ROMA TRE
UNIVERSITÀ DEGLI STUDI

DOCTORATE COURSE IN EARTH SCIENCES

Climate change risk management of earthen archaeological sites: Impact assessment, adaptation strategies, and material stabilization approaches

CYCLE: XXXIII

PhD: Masoud Nakhaeiashtari

Supervisor: Prof. Giancarlo Della Ventura

Co-supervisor: Prof. Mariana Correia

Date: November 2025

Abstract

Climate change poses a significant and escalating threat to cultural heritage worldwide, particularly to earthen archaeological sites. These inherently fragile sites are highly sensitive to environmental fluctuations. Despite growing global awareness, and systematic frameworks for assessing and adapting earthen heritage to climate change, this remains an underdeveloped research area.

This thesis addresses this gap in knowledge by integrating conceptual, empirical, and experimental approaches to develop a comprehensive framework for climate change risk management and adaptation of earthen archaeological sites. The research is structured in three interrelated phases. First, a literature review synthesizes the state of knowledge on climate change impacts, vulnerability assessment, and adaptation strategies for cultural and earthen heritage. It identifies critical gaps in policy integration, the utilization of traditional knowledge, and material-level adaptation. The second phase involves a comparative vulnerability assessment of four representative Iranian earthen heritage sites - Sistan, Yazd, Persepolis, and Tchogha Zanbil - selected for their climatic diversity and cultural significance. Using an IPCC-based model, the study evaluates each site's exposure, sensitivity, and adaptive capacity. Results reveal that arid and semi-arid sites are most at risk due to intensified droughts, flash floods, and socio-economic pressures, which are compounded by limited adaptive capacity and the loss of traditional maintenance practices. The third phase presents an experimental adaptation study focusing on the stabilization of earthen materials under heavy precipitation. Laboratory testing of magnesium oxide and hydrated lime blends demonstrates significant improvement in water resistance, erosion control, and structural durability. Microstructural analyses confirm the formation of brucite, calcite, and hydrotalcite-like phases, which enhance matrix density and resilience while maintaining material compatibility and authenticity.

This thesis develops an integrated climate adaptation framework that connects theoretical models, field-based vulnerability assessments, and material-level innovations. The findings contribute to the broader objectives of the UNFCCC and UNESCO's climate action agendas, providing actionable insights for heritage managers and policymakers seeking sustainable and science-based strategies to enhance the resilience of earthen heritage in the face of accelerating climate change.

General Content

Chapter 1: Introduction……..12

Chapter 2 - Climate change and cultural heritage…….21

Chapter 3 - Impacts of climate change on earthen heritage…….31

Chapter 4 - Adaptation of cultural heritage to climate change:……..……57

Chapter 5: Preserving archaeological sites in a changing climate: barriers to adaptation in earthen archaeological sites 98

Chapter 6 - Climate-resilient earthen heritage conservation: magnesium-based additives for improved adobe erosion resistance 112

Chapter 7 - Improving the resilience of earthen materials to heavy precipitation through hydrated lime and magnesium oxide stabilization.....141

Chapter 8 – Conclusion…….....163

Detailed content

1. Chapter 1: Introduction… 12

1.1. Research Objectives.. 15

1.2. Methodological overview… 15

1.2.1. Phase I - Conceptual and contextual foundation 16

1.2.2. Phase II - Empirical Assessment: Case Studies 17

1.2.3. Phase III – Experimental and Practical Adaptation Strategies 17

1.2.4. Integration and Synthesis 18

2. Chapter 2 - Climate change and cultural heritage……. 21

2.1. Climate change and cultural heritage: an overview…… 22

2.2. Climate change and earthen heritage…… 22

2.3. Climate change and World Heritage properties…… 23

2.4. The World Heritage Convention and climate change…… 24

2.5. Hazard and vulnerability assessment in earthen heritage…… 24

2.6. Intangible cultural heritage, adaptation, and mitigation…… 25

2.7. Summary of Key Issues.. 25

3. Chapter 3 - Impacts of climate change on earthen heritage…….. 31

3.1. Introduction.. 31

3.2. Methodology… 33

3.3. Climate change in the study areas.. 34

3.3.1. Sistan 35

3.3.2. Yazd 36

3.3.3. Persepolis 37

3.3.4. Tchogha Zanbil 38

3.4. Results.. 39

3.4.1. Climate change hazards & Climate variables 39

3.4.2. Vulnerability assessment 40

3.4.3. Climate change impacts 42
3.5. Discussion.. 44
3.5.1. Comparative vulnerability assessment in the studied sites 45
3.6. Adaptation in the studied sites.. 47
3.7. Summary of Key Issues…… 48
4. Chapter 4 - Adaptation of cultural heritage to climate change:……57
4.1. Introduction.. 57
4.2. Method.. 59
4.2.1. Overall Approach 59
4.3. Climate change impacts, risk, and vulnerability assessment for cultural heritage.64
4.4. Adaptation in Response to Climate Change.. 65
4.5. Policy and legal frameworks.. 67
4.6. Adaptive management and planning.. 70
4.7. Sustainable conservation techniques..... 72
4.8. Technological innovations.. 73
4.9. Community engagement and indigenous knowledge.. 75
4.10. Ancient knowledge as adaptive capacity… 77
4.11. Barriers to climate change adaptation.. 78
4.12. Gaps in research.. 79
4.13. Summary of Key Issues.. 80
5. Chapter 5: Preserving archaeological sites in a changing climate: barriers to adaptation in earthen archaeological sites 98
5.1. Introduction.. 98
5.2. Vulnerabilities of EASs to climate change.. 99
5.3. Adaptation of EASs to climate change.. 100
5.4. Barriers to climate change adaptation in EASs..... 101
5.4.1. Forgetting traditional knowledge and lack of awareness of climate change impacts 101

