poor coverage of the network by IoT demonstrates the under-exploitation of this essential technology, which can otherwise be utilized to enhance in-situ monitoring and predictive intervention steps.

This deficiency is indicative of a chronic inadequacy in tropical heritage preservation, wherein accelerating and unnoticed environmental destruction occurs. Addressing such a deficiency through the convergence of AI-IoT platforms with materials science and policy for conservation is critical to the construction of adaptive, sustainable heritage protection.

3.1.2. Geographic Trends in Research Output

Figure 4 illustrates the global distribution of heritage technology research, revealing that countries such as Italy (52 publications), Spain (26), and Romania (19) dominate scholarly output. In contrast, regions like Southeast Asia—including Indonesia—appear significantly underrepresented in the dataset. This highlights a critical research gap, reinforcing the importance of the current study, which focuses precisely on addressing this deficit through an in-depth case study of Lawang Sewu in Semarang, Indonesia.



Region	Country	Freqency (N)
Europe	ITALY	53
	SPAIN	26
	ROMANIA	19
	PORTUGAL	15
	UK	15
	DENMARK	6
	BELGIUM	5
	AUSTRIA	4
	GERMANY	4
	SWEDEN	4
	CZECH REPUBLIC	3
	FRANCE	7
Southeast Asia	Region	Frequency (N)
	Southeast Asia	
	Indonesia	12
	Malaysia	10
	Thailand	8
	China	9
	Vietnam	5
Asia	TURKEY	8
	CHINA	6
	SAUDI ARABIA	4
	JAPAN	2
	MALAYSIA	2
	THAILAND	2
	KAZAKHSTAN	1
	JORDAN	3
	LEBANON	1
	UZBEKISTAN	1
	EGYPT	9
	ALGERIA	2
	KENYA	1
	LIBYA	1
South America	CHILE	8
	BRAZIL	2
	COLOMBIA	1
North America	CANADA	1
	USA	1

Figure 4. Global Distribution of Research Publications from Bibliometrix(Worldbank.org & Logo, 2022)

This gap in the scholarly literature is especially critical when considering heritage sites vulnerable to climate-related stressors. In many tropical nations—often situated within economically under-resourced regions—pressing priorities such as infrastructure expansion, public health, and poverty reduction tend to dominate national agendas. As a result, investment in research and digital preservation initiatives for cultural heritage is frequently deprioritized

The World Bank's income classification reveals a positive correlation between a country's income level and research productivity. The majority of countries in the Global South, such as Indonesia, are underrepresented in climate-heritage research due to inadequate technical infrastructure and limited access to funding channels. This hinders the adoption of AI-IoT innovations that require high initial investments and long-term maintenance capacity(Worldbank.org & Logo, 2022).

To create parity and global resilience in the preservation of heritage, strategic investment in enhancing institutional capacity and technology preparedness is necessary in underdeveloped regions. Regional collaboration, exchange of research, and technology transfer policies are necessary to bridge the knowledge production gap and implement innovative conservation models in the Global South.

The economic implications of these disparities are profound. Countries underrepresented in digital conservation research often lack access to cost-saving technologies that could reduce reliance on manual restoration. By focusing on Indonesia, this study not only fills an academic gap but also proposes economically viable strategies for nations seeking to preserve cultural assets within limited budgets.

3.2 Dimensions of Environmental Hazards Affecting Heritage Architecture

A comparative review of 91 studies was conducted to assess the impact of environmental risk factors on heritage buildings, specifically air pollution, thermal stress, and humidity. Thirty-eight papers were shortlisted for detailed analysis based on precise observation of environmental parameters and documentation of decay phenomena (see Table 3).

Early publications (2014–2016) primarily focused on traditional parameters, including CO2, NO2, SO2, temperature, and relative humidity. New additions (2020–2024) reflect a broader range, including parameters such as particulate matter (PM2.5, PM10), volatile organic compounds (VOCs), acetic and formic acids, air change rates (ACH), and biological growth (e.g., fungi, microflora). Such a trend indicates a shift towards holistic diagnostics, recognizing both chemical and biological agents of degradation.

This evolving set of parameters reflects a growing awareness that heritage preservation necessitates multidisciplinary monitoring systems capable of measuring both short-term climatic fluctuations and long-term pollutant accumulation. The growth in variables considered necessary for risk modeling indicates greater concern with not only structural strength but also the safety of visitors and compatibility of conservation materials.

These results will inform the design of an adaptive monitoring system architecture for the Lawang Sewu case study, with special consideration for Semarang's humid climate, pollutant mix, and seasonal variation in air exchange.

3.2.1. Key Parameters in Environmental Monitoring of Tropical Heritage Sites

A synthesis of 38 peer-reviewed studies provides insight into the diverse environmental indicators monitored in tropical heritage buildings, with a particular focus on indoor and outdoor environmental risks relevant to sites such as Lawang Sewu. Table 3 outlines the parameters tracked between 2015 and 2025, demonstrating the evolving complexity of heritage diagnostics.

Table 3. Rearticulated Overview of Principal Environmental Parameters Examined in Heritage Building Research

Year	Environmental Elements Assessed	Indoor	Outdoor	Reference
2014	Air humidity, ambient temperature, wind velocity, carbon monoxide, sulfur dioxide, nitric oxide, nitrogen dioxide, ozone	–	✓	(Abu-allaban & El-khalili, 2014)
2014	Carbon dioxide concentration, air humidity, temperature	✓	✓	(Varas-Muriel et al., 2014)
2015	Temperature, humidity, NO_2, SO_2, CO_2, O_3, fine particulates (PM2.5), and microbial activity	✓	✓	(Bucur et al., 2015)
2015	Temperature, relative humidity, total rainfall, wind characteristics, solar and thermal radiation, cloud formation, soil temperature, albedo, atmospheric pressure	✓	✓	(Leissner et al., 2015)
2015	Temperature and air moisture content	✓	✓	(Shillito et al., 2022)
2015	Temperature, humidity, and thermal infrared emission	✓	✓	(Silva & Henriques, 2021)
2016	Humidity, thermal conditions, CO, CO_2, and light exposure	✓	–	(Scatigno et al., 2016)
2016	Relative humidity and indoor temperature	✓	–	(Silva & Henriques, 2016)
2017	Airborne pollutants (SO_2, HNO_3, O_3, PM10) and weather variables (e.g., temperature, rainfall, relative humidity)	–	✓	(De Marco et al., 2017)
2017	CO_2 levels, thermal conditions, air movement, and solar radiation	–	✓	(Mouffok et al., 2017)
2018	Ambient temperature, humidity, barometric pressure, ozone, nitrogen oxides, sulfur dioxide	–	✓	(Gibeaux et al., 2018)
2018	Internal temperature and air moisture	✓	✓	(Rajčić et al., 2018)
2019	Humidity and thermal readings	✓	✓	(Aste et al., 2019)
2019	Air humidity and temperature (indoors only)	✓	–	(Coelho et al., 2019)

2020	Temperature, relative humidity, CO_2 levels, ventilation rate	–	✓	(Abdul Hamid et al., 2020)
2020	Thermal data, humidity, PM10 and PM2.5	✓	–	(Martinelli et al., 2025)
2020	Volatile Organic Compounds (VOCs)	✓	✓	(Sánchez et al., 2020)
2021	Humidity and temperature data	✓	–	(Bienvenido-Huertas et al., 2021)
2021	Temperature and humidity monitoring	✓	✓	(Marcelli et al., 2021)
2022	Indoor/outdoor air temperature, globe/surface temperature, humidity, airflow velocity	✓	✓	(Costa-Carrapiço et al., 2022)
2022	Major air pollutants: SO_2, NO_2, O_3, and PM10	–	✓	(Daengprathum et al., 2022)
2022	Temperature and humidity levels	✓	✓	(Florescu et al., 2022)
2022	Moisture and temperature variables	✓	✓	(Mitro et al., 2022)
2023	Thermal readings, humidity, CO_2, PM10, PM2.5	✓	✓	(Alizzio et al., 2023)
2023	Particulate matter (PM10, PM2.5)	✓	✓	(Saraiva et al., 2023)
2024	Temperature, humidity, nitrogen dioxide, sulfur dioxide, ozone, CO_2, acetic and formic acid presence	✓	✓	(Elnaggar et al., 2024)
2024	Temperature and relative moisture	✓	✓	(Metals et al., 2024)

✓ = available; – = unavailable

3.2.2. Environmental Threats to Tropical Heritage Assets

Environmental deterioration of heritage structures in tropical climates is driven by three interlinked domains:

1. Climatic Dynamics: Variables such as heat, humidity, rainfall, wind, and solar radiation affect the physical behavior of materials. Frequent expansion and contraction cycles accelerate wear and lead to structural vulnerabilities.
2. Airborne Pollutants: Pollutants including SO_2, NO_2, O_3, PM2.5, and VOCs interact chemically with building materials, particularly stone and wood, causing corrosion and discoloration. For instance, SO_2 can react with calcium carbonate, a key component of many heritage facades, producing sulfate salts that flake off under humid conditions.
3. Biological and Anthropogenic Stressors: Biological growth (e.g., fungi, algae) flourishes in high-humidity environments, while human-induced pressures like tourism and traffic emissions add physical and chemical stress to sensitive surfaces.