5.4.2. Socio-cultural barriers and limited community engagement 102
5.4.3. Lack of data and information 102
5.4.4. Financial constraints and resource limitations 103
5.4.5. Limited institutional capacity and the lack of risk management plan 104
5.4.6. Conflicting conservation and development priorities 104
5.4.7. The absence of frameworks, criteria, and legal reforms 105
5.5. Overcoming the barriers.. 106
5.6. Summary of Key Issues.. 108
6. Chapter 6 - Climate-resilient earthen heritage conservation: magnesium-based additives for improved adobe erosion resistance 112
6.1. Introduction.. 112
6.1.1. Research aim 114
6.2. Materials and methods.. 114
6.3. Results.. 114
6.3.1. Rainfall simulation tests 115
6.3.2. Capillary water absorption 118
6.3.3. Immersion test 119
6.3.4. Mineralogy and Microstructural examination of adobes 120
6.4. Discussion.. 123
6.4.1. Erosion resistance and stabilizer performance 123
6.4.2. Soil characteristics and mineralogical insights 124
6.5. Implications for heritage conservation 125
6.6. Summary of Key Issues.. 127
6.7. Supplementary material.. 128
6.7.1. Soil characteristics 128
6.7.2. Additive selection and properties 130
6.7.3. Adobe preparation 131

6.7.4. Laboratory studies....131
6.7.4.1. Artificial rain simulation....132
6.7.4.2. Capillarity test....133
6.7.4.3. Immersion tests....134
6.7.4.4. FESEM-EDS analysis....135
7. Chapter 7 - Improving the resilience of earthen materials to heavy precipitation through hydrated lime and magnesium oxide stabilization....141
7.1. Introduction....142
7.2. Materials and Methods....143
7.3. Results....143
7.3.1. Rainfall simulation tests....143
7.3.2. Effect of treatment on capillary water absorption....146
7.3.3. Immersion test....148
7.3.4. Mineralogy and microstructural examination of adobes....149
7.3.5. Scanning Electron Microscopy (SEM–EDS) Analysis....151
7.4. Discussion....153
7.5. Compatibility with heritage earthen materials....158
7.6. Summary of Key Issues....158
8. Chapter 8 – Conclusion....163
8.1. Key findings....163
8.2. Contribution to climate change risk management of earthen heritage....164
8.3. Conclusions....164
8.4. Limitations of the Research....166

List of Figures

Fig. 1.1: Distribution of earthen heritage by country....13
Fig. 1.2: Statistical overview of earthen heritage in the world heritage list....13
Fig. 1.3. Research methodology framework for climate change risk management of earthen archaeological sites....16
Fig 3.1: The status of Iran in relation to climate change on a global scale....35
Fig 3.2: Location of study areas.....35
Fig 3.3: Abandoned earthen heritage in Sistan....36
Fig 3.4: Earthen heritage in Yazd....37
Fig 3.5: Remains of ancient earthen walls in Persepolis....38
Fig 3.6: Aerial photo of Tchogha Zanbil....39
Fig. 4.1: Temporal distribution of publications on cultural heritage adaptation to climate change (2000–2025)....61
Fig. 4.2: Geographic distribution of studies on cultural heritage adaptation to climate change by country....61
Fig. 4.3: Classification of adaptation actions in cultural heritage studies according to the IPCC AR6 typology....63
Fig 5.1: Ancient water risk management system in the Tchogha Zanbil....100
Fig 5.2: Adaptation Strategies for earthen Sites....100
Fig 5.3: Some methods for overcoming barriers....106
Fig. 6.1: Examples of surface erosion condition for samples MgO-10% and SC-10% exposed to simulated rain.....115
Fig. 6.2: Progressive surface degradation of SC-treated and untreated adobe under simulated rainfall....116
Fig. 6.3: Progressive surface degradation of MgO-treated and untreated adobe under simulated rainfall....117
Fig. 6.4. Area-normalized erosion (ANE) volumes of adobe samples under simulated rainfall (Normalized to the reference sample).....118
Fig. 6.5: Comparative capillary water absorption (height) of treated and untreated adobe samples.....119
Fig. 6.6: Physical degradation of adobe samples after 72 hours of water exposure.....120
Fig. 6.7: X-ray diffraction (XRD) results of samples MgO-15% (a) and SC-15% (b).....121
Fig. 6.8: FESEM-BSE images and EDS results from samples MgO-15% (a and b, respectively) and SC-15% (c and d, respectively). (a) and (c) are SEM images for samples MgO-15% and

SC-15%, respectively. (b) and (d) are EDS elemental maps of Mg, Si and Ca, superimposed on the BSEM images for samples MgO-15% and SC-15%, respectively. The areas containing chlorite (see text) and $Mg(OH)_2$/MgO are shown. 122
Fig S1: Granulometric (particle size distribution) curve for a soil sample from Nazzano 129
Fig. S2: Soil texture classification based on particle size distribution 130
Fig S3: XRD analysis of the soils sample from Nazzano (Rome), Italy 130
Fig. S4: Experimental setup for simulated rainfall and surface scanning of the samples 132
Fig. S5: Example of experimental setup of the capillarity test. 133
Fig. S6: Setup of the immersion test showing adobe samples submerged in distilled water for durability evaluation over 72 hours 134
Fig. 7.1: Progressive surface degradation of HL and MgO + HL and untreated adobe under simulated rainfall 145
Fig 7.2: Area-normalized erosion volumes of adobe samples under simulated rainfall 146
Fig. 7.3: Comparative capillary water absorption (height) of treated and untreated adobe samples 147
Fig. 7.4. Immersion test setup with adobe samples submerged in distilled water for 72-hour durability assessment 148
Fig. 7.5: Physical degradation of adobe samples after 72 hours of water exposure 149
Fig. 7.6: X-ray diffraction patterns of (a) hydrated lime–treated adobe and (b) hydrated lime + MgO–treated adobe compared with reference soil. 151
Fig. 7.7. (a) SEM micrograph of lime-stabilized adobe showing compacted matrix of calcite + clay + C–S–H; (b) elemental map of Mg; (c) elemental map of Si; (d) elemental map of Ca 152
Figure 7.8. (a) SEM micrograph of MgO–lime–stabilized adobe showing dense, compact matrix with reacted fragments; (b) elemental Mg map; (c) Si map; (d) Ca map. 153

List of Tables

Table 3.1: Hazard assessment of representative earthen sites in arid and semi-arid regions...39
Table 3.2: Vulnerability assessment of case studies to the impacts of climate change.....41
Table 3.3: Assessment of climate change impacts in the 4 case studies 42
Table 4.1: Diagnostic framework for identifying adaptation action types in cultural heritage studies based on IPCC AR6 categories.....62
Table S1: The chemical analysis of major oxides from the used MgO 131
Table S2: Area-normalized erosion volumes (mm^3) recorded during the artificial rainfall simulation time.....133
Table S3: Effect of treatment on capillary water absorption in adobe samples (Hight of moisture penetration (mm)) 134
Table S4: Deterioration of adobe samples following 72 hours of water immersion.....135
Table 7.1: Area-normalized erosion volumes (mm^3) (ANE) recorded during the artificial rainfall simulation time.....146
Table 7.2: Effect of treatment on capillary water absorption in adobe samples 147
Table 7.3: Deterioration of adobe samples following 72 hours of water immersion.....149

List of Acronyms

AR6: Sixth Assessment Report (Intergovernmental Panel on Climate Change)

C-S-H: Calcium Silicate Hydrate

CCHWG: Climate Change and Cultural Heritage Working Group

CVI: Climate Vulnerability Index

EDS: Energy Dispersive Spectroscopy

EASs: Earthen Archaeological Sites

FESEM: Field Emission Scanning Electron Microscopy

GGA: Global Goal on Adaptation

GIS: Geographic Information System

GCI: Getty Conservation Institute

HL: Hydrated Lime

ICOMOS: International Council on Monuments and Sites

IPCC: Intergovernmental Panel on Climate Change

LM: Lime–Magnesium Blend

MgO: Magnesium Oxide

$Mg(OH)_2$: Magnesium Hydroxide (Brucite)

MgO-HL: Magnesium Oxide–Hydrated Lime Blend

OUV: Outstanding Universal Value (UNESCO World Heritage Convention)

SC: Sorel Cement (Magnesium Oxychloride Cement)

SEM: Scanning Electron Microscopy

UNEP: United Nations Environment Programme

UNESCO: United Nations Educational, Scientific and Cultural Organization

UNFCCC: United Nations Framework Convention on Climate Change

WHS: World Heritage Site

WHEAP: World Heritage Earthen Architecture Programme

XRD: X-ray Diffraction

Acknowledgements

I would like to express my deepest gratitude to my supervisors, whose guidance, insight, and encouragement have shaped every stage of this research. My sincere thanks go to Ahmad Rabiee (UniRoma Tre, Department of Sciences) for his essential assistance with the XRD and SEM analyses. His technical expertise and availability greatly facilitated the mineralogical and microstructural investigations. I am also deeply grateful to Francesca Funiciello and Riccardo Reitano (UniRoma Tre, Department of Sciences) for their support with coding and for providing access to the laboratory facilities used for the rainfall simulation experiments. I would like to extend my appreciation to the reviewers of the articles produced during this doctoral research. Special thanks are due to Sergio Lomastro and Salvatore Pizzichetti (UniRoma Tre, Department of Sciences) for their technical assistance in sample preparation and granulometric analysis. Their precision and support were crucial for the successful execution of several laboratory procedures. I am grateful to Agnese Fischetti (UniRoma Tre, Department of Humanities) for providing the soil samples from Nazzano Romano, which were fundamental to the laboratory investigations developed in this thesis. My sincere appreciation also goes to Silvia Brizzi, whose help with the density analysis contributed to the sample characterization and interpretation of the experimental results. Finally, I am thankful to all colleagues, friends, and collaborators who supported me throughout this research journey.