Despite the availability of smart technologies, many studies reveal limited deployment of IoT-based environmental sensing and AI-driven diagnostics in tropical heritage conservation. Integrating these tools is essential to enable real-time monitoring, predictive modeling, and data-informed maintenance strategies.

3.3. Technological Approaches to Risk Management in Tropical Heritage Buildings

To address the challenges outlined above, researchers have developed varied frameworks using emerging technologies for climate and material monitoring, structural assessment, and resilience enhancement. Table 4 categorizes these efforts by risk type, data origin, methodologies, and applied digital tools.

Table 4. Synthesis of Methodological and Technological Approaches to Risk Management in Heritage Buildings

Source	**Risk Type**	**Source of Data**	**Theoretical Framework**	**Applied Methodology**	**Utilized Technology**
(Addabbo et al., 2019) (CIB W086, 2021)	Structural performance degradation	IoT-based sensor inputs	Smart IoT architecture for heritage oversight	Deployment and calibration of sensing devices	Wireless sensor network (WSN) technologies
(Alizzio et al., 2023) (Bienvenido-Huertas et al., 2021)	Indoor climate and energy inefficiency risks	Sensor readings and energy simulation outputs	Integrated evaluation of energy performance and environmental health	Real-time monitoring combined with dynamic simulation models	IoT devices, Computational Fluid Dynamics (CFD), energy modeling tools
(Bienvenido-Huertas et al., 2020) (Boesgaard et al., 2022)	AI-based environmental control	H-BIM environments and monitored climate datasets	AI-driven decision-making models in heritage building oversight	Application of decision tree models and time-series machine learning	J48 algorithm, H-BIM, GDL scripting, XGBoost, climate sensors
(Carpio et al., 2021)	Material deterioration and structural detection	Visual archives from historic assets	Deep learning architecture for automated decay mapping	Image-based detection and segmentation with neural networks	Mask R-CNN, Computer Vision frameworks
(Haznedar et al., 2023) (Laohavirapha p & Waroonkun, 2024a)	Moisture-related risks and structural decay	3D scans, photogrammetry, point cloud models	Hybrid AI-HBIM for digital preservation	Semantic segmentation, classification, and automated modeling	YOLOv8, PointNet, ML clustering, 3D point cloud tools
(Lerario & Varasano, 2020) (Li, 2024)	Environmental threats and disaster vulnerability	Historical records and sensor-based platforms	Disaster risk reduction (DRR) integrated with conservation strategy	Preventive analysis, SHM systems, geospatial mapping	IoT, SHM, GIS, satellite imaging, early-warning systems
(Luo & Wang, 2024)	Urban heritage transformatio	3D laser scans, façade imagery	AI and DL-enabled	Style generation, deep	CGAN, Mask R-CNN, FCN, DL toolkits

	n and cracking pathology		restoration planning	segmentation, anomaly detection	
(Martinelli et al., 2025)	Air quality deterioration and environmental instability	Indoor air sensors and long-term environmental logs	IoT-assisted preservation and H-BIM integration	Multivariable tracking and resilience modeling	NB-IoT, H-BIM, RFID, Node-RED, cloud IoT databases
(Mohamed El Abd, 2023)	Radiation exposure and seasonal microclimate fluctuation	Edge device readings, radon, humidity, pressure sensors	AI-aided environmental prediction system	Fourier analysis and predictive thermal profiling	LoRa, FFT, Rn-sensors, DHT11, MPL3115A2 modules
(Mohamed El Abd, 2023) (Mohamed El Abd, 2023)	Style degradation and resilience in heritage reuse	Photographic scans and laser point cloud data	Digital Twin modeling and BIM-driven AI workflows	Damage segmentation, architectural anomaly prediction	UAV photogrammetry, SfM, CNNs, TLS systems

These studies demonstrate the potential of combining point cloud processing, IoT environmental data, and AI segmentation for comprehensive risk mapping. Of particular relevance for Lawang Sewu, is the integration of H-BIM with sensor-based environmental monitoring and predictive analytics tailored to humid tropical conditions.

These frameworks support future policy and conservation strategies aimed at extending the functional life of heritage structures through intelligent, sustainable monitoring.

3.3.1. Risk Categories

The outlined studies encompass a wide spectrum of risk types confronting tropical heritage buildings. These include challenges such as structural deterioration, climate-induced micro-environmental shifts, and predictive maintenance via AI-powered analytics. The technologies employed are selected based on the specific nature of the risks:

- Structural Stability Threats: Structural health is monitored using real-time data from IoT sensors that detect parameters like vibration and load shifts. AI algorithms, combined with Heritage Building Information Modeling (H-BIM), facilitate forecasting long-term degradation. Photogrammetry adds value by documenting visible damage to surfaces.
- Microclimatic and Environmental Hazards: Temperature, humidity, and pollutant levels are continuously monitored through IoT systems, while Computational Fluid Dynamics (CFD) simulations replicate airflow patterns. AI models offer predictive insight into evolving environmental conditions.
- Energy Performance Vulnerabilities: Energy consumption is tracked via IoT nodes, while simulation-based models evaluate efficiency. AI forecasts energy demand and guides sustainable retrofitting measures.
- Surface Decay and Material Degradation: High-resolution photogrammetry and DL models like Mask R-CNN detect surface-level deterioration. AI extrapolates trends in material wear, enabling timely maintenance.
- Cultural-Architectural Significance: H-BIM archives design intent, materials, and alterations. AI helps assess how proposed modifications may impact heritage values, guiding culturally sensitive interventions.

3.3.2. Data Acquisition Sources

IoT infrastructure remains the cornerstone of data gathering, providing real-time environmental and structural insights. Additionally, the use of image-based datasets, particularly those derived from drone and laser scanning, reflects the growing integration of computer vision and ML into heritage assessment methodologies.

3.3.3. Operational Frameworks

Risk management strategies in heritage conservation are predominantly shaped by IoT-enabled diagnostic infrastructures and AI-driven decision-support systems. These are primarily designed to handle structural, environmental, and energy-related hazards. Some frameworks also adopt a sustainability lens, integrating heritage preservation within broader environmental goals.

3.3.4. Methodological Tools

The methodologies employed show a clear orientation towards advanced AI paradigms. Techniques such as convolutional neural networks (CNNs), Mask R-CNN, and fuzzy inference logic are used for visual detection and risk forecasting. Simulation-driven models like energy performance simulations and time-series-based AI analyses also feature prominently.

3.3.5. Technological Ecosystem

An array of digital technologies supports the detection, monitoring, and mitigation of heritage conservation risks:

1. Artificial Intelligence (AI): A wide array of AI tools—ranging from machine learning algorithms like J48 and XGBoost to deep learning models including Mask R-CNN and YOLOv4—are used to interpret sensor data and visual inputs. These systems enable predictive insights into structural decay, environmental threats, and energy consumption trends. Image-based diagnostics, such as crack detection, leverage CNNs, ResNet, and custom DL models implemented in Python. These tools enhance the precision and adaptability of conservation analytics (Bruno et al., 2023); (Croce et al., 2023a).
2. Internet of Things (IoT): IoT systems provide the real-time backbone of environmental and structural diagnostics. Technologies include NB-IoT smart sensors (e.g., Sensirion SHTC3, Bosch BME280), LoRa edge devices, and Arduino modules, which enable low-energy data transmission. Platforms like Node-RED and FIWARE coordinate this sensor network, linking to SHM systems. These tools facilitate the early identification of anomalies and integrate risk scoring models like Art-Risk 3.5, enabling predictive maintenance (Marcelli et al., 2020); (Martinelli et al., 2025); (Nunes et al., 2023).
3. Heritage Building Information Modeling (H-BIM): H-BIM offers an integrative digital model capturing geometric, material, and historical data of heritage assets. It interfaces seamlessly with IoT, AI, and simulation tools, aided by platforms like MongoDB, Revit plug-ins, and GDL scripting for precise parametric modeling. This facilitates real-time diagnostics, historical tracking, and preservation planning. (Bienvenido-Huertas et al., 2020); (Yiğit & Uysal, 2024); (Ceccarelli et al., 2023).
4. High-Resolution Imaging and 3D Scanning: Photogrammetry and TLS (e.g., Leica BLK360) are used to generate accurate 3D point clouds, essential for monitoring surface degradation. UAV-based photogrammetry, such as with Anafi Parrot drones and SfM algorithms, enhances coverage and resolution. Cyclone Register 360 assists in aligning multi-source scan data. (Vandenabeele et al., 2024); (Wojtkowska et al., 2021).

5. Computational Fluid Dynamics (CFD): CFD techniques are utilized to replicate environmental parameters such as temperature distribution, air movement, and humidity levels. These simulations are essential for analyzing the behavior of heritage interiors when exposed to diverse climatic pressures. The incorporation of fuzzy logic systems—such as Xfuzzy 3.0—enhances predictive modeling capabilities, particularly when projecting future climate scenarios like RCP2.6 and RCP8.5.(Prieto et al., 2020); (Prizeman et al., 2020).
6. Digital Twin (DT): DT models act as dynamic virtual replicas of heritage buildings, fusing real-time IoT data with structural and environmental metadata. They simulate real-world behaviors under stress, offering a proactive lens into conservation planning. DTs are particularly effective when embedded with AI, CFD, H-BIM, and imaging technologies, allowing a seamless feedback loop between physical and digital environments. (Ladiana & Di Sivo, 2019); (Martinelli et al., 2025); (Croce et al., 2023b).

Discussion

1. Economic Relevance of Smart Heritage Management

The integration of AI and IoT into heritage conservation introduces new economic efficiencies. Real-time monitoring reduces unplanned repair costs, extends building life cycles, and preserves revenue generated through heritage tourism. Furthermore, the digitization of heritage assets enables long-term data-driven policy development and prioritization of budget allocation. These benefits are particularly critical in tropical cities like Semarang, where heritage protection often competes with other pressing urban infrastructure needs.

2. Global Developments and Regional Inequities in AI and IoT Integration for Tropical Heritage Conservation

The review underscores a significant surge in scholarly interest in the deployment of IoT-enabled sensing systems for the real-time monitoring and conservation of heritage buildings. These technologies are particularly effective in capturing and analyzing environmental stressors—such as humidity, temperature fluctuations, and air quality—and in evaluating the structural responses of heritage assets under such conditions. The integration of AI-based predictive diagnostics adds interpretive depth to the collected data, enabling more informed and proactive conservation strategies.

Despite these advancements, the geographical distribution of such technological interventions remains uneven. Research and implementation efforts are largely concentrated in digitally advanced European countries, notably Italy, Spain, and Romania, where strong institutional infrastructures and a high density of culturally significant sites—such as the Royal Alcázar of Seville and the Monastery of Jerónimos—provide fertile ground for innovation and experimentation4. (Silva & Henriques, 2021); (Sitzia et al., 2022).

In contrast, culture-rich but climatically vulnerable regions of Southeast Asia, sub-Saharan Africa, and South America remain heavily underrepresented. These imbalances are, in significant part, a function of budgetary limitations, limited access to high-cost research facilities, and competing development priorities. According to the World Bank classification (Sitzia et al., 2022), low- and middle-income countries face structural capacity limitations in investing in digital heritage initiatives.

To bridge this technological gap, specific mechanisms are essential, including international heritage grants, North-Southbalanced collaborative research, localized training initiatives, and open-access digital repositories. This focus on case studies from temperate climates restricts the construction of adaptive frameworks for hot-humid, monsoon-prone, or arid conditions—conditions prevalent in tropical cities like Semarang, Indonesia. Locations like Lawang Sewu demonstrate the need for context-aware equipment that can withstand high humidity, urban air pollution, and fluid microclimates. Technological feasibility—demonstrated through IoT exhibits in Romanian museums (Ilieș et al., 2022) and AI platforms in Suzhou (Quesada-Ganuza et al., 2023)—emphasizes the need for adaptable platforms that can scale and port to resource-constrained settings.

3. Parameters Governing Environmental and Structural Assessment

IoT technologies have proven to be crucial in tracking live environmental and structural data in tropical heritage environments. The discussed articles reveal parameters that are critical to material preservation and structural response to tropical stresses:

- Variability of Temperature and Humidity: A common finding across all studies, these parameters play a crucial role in determining material stress due to thermal expansion and contraction cycles, particularly for wood and stone structures (Marcelli et al., 2020); (Bertolin et al., 2015).
- Airborne Pollutants: SO2, NO2, O3, CO2, PM2.5, PM10, and VOCs trigger corrosive assaults, particularly on limestone, stucco, and wood. These were measured several times (Abdul Hamid et al., 2020); (Daengprathum et al., 2022); (Daengprathum et al., 2022).
- Indoor Microclimate Indicators: Factors such as air exchange rates, light exposure, and microbial agents provide a better understanding of indoor degradation processes (Daengprathum et al., 2022); (Saraiva et al., 2023).

Multi-parameter monitoring, both within and outside the environment, enables advanced diagnosis and planning of responses, particularly in high-risk tropical environments.

4. Synergies of Technologies for Proactive Conservation

4.1. Real-Time Risk Prediction Through AI-IoT Convergence

The integration of IoT sensor networks and AI analysis facilitates an anticipatory risk assessment model. In tropical cultural heritage sites, such as Lawang Sewu, environmental data like humidity and CO2 can be used with ML algorithms to predict pollutant accumulation and thermal stress (Leonel J. R. Nunes , António Curado, n.d.); (Leonel J. R. Nunes , António Curado, n.d.). AI-based alerts allow conservation workers to anticipate damage before it becomes irreversible.

International literature provides examples of the effectiveness of this approach: IoT Hub-based integrated platforms have optimized indoor air ventilation by correlating VOCs with occupancy and environmental conditions (Laohaviraphap & Waroonkun, 2024a).

4.2. Digital Twins for Dynamic Conservation Management

DT systems—a combination of H-BIM, AI analytics, and IoT data—provide living digital replicas of heritage structures. Such systems simulate environmental occurrences (e.g., El Niño, which leads to humidity spikes) and predict material reactions (Yiğit & Uysal, 2024). Projects that integrate DTs into 3D BIM models allow stakeholders to virtually test conservation strategies. For tropical structures, this is vital for simulating moisture absorption in porous material in monsoon environments(Yiğit & Uysal, 2024); (Hu & Assaad, 2024).

4.3. Smart Environmental Management for Indoor Air Quality

The applicationThe application of IoT for tracking indoor surroundings enhances air quality control. Smart sensors tracking PM, temperature, and volatile compounds are combined with artificial intelligence software that regulates climate systems autonomously. These measures not only saved artifacts but also maintained occupant health. Case studies have indicated reductions in humidity variation of over 30% through the use of adaptive technology (Laohaviraphap & Waroonkun, 2024a); (Laohaviraphap & Waroonkun, 2024a).

4.4. Conservation AI Models for Specific Conservation Problems

Advanced AI tools, such as fuzzy logic, models, and GANs, have already found applications in solving complex problems related to the conservation of historic buildings. Fuzzy models aid in forecasting deterioration in conjunction with long-term climate predictions (Laohaviraphap & Waroonkun, 2024a), and inform strategic planning. GANs, on the other hand, help restore historically accurate façade components (Laohaviraphap & Waroonkun, 2024a), facilitating culturally sensitive restoration in rapidly urbanizing areas.