1. Chapter 1: Introduction

This opening chapter establishes the conceptual foundation of the research by framing the global challenge of climate change as a critical risk factor for cultural heritage, with a particular focus on earthen archaeological sites. It defines the research problem, objectives, and introduces the conceptual model considered, based on the IPCC framework for vulnerability and risk. The chapter also outlines the methodological approach adopted to link theoretical inquiry, empirical analysis, and practical experimentation. It is widely acknowledged that climate change represents one of the greatest threats to cultural heritage, posing significant challenges to the conservation of monuments, archaeological sites, and landscapes (Heron et al., 2022; Jones et al., 2022; Nakhaei & Correia, 2020). Fluctuations in average weather conditions and the growing intensity of extreme events have made climate change one of the most complex problems for heritage managers (Phillips, 2015; Sesana et al., 2020; Day et al., 2019). The effects of these changes are both direct, manifesting as physical deterioration, and indirect, through shifts in socioeconomic and ecological systems that sustain heritage values.

Among the different categories of heritage, earthen architecture is one of the most climate-sensitive, due to the fragility of its constituent materials. Analysis of the current World Heritage List demonstrates the disproportionate vulnerability of earthen heritage within the global portfolio of inscribed properties. Of the 1,248 World Heritage sites, 194 (15.5%) are classified as earthen heritage (Fig. 1.1). However, of the 53 properties currently inscribed on the List of World Heritage in Danger, 16 (30.2%) are earthen, indicating that earthen sites are nearly twice as likely to be endangered compared to the overall World Heritage population. While only 4.2% of all World Heritage properties are listed as endangered, this proportion rises to 8.3% for earthen heritage sites (Fig. 1.2). These sites are increasingly threatened by changes in humidity, temperature, cloudburst rain events, and wind, which accelerate weathering and erosion processes (Erdogan, 2022). The inherent vulnerabilities of earthen materials, particularly their susceptibility to water, compound visible damages, contribute to long-term deterioration (Trizio et al., 2022). Consequently, earthen heritage is exposed to new pressures, risks, and conflicts, and the relevance of conventional risk assessment standards is being questioned.

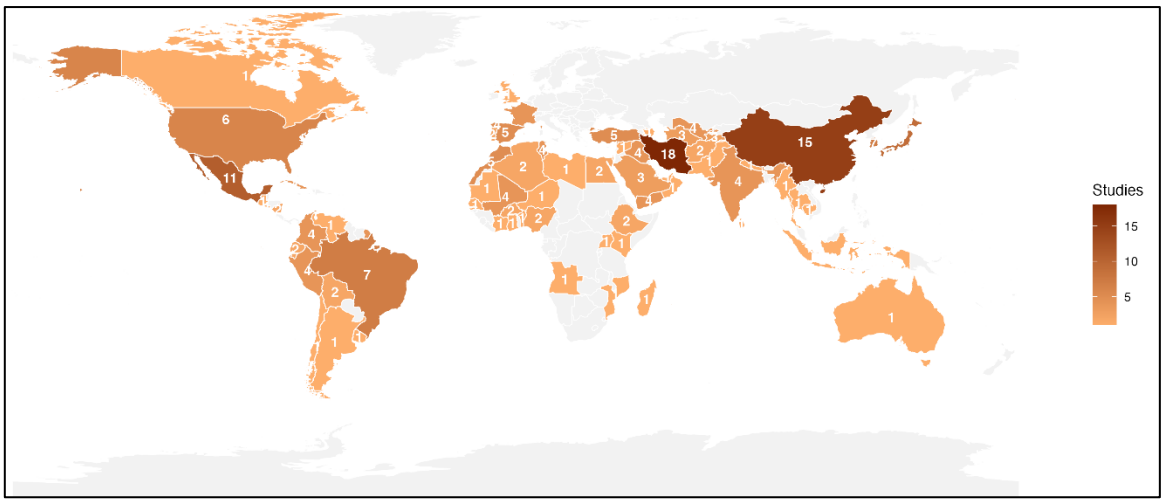


Fig. 1.1: Distribution of earthen heritage by country (Nakhaei and Correia., 2025)