4.5. Standardization of Knowledge and Ecosystems for Collaboration

The effectiveness of digital conservation technologies is enhanced by interdisciplinary synergy. H-BIM-based systems enhance the free exchange of data among architects, conservation scientists, and policymakers. Standardization of acquisition, storage, and interpretation protocols ensures uniformity and improved outcomes across projects and regions (Laohaviraphap & Waroonkun, 2024a); (Laohaviraphap & Waroonkun, 2024a); (Ceccarelli et al., 2023).

5. Future Research Roadmap: A Seven-Phase Adaptive Framework

A plug-and-play conservation bundle is promoted and founded on iterative monitoring and predictive analytics. The master plan integrates AI, IoT, H-BIM, DT, and environmental simulations to create a digitally resilient system for heritage management.

5.1. Phase 1: Situational Analysis and Baseline Evaluation

The process begins with an overall assessment of the site's physical, climatic, and historical attributes. For Lawang Sewu, pre-damage mapping and airflow simulation using CFD can determine ventilation inefficiencies (Laohaviraphap & Waroonkun, 2024a). This informs the selection of context-specific technologies.

5.2. Phase 2: Sensor Deployment and Data Logging

IoT networks are deployed to measure structural dynamics (strain, displacement) and environmental conditions (temperature, RH, PM2.5, VOCs). Installation protocols target sensitive materials and regions where condensation occurs. Data pipelines are constructed using NB-IoT and LoRaWAN protocols due to their reliability in high-density urban environments (Abdul Hamid et al., 2020); (Abdul Hamid et al., 2020); (Abdul Hamid et al., 2020).

5.3. Phase 3: Data Fusion and AI Model Calibration

Sensor feeds are integrated into the H-BIM platform together with archival material records. AI models, including decision trees, CNNs, and time-series predictors, are trained on this data. Pattern and anomaly detection can be performed at temporal and spatial scales (Abdul Hamid et al., 2020); (Abdul Hamid et al., 2020)in this stage.

5.4. Phase 4: Virtualization through Digital Twins

A DT is constructed, integrating real-time inputs with simulated environmental variables. With this dynamic model, material and environmental control systems can be stress tested (Abdul Hamid et al., 2020); (Abdul Hamid et al., 2020). For the tropical climate, it models cyclic extremes of humidity and monsoonal impacts on permeable façades.

5.5. Phase 5: Field and Historical Comparisons Validation

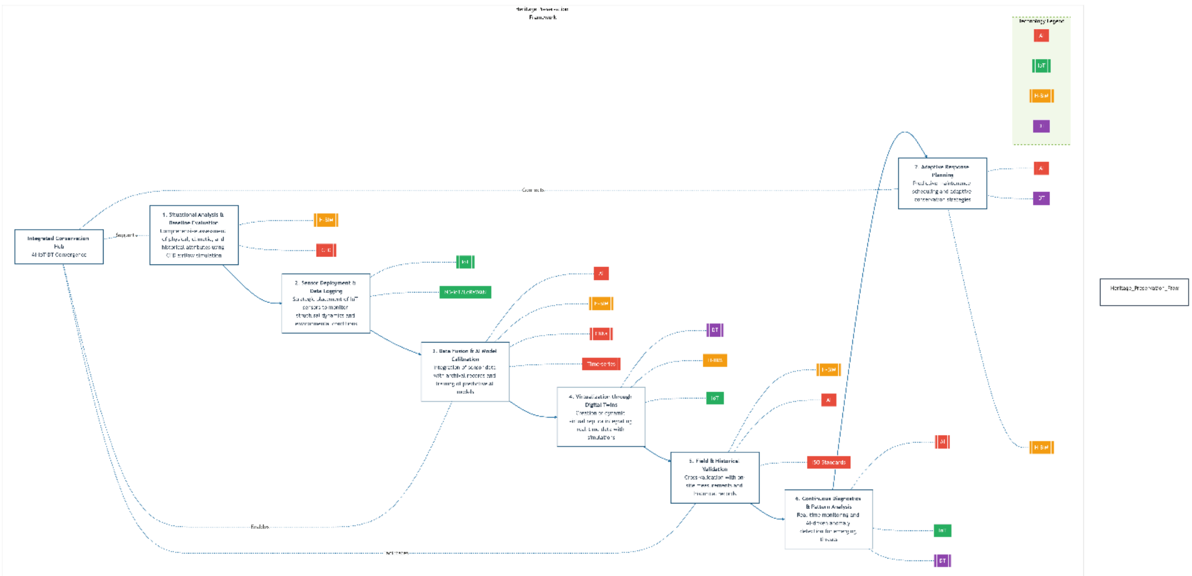
Model results are cross-validated with on-site information, historical damage records, and industry-standard guidelines (e.g., ASHRAE, ISO heritage standards) (Abdul Hamid et al., 2020). This stage ensures that the DT is a reliable predictive tool.

5.6. Phase 6: Continuous Diagnostics and Pattern Analysis

The DT system continuously inputs real-time data into the AI engine for predictive diagnosis. Seasonal variations and daily cycle variations are tracked to detect anomalies characteristic of nascent or growing threats. Monitoring in real-time the changes in pollutants, such as $SO2$ and $NO2$, in Gadara, Jordan would provide information on the deterioration of materials(Abdul Hamid et al., 2020).

5.7. Phase 7: Maintenance Modeling and Adaptive Response Planning

It is included in a preventive maintenance schedule based on the knowledge acquired through continuous monitoring—predictions made by AI guide optimal intervention time and degree. Conservation efforts are monitored and adjusted based on performance data. Indoor air quality was regulated in real-time in Sweden (Abdul Hamid et al., 2020), and ANN-processed point cloud data were utilized to detect deformation in Poland's Nożyk Synagogue (Abdul Hamid et al., 2020).



A-

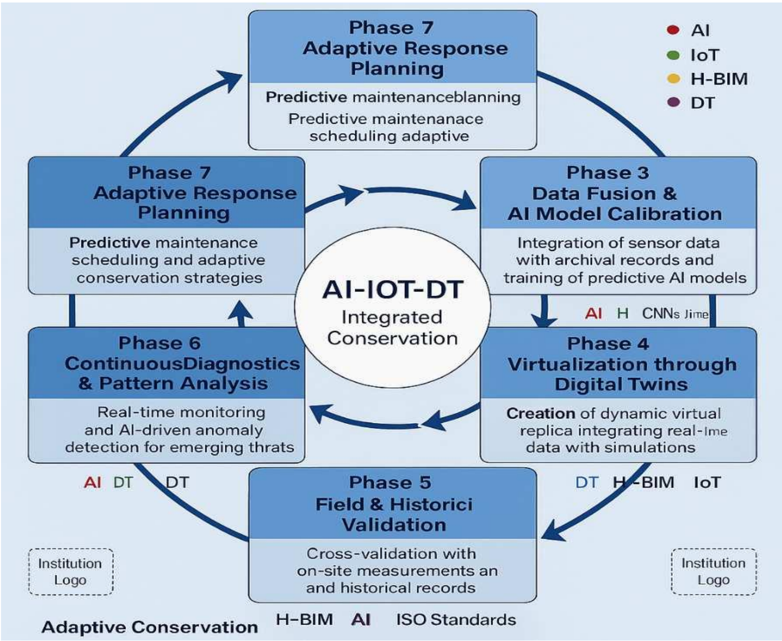
This diagram presents a modular, seven-phase digital framework designed for the proactive conservation of tropical heritage buildings, exemplified by sites such as Lawang Sewu. The framework integrates key technologies—including Artificial Intelligence (AI), the Internet of Things (IoT), Heritage Building Information Modeling (H-BIM), and Digital Twin (DT) systems—within an iterative process anchored by a centralized Integrated Conservation Hub.