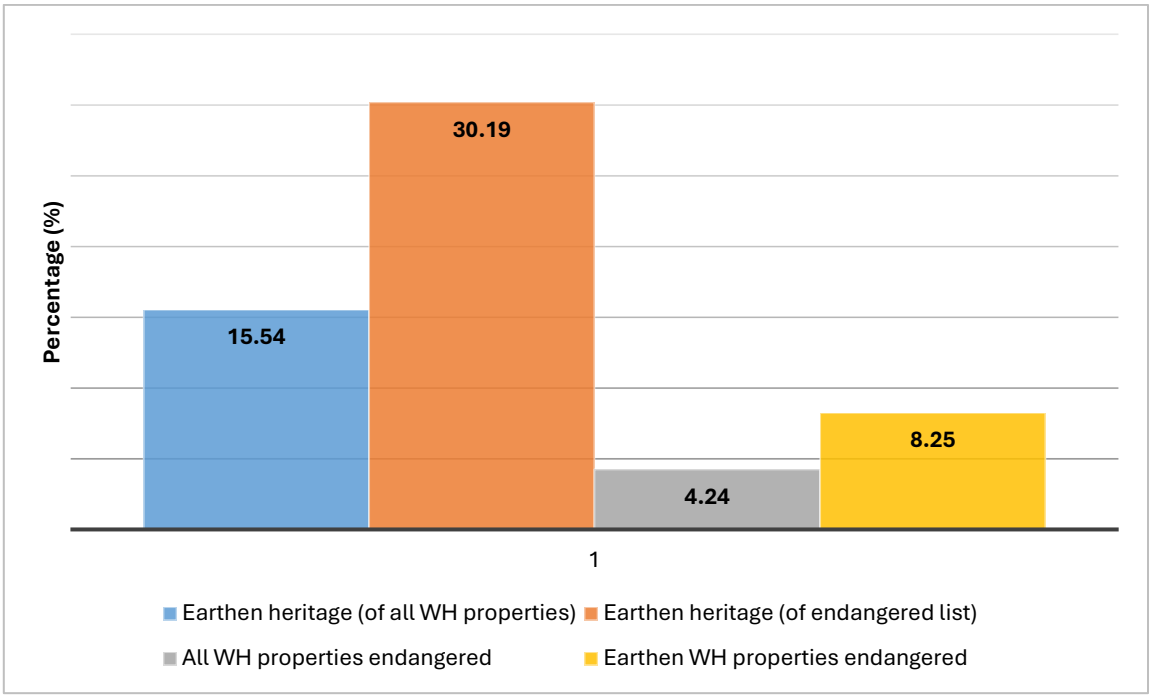


Fig. 1.2: Statistical overview of earthen heritage in the world heritage list

Despite a substantial body of research on climate change and cultural heritage, adaptation planning for earthen sites remains limited. Most studies have focused on stone monuments and landscapes, with geographic coverage cantered in Europe, China, North America, and Australia (Sesana et al., 2021; Richards et al., 2019). Yet the effects of climate change are global, and observations reveal that the Middle East has been among the regions most affected in recent decades, underscoring the urgency of addressing threats to earthen archaeological sites located there. Literature also highlights that both tangible and intangible values of earthen World Heritage Sites are directly and indirectly impacted by climate variability and extreme weather events (Findlay, 2020; Richards et al., 2020).

Earthen materials are particularly sensitive to water in all its forms, including rainfall, groundwater, and freeze-thaw cycles. With rising global temperatures and altered diurnal temperature range, the effects of moisture are becoming increasingly destructive. The fragility of earthen structures complicates the application of adaptive measures: while materials can be modified to improve performance, interventions often risk altering authenticity or generating unforeseen consequences (Tawab, 2013; Phillips, 2015).

The United Nations Framework Convention on Climate Change (UNFCCC) defines adaptation as adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli, aimed at moderating potential damage or harnessing opportunities. Crucially, adaptation must be informed by both scientific research and traditional knowledge (UNFCCC, 2018). In this context, stabilization of earthen materials, a practice with a long history in conservation, may be considered a form of material adaptation. Stabilization seeks to enhance durability, thereby reducing risks of maladaptation and the technical failures that often threaten archaeological earthen sites. However, conventional stabilization techniques face several challenges. Most do not adequately address the expansion and contraction of clay minerals in response to humidity changes, the primary driver of deterioration. In addition, many tested stabilizers lead to irreversible pollution of archaeological sites and are nearly impossible to remove once applied. The lack of standardized experimental protocols and the high cost of additives further limit their widespread adoption (Oliver, 2000; Wang et al., 2020).

Recent advances provide important insights into both the physical and cultural dimensions of climate risk management for earthen heritage. For example, research in Turkey, the Western Himalaya, and China has shown that environmental factors such as moisture and wind directly influence deterioration, while model-based approaches like cellular automata highlight uncertainties in predicting future conditions (Sikka et al., 2009; Findlay, 2020; Richards et al., 2020; Erdogan, 2022). Studies on frost vulnerability in northwestern China reveal that higher-density earthen materials may paradoxically be more at risk than lower-density ones (Richards et al., 2022). Beyond material science, investigations into authenticity show that non-material attributes often outweigh material aspects, reframing conservation priorities in the context of climate change (Tawab, 2013). Despite international recognition of the urgent need for climate adaptation (UNFCCC, 2018), research reveals that for most earthen heritage, systematic climate change adaptation planning has not yet been developed (Daly et al., 2022; Fatorić, S., & Biesbroek, R. (2020).

1.1. Research Objectives

To synthesize existing knowledge on climate change impacts, risk assessment frameworks, and adaptation strategies relevant to cultural and earthen heritage through an extensive literature review.

To assess climate-related impacts and vulnerabilities of selected earthen archaeological sites using an IPCC-based framework that evaluates exposure, sensitivity, and adaptive capacity.

To identify different barriers that hinder the effective implementation of climate change adaptation measures at earthen archaeological sites.

To develop and test material-level adaptation strategies through laboratory experimentation using magnesium-based stabilizers and hydrated lime under simulated hydraulic stress conditions.

1.2. Methodological overview

This research adopts a multi-layered and interdisciplinary methodology designed to examine, interpret, and respond to the impacts of climate change on earthen archaeological sites. The study integrates theoretical inquiry, empirical analysis, and experimental testing to develop an adaptable framework for climate change risk management in earthen heritage.

The methodology unfolds in three interrelated phases, each corresponding to specific chapters of the thesis: (1) Conceptual and contextual foundation; (2) Empirical and comparative assessment of impacts and vulnerabilities; and (3) Material-level experimentation and innovation for adaptive conservation (Fig. 1.1).

The structure of this thesis reflects a publication-oriented framework, with each chapter corresponding to either a published article or a manuscript prepared for submission. Moreover, the organization, and the conceptual orientation of this research are aligned with the international climate adaptation frameworks established by the United Nations Framework Convention on Climate Change (UNFCCC, 2023), the Intergovernmental Panel on Climate Change (IPCC, 2022), and UNESCO's World Heritage Climate Action initiatives (UNESCO, 2023). The progression of this thesis, from assessing climate change impacts on earthen heritage to developing and testing practical adaptation strategies, mirrors the UNFCCC's adaptation cycle.