Phase-by-Phase Breakdown:

1. **Situational Analysis & Baseline Evaluation**
   - **Goal:** Comprehensive site diagnosis (climate, structure, history)
   - **Tools:** CFD airflow simulation, H-BIM modeling
2. **Sensor Deployment & Data Logging**
   - **Goal:** Real-time monitoring of humidity, pollutants, vibration

- **Tools:** IoT, NB-IoT, LoRaWAN

3. **Data Fusion & AI Model Calibration**
   - **Goal:** Integration of sensor + archival data for AI training
   - **Tools:** H-BIM, CNNs, Time-Series AI
4. **Virtualization through Digital Twins**
   - **Goal:** Create real-time digital replica of the structure
   - **Tools:** DT, AI simulations, environmental input layers
5. **Field & Historical Validation**
   - **Goal:** Cross-validate DT outputs with site visits and ISO/ASHRAE data
   - **Tools:** IoT, H-BIM, ISO standards
6. **Continuous Diagnostics & Pattern Analysis**
   - **Goal:** Monitor anomalies and environmental threats dynamically
   - **Tools:** AI prediction engine, IoT, DT
7. **Adaptive Response Planning**
   - **Goal:** Schedule preventive maintenance, optimize resource use
   - **Tools:** DT platforms, AI planning tools, H-BIM



B-

Figure 5. (A, B) A Seven-Stage Proactive Preservation Framework for Tropical Heritage Buildings in a Holistic Approach. The graphical model depicts a seven-stage process that involves AI, IoT, DT, and H-BIM for real-time risk assessment and cultural continuity.

4. CONCLUSION

This study has demonstrated the potential of integrating Artificial Intelligence (AI), the Internet of Things (IoT), Heritage Building Information Modeling (H-BIM), and Digital Twin (DT) technologies into a unified framework for smart and economically sustainable heritage management. Focusing on Lawang Sewu in Semarang, Indonesia, the research addressed the urgent need for proactive conservation strategies in tropical urban environments where climate volatility, pollution, and infrastructure pressures converge. Through a rigorous combination of systematic literature review, bibliometric mapping, and thematic synthesis, the study identified global trends in digital heritage technologies and highlighted the lack of context-specific frameworks in the Global South.

The proposed seven-phase adaptive framework provides a replicable and modular model for integrating real-time monitoring, AI-driven diagnostics, and digital simulation into localized heritage management systems. Findings reveal that AI algorithms can detect and anticipate deterioration patterns with high precision using limited data inputs, while IoT-based sensors deliver granular, continuous environmental feedback that supports predictive maintenance. H-BIM and Digital Twins offer powerful tools for cross-disciplinary coordination and decision-making, aligning cultural preservation with operational efficiency.

Crucially, this research redefines heritage conservation as a strategic economic investment. Digital approaches not only mitigate long-term restoration costs but also preserve revenue-generating functions such as tourism and community use. The case of Lawang Sewu illustrates how tropical heritage buildings can become drivers of innovation and economic resilience when equipped with intelligent infrastructure and stakeholder engagement. By aligning this framework with Sustainable Development Goals (notably SDG 11 and SDG 8), the study advances a vision of heritage conservation that is forward-looking, inclusive, and grounded in both cultural and financial sustainability.

Future research should focus on field-based validation across diverse heritage types and climate zones, expansion of open-source AI training datasets, and collaborative capacity-building between institutions in the Global South. As digital heritage continues to evolve, investments in equitable access, local adaptability, and policy integration will be vital to ensuring that no region is left behind in the pursuit of smart, sustainable preservation.

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Credit and statement of contribution:

Hassan Gbran: Writing – Original Draft, Conceptualization.

Siti Rukayah: Supervision,

Atik Suprapti: Supervision,

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Disclosure of Use of Artificial Intelligence

The AI-powered Grammarly tool was used to improve the language quality and proofread this manuscript. The tool was used solely to improve style and clarity, under the supervision and review of the authors. The tool was not used to generate any scholarly content, and the authors remain fully responsible for the accuracy and content of the work.

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5. REFERENCES

Abdul Hamid, A., Johansson, D., & Bagge, H. (2020). Ventilation measures for heritage office buildings in temperate climate for improvement of energy performance and IEQ. Energy and Buildings, 211, 109822. https://doi.org/10.1016/j.enbuild.2020.109822

Abu-allaban, M., & El-khalili, M. M. M. (2014). Antiquity Impact of Air Pollution. Mediterranean Archaeology and Archaeometry, 14(1), 191–199.

Addabbo, T., Fort, A., Mugnaini, M., Panzardi, E., Pozzebon, A., & Vignoli, V. (2019). A city-scale IoT architecture for monumental structures monitoring. Measurement, 131, 349–357. https://doi.org/10.1016/j.measurement.2018.08.058

Akyol, G., & Avcı, A. B. (2023). AI applications in cultural heritage preservation: technologcal advancements for the conservation. Baskent International Conference on Multidisciplinary Studies, August, 94–101. https://doi.org/10.6084/m9.figshare.24077862

Alahi, E. E., Sukkuea, A., Tina, F. W., Nag, A., Kurdthongmee, W., Suwannarat, K., & Mukhopadhyay, S. C. (2023). Integration of IoT-Enabled Technologies and Artificial Advancements and Future Trends. *Sensors (Switzerland)*, *23*(5206).

Ali, H., Phoumin, H., Weller, S. R., & Suryadi, B. (2021). Cost–benefit analysis of hele and subcritical coal-fired electricity generation technologies in southeast asia. *Sustainability (Switzerland)*, *13*(3), 1–16. https://doi.org/10.3390/su13031591

Alizzio, D., De Capua, C., Fulco, G., Lugarà, M., Palco, V., & Ruffa, F. (2023). IOT enviromental quality monitoring in smart buildings in presence of measurement uncertainty: a decision making approach. *Acta IMEKO*, *12*(2), 1–8. https://doi.org/10.21014/actaimeko.v12i2.1421

Arachchige, G. R. P., Thorstensen, E. B., Coe, M., McKenzie, E. J., O'Sullivan, J. M., & Pook, C. J. (2021). LC-MS/MS quantification of fat soluble vitamers – A systematic review. *Analytical Biochemistry*, *613*, 113980. https://doi.org/10.1016/j.ab.2020.113980

Aria, M., & Cuccurullo, C. (2017). bibliometrix : An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Aste, N., Adhikari, R. S., Buzzetti, M., Della Torre, S., Del Pero, C., Huerto C, H. E., & Leonforte, F. (2019). Microclimatic monitoring of the Duomo (Milan Cathedral): Risks-based analysis for the conservation of its cultural heritage. *Building and Environment*, *148*, 240–257. https://doi.org/10.1016/j.buildenv.2018.11.015

Bertolin, C. (2019). Preservation of Cultural Heritage and Resources Threatened by Climate Change. *Geosciences*, *9*(6), 250. https://doi.org/10.3390/geosciences9060250

Bertolin, C., Camuffo, D., & Bighignoli, I. (2015). Past reconstruction and future forecast of domains of indoor relative humidity fluctuations calculated according to EN 15757:2010. *Energy and Buildings*, *102*, 197–206. https://doi.org/10.1016/j.enbuild.2015.05.028

Bienvenido-Huertas, D., León-Muñoz, M., Martín-del-Río, J. J., & Rubio-Bellido, C. (2021). Analysis of climate change impact on the preservation of heritage elements in historic buildings with a deficient indoor microclimate in warm regions. *Building and Environment*, *200*, 107959. https://doi.org/10.1016/j.buildenv.2021.107959

Bienvenido-Huertas, D., Nieto-Julián, J. E., Moyano, J. J., Macías-Bernal, J. M., & Castro, J. (2020). Implementing Artificial Intelligence in H-BIM Using the J48 Algorithm to Manage Historic Buildings. *International Journal of Architectural Heritage*, *14*(8), 1148–1160. https://doi.org/10.1080/15583058.2019.1589602

Boesgaard, C., Hansen, B. V., Kejser, U. B., Mollerup, S. H., Ryhl-Svendsen, M., & Torp-Smith, N. (2022). Prediction of the indoor climate in cultural heritage buildings through machine learning: first results from two field tests. *Heritage Science*, *10*(1), 176. https://doi.org/10.1186/s40494-022-00805-3

Bramer, W. M., Giustini, D., De Jonge, G. B., Holland, L., & Bekhuis, T. (2016). De-duplication of database search results for systematic reviews in EndNote. *Journal of the Medical Library Association*, *104*(3). https://doi.org/10.5195/jmla.2016.24

Broomandi, P., Jahanbakhshi, A., Fathian, A., Darynova, Z., Janatian, N., Nikfal, A., Kim, J. R., & Karaca, F. (2022). Impacts of ambient air pollution on UNESCO world cultural heritage sites in Eastern Asia: Dose-response calculations for material corrosions. *Urban Climate*, *46*, 101275. https://doi.org/10.1016/j.uclim.2022.101275

Bruno, S., Galantucci, R. A., & Musicco, A. (2023). Decay detection in historic buildings through image-based deep learning. *VITRUVIO - International Journal of Architectural Technology and Sustainability*, *8*, 6–17. https://doi.org/10.4995/vitruvio-ijats.2023.18662

Bucur, E., Vasile, A., Diodiu, R., Catrangiu, A., & Petrescu, M. (2015). Assessment of indoor air quality in a wooden church for preventive conservation. *Journal of Environmental Protection and Ecology*, *16*(1), 7–17.

Buenafe, K. C. V., Dunn, D. C., Everett, J. D., Brito-Morales, I., Schoeman, D. S., Hanson, J. O., Dabalà, A., Neubert, S., Cannicci, S., Kaschner, K., & Richardson,

A. J. (2023). A metric-based framework for climate-smart conservation planning. *Ecological Applications*, *33*(4), 1–29. https://doi.org/10.1002/eap.2852

Carpio, M., Ortega, J., & Prieto, A. J. (2021). EXPERT PANEL ON IN-SITU VISUAL INSPECTIONS FOR MASONRY CHURCHES MAINTENANCE STAGE. *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT*, *27*(6), 454–471. https://doi.org/10.3846/jcem.2021.15256

Ceccarelli, L., Bevilacqua, M. G., Caroti, G., Castiglia, R. B. F., & Croce, V. (2023). Semantic segmentation through Artificial Intelligence from raw point clouds to H-BIM representation. *Disegnarecon*, *16*(30), 171–178. https://doi.org/10.20365/disegnarecon.30.2023.17

CIB W086. (2021). New Trends on Building Pathology. *CIB WO86 Building Pathology*, 1–126.

Coelho, G. B. A., Silva, H. E., & Henriques, F. M. A. (2019). Impact of climate change on cultural heritage: a simulation study to assess the risks for conservation and thermal comfort. *International Journal of Global Warming*, *19*(4), 382. https://doi.org/10.1504/IJGW.2019.104268

Costa-Carrapiço, I., González, J. N., Raslan, R., Sánchez-Guevara, C., & Redondas Marrero, M. D. (2022). Understanding thermal comfort in vernacular dwellings in Alentejo, Portugal: A mixed-methods adaptive comfort approach. *Building and Environment*, *217*, 109084. https://doi.org/10.1016/j.buildenv.2022.109084

Croce, V., Caroti, G., Piemonte, A., De Luca, L., & Véron, P. (2023a). H-BIM and Artificial Intelligence: Classification of Architectural Heritage for Semi-Automatic Scan-to-BIM Reconstruction. *Sensors*, *23*(5), 2497. https://doi.org/10.3390/s23052497

Croce, V., Caroti, G., Piemonte, A., De Luca, L., & Véron, P. (2023b). H-BIM and Artificial Intelligence: Classification of Architectural Heritage for Semi-Automatic Scan-to-BIM Reconstruction. *Sensors*, *23*(5), 2497. https://doi.org/10.3390/s23052497

Daengprathum, N., Onchang, R., Nakhapakorn, K., Robert, O., Tipayarom, A., & Johann Sturm, P. (2022). Estimation of Effects of Air Pollution on the Corrosion of Historical Buildings in Bangkok: 10.32526/ennrj/20/202200071. *Environment and Natural Resources Journal*, *20*(5 SE-Original Research Articles), 505–514. https://ph02.tci-thaijo.org/index.php/ennrj/article/view/247080

DataCalculus. (2024). *Climate Data Analyst: Predictive Analytics for Biodiversity Conservation*. https://datacalculus.com/

De Marco, A., Screpanti, A., Mircea, M., Piersanti, A., Proietti, C., & Fornasier, M. F.

(2017). High resolution estimates of the corrosion risk for cultural heritage in Italy. *Environmental Pollution*, *226*, 260–267. https://doi.org/10.1016/j.envpol.2017.03.066

Elfadaly, A., Attia, W., Qelichi, M. M., Murgante, B., & Lasaponara, R. (2018). Management of Cultural Heritage Sites Using Remote Sensing Indices and Spatial Analysis Techniques. *Surveys in Geophysics*, *39*(6), 1347–1377. https://doi.org/10.1007/s10712-018-9489-8

Elnaggar, A., Said, M., Kraševec, I., Said, A., Grau-Bove, J., & Moubarak, H. (2024). Risk analysis for preventive conservation of heritage collections in Mediterranean museums: case study of the museum of fine arts in Alexandria (Egypt). *Heritage Science*, *12*(1), 59. https://doi.org/10.1186/s40494-024-01170-z

Fatorić, S., & Seekamp, E. (2017). Securing the Future of Cultural Heritage by Identifying Barriers to and Strategizing Solutions for Preservation under Changing Climate Conditions. *Sustainability*, *9*(11), 2143. https://doi.org/10.3390/su9112143

Florescu, O., Ichim, P., Sfîcă, L., Kadhim-Abid, A.-L., Sandu, I., & Nănescu, M. (2022). Risk Assessment of Artifact Degradation in a Museum, Based on Indoor Climate Monitoring—Case Study of "Poni-Cernătescu" Museum from Iași City. *Applied Sciences*, *12*(7), 3313. https://doi.org/10.3390/app12073313

Franco, A., Crisostomi, E., Dalmiani, S., & Poletti, R. (2024). Synergy in Action: Integrating Environmental Monitoring, Energy Efficiency, and IoT for Safer Shared Buildings. *Buildings*, *14*(4), 1077. https://doi.org/10.3390/buildings14041077

Gbran, H., & Ratih Sari, S. (2024). Studying the visual impact of modern construction on historic cityscapes: a case study of Lawang Sewu building, Indonesia. *Contexto*, *18*(28), 15–34. https://doi.org/10.29105/contexto18.28-410

Gbran, H., & Sari, S. R. (2023). The Visual Impact of Modern Constructions on the Old Cities in Indonesia: The Lawang Sewu Building in Semarang. *ISVS E-Journal*, *10*(2), 71–90.

Gibeaux, S., Martínez-Garrido, M. I., Vázquez, P., Thomachot-Schneider, C., & Fort, R. (2018). Wireless environmental monitoring coupled to NDT for decay risk analysis (at St. Joseph Chapel in Reims, France). *Sensors and Actuators A: Physical*, *272*, 102–113. https://doi.org/10.1016/j.sna.2017.12.016

Grigore, A.-M. (2017). The Economic Dimension in Valuing the Cultural Heritage. *International Conference on Economics and Administration*, *February*, 39–44.

Hamishebahar, Y., Guan, H., So, S., & Jo, J. (2022). A Comprehensive Review of Deep Learning-Based Crack Detection Approaches. *Applied Sciences (Switzerland)*, *12*(3). https://doi.org/10.3390/app12031374

Haznedar, B., Bayraktar, R., Ozturk, A. E., & Arayici, Y. (2023). Implementing PointNet for point cloud segmentation in the heritage context. *Heritage Science*, *11*(1), 2. https://doi.org/10.1186/s40494-022-00844-w

Hollesen, J. (2022). Climate change and the loss of archaeological sites and landscapes: a global perspective. *Antiquity*, *96*(390), 1382–1395. https://doi.org/10.15184/aqy.2022.113

Hu, X., & Assaad, R. H. (2024). A BIM-enabled digital twin framework for real-time indoor environment monitoring and visualization by integrating autonomous robotics, LiDAR-based 3D mobile mapping, IoT sensing, and indoor positioning technologies. *Journal of Building Engineering*, *86*, 108901. https://doi.org/10.1016/j.jobe.2024.108901

ICCROM. (2025). *The International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM)*. https://whc.unesco.org/en/partners/284

Ilieș, A., Caciora, T., Marcu, F., Berdenov, Z., Ilieș, G., Safarov, B., Hodor, N., Grama, V., Shomali, M. A. Al, Ilies, D. C., Gaceu, O., Costea, M., & Kieti, D. (2022). Analysis of the Interior Microclimate in Art Nouveau Heritage Buildings for the Protection of Exhibits and Human Health. *International Journal of Environmental Research and Public Health*, *19*(24), 16599. https://doi.org/10.3390/ijerph192416599

Karatzas, S., Papageorgiou, G., Lazari, V., Bersimis, S., Fousteris, A., Economou, P., & Chassiakos, A. (2024). A text analytic framework for gaining insights on the integration of digital twins and machine learning for optimizing indoor building environmental performance. *Developments in the Built Environment*, *18*, 100386. https://doi.org/10.1016/j.dibe.2024.100386

Karnowahadi, S., Poerbo, E., & Setyadi, S. N. (2021). Determinants of lawang sewu tourism demand in semarang city. *Indonesia. Academy of Entrepreneurship Journal (AEJ)*, *27*(5), 1–6.