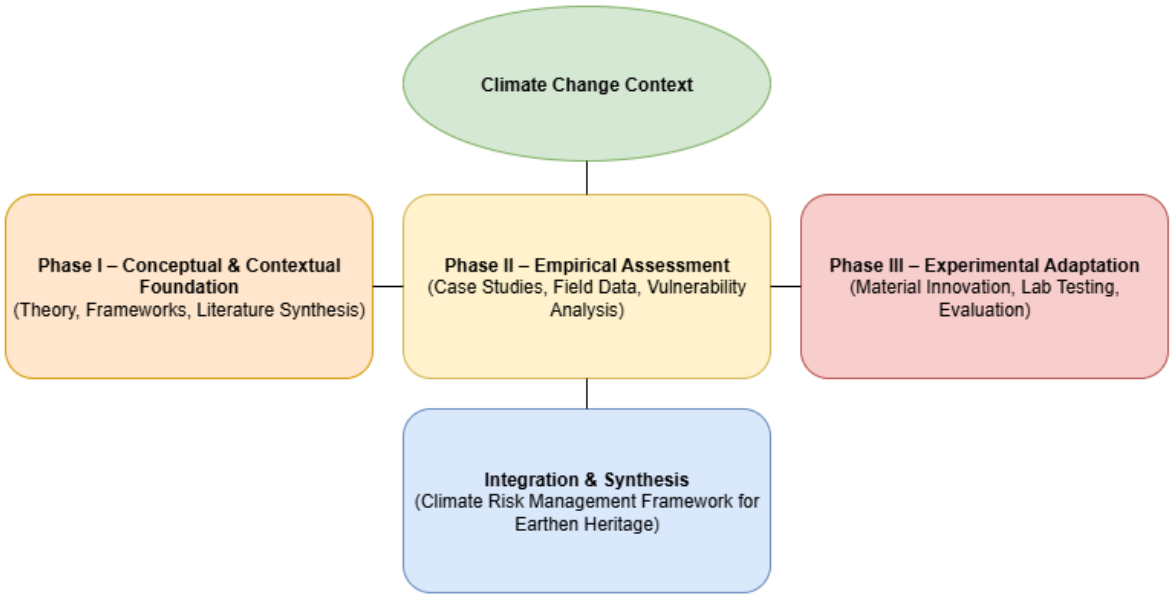


Fig. 1.3. Research methodology framework for climate change risk management of earthen archaeological sites

1.2.1. Phase I – Conceptual and contextual foundation

The first phase establishes the theoretical and conceptual framework for understanding the relationship between climate change and cultural heritage. Chapter 2 provides a general overview of climate change and its implications for tangible and intangible cultural heritage, with particular emphasis on earthen structures that are inherently vulnerable due to their physical properties and environmental exposure. It also introduces international frameworks such as the World Heritage Convention, UNESCO, and IPCC guidelines that underpin heritage risk assessment and climate policy. Chapter 4 extends this foundation through a systematic literature review focusing on global and regional adaptation strategies. Peer-reviewed articles, policy documents, and institutional reports were critically analysed using thematic synthesis to identify patterns of impact, adaptive management approaches, and persistent gaps in knowledge. Specific attention was given to adaptation models, technological innovations, indigenous knowledge systems, and barriers to implementation. This phase established the conceptual model guiding the study, one based on the IPCC risk framework, where vulnerability is defined as a function of exposure, sensitivity, and adaptive capacity. The outcomes of this phase directed the empirical focus and methodological choices of the subsequent stages.

1.2.2. Phase II - Empirical Assessment: Case Studies

The second phase applies the conceptual insights to a comparative analysis of Iranian case studies, chosen for their cultural significance, typological diversity, and climatic variability. Iran provides a unique and relevant context: it contains one of the world's most extensive collections of earthen archaeological and architectural heritage, spanning prehistoric, Achaemenid, and Islamic periods, while also experiencing acute climate-related hazards such as droughts, floods, desertification, and heatwaves. These conditions make it an ideal living laboratory for examining climate-induced deterioration and testing adaptation responses.

Four representative case studies were selected including Sistan, Yazd, Persepolis, and Tchogha Zanbil. Each site was analysed using an integrated mixed-method approach, combining quantitative environmental data with qualitative heritage assessments. The empirical process included climate and environmental analysis such as review of meteorological data, satellite imagery, and local climate projections to determine exposure levels. Field documentation included observation and recording of deterioration patterns, erosion mechanisms, and conservation conditions. Stakeholder interviews and expert consultation embrace engagement with local site managers, conservation authorities, and community representatives to evaluate adaptive capacity and identify barriers to implementation. Vulnerability assessment included application of the IPCC-based model to assess each site's vulnerability, categorizing results from low to very high. Chapter 3 presents the results of this analysis, detailing the types of climate impacts affecting earthen heritage and their spatial distribution. Chapter 5 then interprets these results in the context of institutional, socio-economic, and technical barriers that hinder adaptation, thereby bridging scientific understanding with heritage management realities.