Ladiana, D., & Di Sivo, M. (2019). Programmed conservation of historical and architectural heritage. tools for optimising a process based on knowledge and information. *International Journal of Design and Nature and Ecodynamics*, *14*(3), 229–240. https://doi.org/10.2495/DNE-V14-N3-229-240

Laohaviraphap, N., & Waroonkun, T. (2024a). Integrating Artificial Intelligence and the Internet of Things in Cultural Heritage Preservation: A Systematic Review of Risk Management and Environmental Monitoring Strategies. *Buildings*, *14*(12). https://doi.org/10.3390/buildings14123979

Laohaviraphap, N., & Waroonkun, T. (2024b). Integrating Artificial Intelligence and the Internet of Things in Cultural Heritage Preservation: A Systematic Review of Risk Management and Environmental Monitoring Strategies. *Buildings*, *14*(12), 3979. https://doi.org/10.3390/buildings14123979

Leissner, J., Kilian, R., Kotova, L., Jacob, D., Mikolajewicz, U., Broström, T., Ashley-Smith, J., Schellen, H. L., Martens, M., van Schijndel, J., Antretter, F., Winkler, M., Bertolin, C., Camuffo, D., Simeunovic, G., & Vyhlídal, T. (2015). Climate for Culture: assessing the impact of climate change on the future indoor climate in historic buildings using simulations. *Heritage Science*, *3*(1), 38. https://doi.org/10.1186/s40494-015-0067-9

Leonel J. R. Nunes , António Curado, S. I. L. (n.d.). Understanding Seasonal Indoor Radon Variability from Data Collected with a LoRa-Enabled IoT Edge Device. *Applied Sciences*. doi: 10.3390/app13084735

Lerario, A., & Varasano, A. (2020). An IoT Smart Infrastructure for S. Domenico Church in Matera's "Sassi": A Multiscale Perspective to Built Heritage Conservation. *Sustainability*, *12*(16), 6553. https://doi.org/10.3390/su12166553

Li, M. (2024). Disaster risk management of cultural heritage: A global scale analysis of characteristics, multiple hazards, lessons learned from historical disasters, and issues in current DRR measures in world heritage sites. *International Journal of Disaster Risk Reduction*, *110*, 104633. https://doi.org/10.1016/j.ijdrr.2024.104633

Luo, S., & Wang, H. (2024). Digital Twin Research on Masonry–Timber Architectural Heritage Pathology Cracks Using 3D Laser Scanning and Deep Learning Model. *Buildings*, *14*(4), 1129. https://doi.org/10.3390/buildings14041129

Maietti, F. (2023). Heritage Enhancement through Digital Tools for Sustainable Fruition—A Conceptual Framework. *Sustainability (Switzerland)*, *15*(15). https://doi.org/10.3390/su151511799

Marcelli, A., Sebastianelli, M., Conte, A., Lucci, F., & Della Ventura, G. (2020). Micro-climatic investigation and particulate detection in indoor environments: the case of the historical museum of Bersaglieri in Rome. *Rendiconti Lincei. Scienze Fisiche e Naturali*, *31*(3), 807–817. https://doi.org/10.1007/s12210-020-00935-5

Marcelli, A., Sebastianelli, M., Conte, A., Lucci, F., & Della Ventura, G. (2021). Micro-climatic investigation and particulate detection in indoor environments: the case of the historical museum of Bersaglieri in Rome. *Rendiconti Lincei. Scienze Fisiche e Naturali*, *31*(3), 807–817. https://doi.org/10.1007/s12210-020-00935-5

Martinelli, L., Calcerano, F., Adinolfi, F., Chianetta, D., & Gigliarelli, E. (2025). Open HBIM-IoT Monitoring Platform for the Management of Historical Sites and Museums. An Application to the Bourbon Royal Site of Carditello. *International Journal of Architectural Heritage*, *19*(2), 153–170.

https://doi.org/10.1080/15583058.2023.2272130

Marzouk, M., & Atef, M. (2022). Assessment of Indoor Air Quality in Academic Buildings Using IoT and Deep Learning. *Sustainability*, *14*(12), 7015. https://doi.org/10.3390/su14127015

Merciu, F. C., Petrişor, A. I., & Merciu, G. L. (2021). Economic valuation of cultural heritage using the travel cost method: The historical centre of the municipality of bucharest as a case study. *Heritage*, *4*(3), 2356–2376. https://doi.org/10.3390/heritage4030133

Metals, M., Lesinskis, A., Borodinecs, A., & Turauskis, K. (2024). Study on indoor air temperature and moisture behaviour in historical churches. *Energy and Buildings*, *310*, 114083. https://doi.org/10.1016/j.enbuild.2024.114083

Mishra, M., & Lourenço, P. B. (2024). Artificial intelligence-assisted visual inspection for cultural heritage: State-of-the-art review. *Journal of Cultural Heritage*, *66*, 536–550. https://doi.org/10.1016/j.culher.2024.01.005

Mitro, N., Krommyda, M., & Amditis, A. (2022). Smart Tags: IoT Sensors for Monitoring the Micro-Climate of Cultural Heritage Monuments. *Applied Sciences*, *12*(5), 2315. https://doi.org/10.3390/app12052315

Mohamed El Abd, N. (2023). Smart monitoring solution through internet of things utilization to achieve resilient preservation. *Ain Shams Engineering Journal*, *14*(6), 102176. https://doi.org/10.1016/j.asej.2023.102176

Mohd Dzulkifli, S. N., Abdullah, A. H., & Leman, A. M. (2016). Design and material in museum: Does it affect the ventilation in indoor air quality? *ARPN Journal of Engineering and Applied Sciences*, *11*(11), 7341–7348.

Morkunaite, Z., Podvezko, V., Zavadskas, E. K., & Bausys, R. (2019). Contractor selection for renovation of cultural heritage buildings by PROMETHEE method. *Archives of Civil and Mechanical Engineering*, *19*(4), 1056–1071. https://doi.org/10.1016/j.acme.2019.05.008

Mouffok, M., Zemmouri, N., Aidaoui, L., Lasbet, Y., & De Herde, A. (2017). Effects of building morphologies on CO2 air pollution case study: The vernacular urban fabric, city of Ghardaïa (Algeria). *Asian Journal of Civil Engineering*, *18*(1), 1–19.

Murzyn-Kupisz, M. (2012). Cultural, economic and social sustainability of heritage tourism: issues and challenges. *Economic and Environmental Studies*, *12*(2), 113–133. www.ees.uni.opole.pl

Nawaz, M., & Babar, M. I. K. (2024). IoT and AI: a panacea for climate change-resilient smart agriculture. *Discover Applied Sciences*, *6*(10). https://doi.org/10.1007/s42452-024-06228-y

Nunes, L. J. R., Curado, A., & Lopes, S. I. (2023). Understanding Seasonal Indoor Radon Variability from Data Collected with a LoRa-Enabled IoT Edge Device. *Applied Sciences*, *13*(8), 4735. https://doi.org/10.3390/app13084735

Nurul, U. (2019). Too Many Meanings: Contestation of Lawang Sewu as a Heritage Tourism Attraction. In *Tourisma: Jurnal Pariwisata* (Vol. 1, Issue 2, p. 55). https://doi.org/10.22146/gamajts.v1i2.47475

Ocón, D. (2020). *Digitalising endangered cultural heritage in Southeast Asian cities: preserving or replacing?* https://doi.org/doi.org/10.1080/13527258.2021.1883711

Ocón, D. (2022). *Digitalising endangered cultural heritage in Southeast Asian cities: preserving or replacing?* https://doi.org/10.1080/13527258.2021.1883711

Of, A. (2022). I. (2022). *Impact of air pollution on outdoor cultural heritage objects and decoding the role of particulate matter*. https://doi.org/doi.org/10.1007/s11356-022-20309-8

Oliveira, M. L. S., Neckel, A., Pinto, D., Maculan, L. S., Dotto, G. L., & Silva, L. F. O. (2021). The impact of air pollutants on the degradation of two historic buildings in Bordeaux, France. *Urban Climate*, *39*, 100927. https://doi.org/10.1016/j.uclim.2021.100927

Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … McKenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*, n160. https://doi.org/10.1136/bmj.n160

Paschalidou, E., Fafet, C., & Milios, L. (2022). A Strong Sustainability Framework for Digital Preservation of Cultural Heritage: Introducing the Eco-Sufficiency Perspective. *Heritage*, *5*(2), 1066–1088. https://doi.org/10.3390/heritage5020058

Poston, O. (2025). *Designing with Humidity: How Architecture Adapts to the World's Dampest Climates*. https://www.archdaily.com/1027537/designing-with-humidity-how-architecture-adapts-to-the-worlds-dampest-climates

Prieto, A. J., Verichev, K., Silva, A., & de Brito, J. (2020). On the impacts of climate change on the functional deterioration of heritage buildings in South Chile. *Building and Environment*, *183*, 107138. https://doi.org/10.1016/j.buildenv.2020.107138

Prizeman, O., Pezzica, C., Taher, A., & Boughanmi, M. (2020). Networking Historic Environmental Standards to Address Modern Challenges for Sustainable Conservation in HBIM. *Applied Sciences*, *10*(4), 1283. https://doi.org/10.3390/app10041283

Quesada-Ganuza, L., Garmendia, L., Alvarez, I., & Roji, E. (2023). Vulnerability assessment and categorization against heat waves for the Bilbao historic area. *Sustainable Cities and Society*, *98*, 104805. https://doi.org/10.1016/j.scs.2023.104805

Rajčić, V., Skender, A., & Damjanović, D. (2018). An innovative methodology of assessing the climate change impact on cultural heritage. *International Journal of Architectural Heritage*, *12*(1), 21–35. https://doi.org/10.1080/15583058.2017.1354094

Sánchez, B., de Oliveira Souza, M., Vilanova, O., & Canela, M. C. (2020). Volatile organic compounds in the Spanish National Archaeological Museum: Four years of chemometric analysis. *Building and Environment*, *174*, 106780. https://doi.org/10.1016/j.buildenv.2020.106780

Saraiva, N. B., Pereira, L. D., Gaspar, A. R., & Costa, J. J. (2023). Measurement of particulate matter in a heritage building using optical counters: Long-term and spatial analyses. *Science of The Total Environment*, *862*, 160747. https://doi.org/10.1016/j.scitotenv.2022.160747

Scatigno, C., Moricca, C., Tortolini, C., & Favero, G. (2016). The influence of environmental parameters in the biocolonization of the Mithraeum in the roman masonry of casa di Diana (Ostia Antica, Italy). *Environmental Science and Pollution Research*, *23*(13), 13403–13412. https://doi.org/10.1007/s11356-016-6548-x

Shillito, L.-M., Namdeo, A., Bapat, A. V., Mackay, H., & Haddow, S. D. (2022). Analysis of fine particulates from fuel burning in a reconstructed building at Çatalhöyük World Heritage Site, Turkey: assessing air pollution in prehistoric settled communities. *Environmental Geochemistry and Health*, *44*(3), 1033–1048. https://doi.org/10.1007/s10653-021-01000-2

Siccardi, S., & Villa, V. (2022). Trends in Adopting BIM, IoT and DT for Facility Management: A Scientometric Analysis and Keyword Co-Occurrence Network Review. *Buildings*, *13*(1), 15. https://doi.org/10.3390/buildings13010015

Silva, H. E., & Henriques, F. M. A. (2016). Hygrothermal analysis of historic buildings. *Structural Survey*, *34*(1), 12–23. https://doi.org/10.1108/SS-07-2015-0030

Silva, H. E., & Henriques, F. M. A. (2021). The impact of tourism on the conservation and IAQ of cultural heritage: The case of the Monastery of Jerónimos (Portugal). *Building and Environment*, *190*, 107536. https://doi.org/10.1016/j.buildenv.2020.107536

Sitzia, F., Peters, M. J. H., & Lisci, C. (2022). Climate change and its outcome on the archaeological areas and their building materials. The case study of Tharros (Italy). *Digital Applications in Archaeology and Cultural Heritage*, *25*, e00226.

https://doi.org/10.1016/j.daach.2022.e00226

SMART. (2025). *Collect, measure and evaluate data to improve the effectiveness of your wildlife conservation efforts*. https://smartconservationtools.org/en-us/

Tabernik, D., Šela, S., Skvarč, J., & S. (2024). *Segmentation-based deep-learning approach for surface-defect detection*. https://doi.org/doi.org/10.1007/s10845-019-01476-x

Team, N. R. and T. A. E. (2022). *ASEAN Going Digital to Preserve the Region's Cultural Heritage*. ASEAN Socio-Cultural Community Department. https://theaseanmagazine.asean.org/article/asean-going-digital-to-preserve-the-regions-cultural-heritage/

United Nations. (2024). *Department of Economic and Social Affairs Sustainable Development*. https://sdgs.un.org/goals

Vandenabeele, L., Loverdos, D., Pfister, M., & Sarhosis, V. (2024). Deep Learning for the Segmentation of Large-Scale Surveys of Historic Masonry: A New Tool for Building Archaeology Applied at the Basilica of St Anthony in Padua. *International Journal of Architectural Heritage*, *18*(11), 1749–1761. https://doi.org/10.1080/15583058.2023.2260771

Varas-Muriel, M. J., Fort, R., Martínez-Garrido, M. I., Zornoza-Indart, A., & López-Arce, P. (2014). Fluctuations in the indoor environment in Spanish rural churches and their effects on heritage conservation: Hygro-thermal and CO 2 conditions monitoring. *Building and Environment*, *82*, 97–109. https://doi.org/10.1016/j.buildenv.2014.08.010

Vina, A. (2024). *Using AI for crack detection and segmentation*. https://www.ultralytics.com/blog/using-ai-for-crack-detection-and-segmentation

Wei, W., & Jiang, Z. (2023). A bibliometrix-based visualization analysis of international studies on conversations of people with aphasia: Present and prospects. *Heliyon*, *9*(6), e16839. https://doi.org/10.1016/j.heliyon.2023.e16839

Wojtkowska, M., Kedzierski, M., & Delis, P. (2021). Validation of terrestrial laser scanning and artificial intelligence for measuring deformations of cultural heritage structures. *Measurement*, *167*, 108291. https://doi.org/10.1016/j.measurement.2020.108291

Worldbank.org, & Logo, W. B. B. (2022). *World Bank country classifications by income level for 2024-2025*. https://blogs.worldbank.org/en/opendata/world-bank-country-classifications-by-income-level-for-2024-2025

Yiğit, A. Y., & Uysal, M. (2024). Automatic crack detection and structural inspection of cultural heritage buildings using UAV photogrammetry and digital twin technology. *Journal of Building Engineering*, *94*, 109952.

https://doi.org/10.1016/j.jobe.2024.109952

Yordanov, V. (2025). *Industrial IoT Wireless Air Quality CO2 Temperature Humidity Particulate Matter Sensor API Overview*. https://ncd.io/blog/industrial-iot-wireless-air-quality-co2-temperature-humidity-particulate-matter-sensor-api-overview/

Zhu, J., & Liu, W. (2020). A tale of two databases: the use of Web of Science and Scopus in academic papers. *Scientometrics*, *123*(1), 321–335. https://doi.org/10.1007/s11192-020-03387-8

Živković, V., & Džikić, V. (2015). Return to basics—Environmental management for museum collections and historic houses. *Energy and Buildings*, *95*, 116–123. https://doi.org/10.1016/j.enbuild.2014.11.023