1.2.3. Phase III – Experimental and Practical Adaptation Strategies

The third phase translates the conceptual and analytical findings into practical conservation experiments focused on material resilience. Recognizing that the structural stability of earthen architecture depends heavily on its material composition, this phase investigates magnesium-based stabilization as a potential adaptive measure against erosion and moisture degradation. Laboratory experiments were conducted on adobe samples formulated with traditional soil, sand, and straw mixtures to reflect historical building techniques. Controlled additions of

magnesium oxide and Sorel cement in varying concentrations (5%, 10%, and 15% by weight) were used to assess their effects on performance. The samples underwent environmental simulation tests, including rainfall exposure, capillary absorption, and immersion experiments, to evaluate physical resistance, water absorption, and erosion rates.

1.2.4. Integration and Synthesis

Collectively, these three phases form a coherent methodological pathway, from understanding global concepts to testing practical interventions. The integration of theoretical review, empirical vulnerability analysis, and experimental adaptation enables a comprehensive evaluation of how climate change affects earthen archaeological sites and how their resilience can be strengthened. The final synthesis, presented in Chapter 7, unites these findings into a conceptual and operational framework for climate change risk management of earthen heritage. This framework contributes to both academic understanding and professional practice by offering an adaptable model applicable to similar heritage contexts worldwide.

By clarifying the rationale, scope, and structure of the study, this chapter sets the stage for the theoretical exploration that follows. The next chapter expands the conceptual background by situating cultural heritage within the broader discourse on climate change, identifying how climatic stressors interact with heritage values and materials.

References

Correia, M. R. A. R. (2016). Conservation in earthen heritage: Assessment and significance of failure, criteria, conservation theory, and strategies. *Cambridge Scholars Publishing*.

Daly, C., Fatorić, S., Carmichael, B., Pittungnapoo, W., Adetunji, O., Hollesen, J., Nakhaei, M., & Diaz, A. H. (2022). Climate change adaptation policy and planning for cultural heritage in low- and middle-income countries. *Antiquity*, *96*(390), 1427–1442. https://doi.org/10.15184/aqy.2022.114

Day, J. C., Heron, S. F., Markham, A., Downes, J., Gibson, J., Hyslop, E., Jones, R and Lyall, A. (2019). Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site.

Erdogan, B. G. (2022) A study on Risks of Earthen Architecture due to Climate Change. *Kerpic'22, Re-Thinking Earthen Architecture for Sustainable Development 9th International Conference, İstanbul, Turkey*, 30 June –3 July 2022.

Fatorić, S., & Biesbroek, R. (2020). Adapting cultural heritage to climate change impacts in the Netherlands: Barriers, interdependencies, and strategies for overcoming them. *Climatic Change*, *162*(2), 301–320. https://doi.org/10.1007/s10584-020-02831-1

Findlay, A. (2020). Conservation under climate change. *Nature Climate Change*, *10*(12), 1069-1069. https://doi.org/10.1038/s41558-020-00961-z.

Heron, S.F., Day, J.D., Mbogelah, M., Bugumba, R., Abraham, E., Sadi, M.B., Noah, P., Khamis, M.S., Madenge, S. and Megarry, W. (2022). Application of the Climate Vulnerability Index for the ruins of Kilwa Kisiwani and the ruins of Songo Mnara, Tanzania.

ICOMOS. (2019). The Future of Our Pasts: Engaging Cultural Heritage in Climate Action. Paris: ICOMOS.

Intergovernmental Panel on Climate Change (IPCC). (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press.* https://doi.org/10.1017/9781009325844

Jones, R. H., Davies, M. H., Day, J. C., & Heron, S. F. (2022). Developing Climate Risk Assessments for World Heritage: The Climate Vulnerability Index. *Internet Archaeology*, *60*.

Nakhaei, M., & Correia, M. (2020). *Water-risk management in Tchogha Zanbil World Heritage Site in Iran, with a focus on the Ancient Management System*. https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-683-2020

Oliver, Anne, Getty Adobe Project, Getty Conservation Institute, and Museum of New Mexico. 2000. *Fort Selden Adobe Test Wall Project: Phase I: Final Report*. Los Angeles, CA: Getty Conservation Institute. http://hdl.handle.net/10020/gci_pubs/fort_selden_project.

Phillips, H. (2015). The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. *Environmental Science and Policy*, *47*, 118–125. https://doi.org/10.1016/j.envsci.2014.11.003

Phillips, H. (2015). The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. *Environmental Science & Policy*, *47*, 118–125. https://doi.org/10.1016/j.envsci.2014.11.003

Richards, J., Bailey, R., Mayaud, J., Viles, H., Guo, Q., & Wang, X. (2020). Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty. *Scientific Reports*, *10*(1), 16419. https://doi.org/10.1038/s41598-020-73456-8

Richards, J., Guo, Q., Viles, H., Wang, Y., Zhang, B., & Zhang, H. (2022). Moisture content and material density affects severity of frost damage in earthen heritage. *Science of the Total Environment*, *819*, 153047.

Richards, J., Zhao, G., Zhang, H., & Viles, H. (2019). A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain. *Heritage Science*, *7*, 1-13.

Sesana, E., Gagnon, A. S., Bonazza, A., & Hughes, J. J. (2020). An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *Journal of Cultural Heritage*, *41*, 211–224. https://doi.org/10.1016/j.culher.2019.06.013

Sesana, E., Gagnon, A. S., Ciantelli, C., Cassar, J., & Hughes, J. J. (2021). Climate change impacts on cultural heritage: A literature review. *WIREs Climate Change*, *12*(4), e710. https://doi.org/10.1002/wcc.710

Sikka, S., Chaudhry, C., & Valletta, M. (2009, October). Climate change in western himalaya impacts, mitigation and adaptation of historic earthen structures. In *COMOS Scientific Symposium–Malta*.

Tawab, A. G. A. (2013). Evaluating the authenticity of earthen heritage: The case of Ramses Wissa Wassef art centre in Egypt. *Alexandria Engineering Journal*, *52*(3), 489-498.

Trizio, F., Garzón-Roca, J., Eguibar, M. Á., Bracchi, P., & Torrijo, F. J. (2022). Above the Ravines: Flood Vulnerability Assessment of Earthen Architectural Heritage in Quito (Ecuador). *Applied Sciences*, *12*(23), 11932.

United Nations Framework Convention on Climate Change (UNFCCC). (2015). Adoption of the Paris Agreement, 21st Conference of the Parties, Paris: United Nations.

United Nations Framework Convention on Climate Change (UNFCCC). (2023). Technical Paper on the Global Goal on Adaptation (GGA): Progress and Way Forward. *Bonn: UNFCCC Secretariat.*

Wang, X. D., Zhang, B., Pei, Q. Q., Guo, Q. L., Chen, W. W., & Li, F. J. (2020). Experimental studies on sacrificial layer in conservation of earthen sites. *Journal of Cultural Heritage*, *41*, 74-83.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2023). World Heritage and Climate Change: Updating of the Policy Document on climate action for World Heritage. Paris: UNESCO World Heritage Centre.

2. Chapter 2 - Climate change and cultural heritage

Building on the introductory framework, this chapter provides a theoretical and contextual overview of how climate change affects cultural heritage systems worldwide. It examines the range of climatic hazards, the mechanisms of impact, and the key international policy frameworks guiding heritage adaptation and risk management.

The relationship between climate change and cultural heritage has become an urgent field of inquiry, as heritage is both directly exposed to climatic hazards and deeply interlinked with the resilience of local communities. Scholarships increasingly emphasize the need for adaptation and risk management, yet evidence shows that current strategies remain fragmented and uneven. Research demonstrates that while hazard assessments and vulnerability models have advanced, much of the focus has been placed on stone heritage and European contexts, leaving earthen architecture and sites in Asia, Africa, and South America significantly underrepresented.

Earthen heritage exhibits acute vulnerability to fluctuations in humidity, precipitation, wind, and temperature. Case studies from Turkey, China, Egypt, and the Western Himalaya demonstrate how climatic stressors accelerate erosion, cracking, and frost damage, with research increasingly pointing to the necessity of integrating both scientific innovation and traditional knowledge in adaptation planning. At the same time, studies of World Heritage properties reveal that conventional management frameworks are insufficient to safeguard Outstanding Universal Value under projected climate scenarios, with high-resolution modeling indicating a sharp increase in damage by the end of the century.

The World Heritage Convention provides a critical legal and institutional framework, obligating States Parties to integrate mitigation and adaptation strategies into management processes. However, implementation challenges persist, including the need for better alignment with international climate agreements and the development of tools for site-specific vulnerability assessment. A growing body of scholarship highlights the crucial role of intangible heritage and traditional practices in adaptation, as they contribute to both conservation effectiveness and community resilience.

The literature highlights significant progress in hazard and vulnerability assessment while identifying persistent gaps in systematic adaptation planning, especially for earthen heritage.

Addressing these gaps requires interdisciplinary collaboration, integration of traditional knowledge, and the development of innovative conservation practices capable of responding to the escalating impacts of climate change on cultural heritage.

2.1. Climate change and cultural heritage: an overview

The relationship between climate change and cultural heritage has been widely recognized in recent decades, with scholars emphasizing the urgency of adaptation and risk management. Cultural heritage is not only exposed to climate-related hazards but also deeply interconnected with the resilience of local communities. For instance, Nakhaei (2022b) highlights that in Iran, World Heritage Sites (WHS) play a crucial role in enhancing local community resilience to environmental change, while at the same time, the degree of climate change exposure is heavily influenced by the vulnerability of these surrounding communities. At a global level, Sesana et al. (2021) carried out a systematic assessment of climate change impacts on tangible heritage by developing hazard-impact diagrams from international literature. Their findings revealed that most studies rely on only one scenario and one climate model, neglecting the inherent uncertainties of climate projections. They further argue that hotter and drier climates will accelerate desertification, posing greater risks to cultural heritage, and call for more research in underrepresented regions such as Asia, Africa, and Central and South America. Complementary to this, Sesana et al. (2020) proposed an integrated vulnerability assessment methodology, allowing interventions to be more precisely targeted to protect and strengthen heritage resilience. Several scholars have also addressed the challenges of adaptive capacity and policy frameworks. Phillips (2015) warns that adaptive measures, while necessary, can sometimes compromise heritage significance, calling for more balanced approaches. Dastgerdi et al. (2019) argue that cultural heritage remains a neglected factor in climate-resilient policies, despite both its tangible and intangible attributes being directly and indirectly impacted by climate change. Meanwhile, the ICOMOS Climate Change and Cultural Heritage Working Group (CCHWG, 2019) stresses the importance of integrating traditional knowledge into adaptation strategies, asserting that local adaptation practices can inform innovative management approaches for both movable and immovable heritage.

2.2. Climate change and earthen heritage

Among the most vulnerable cultural heritage materials, earthen architecture stands out due to its sensitivity to climatic conditions such as humidity, wind, and precipitation. Erdogan (2022),

focusing on Turkey, identifies atmospheric humidity, temperature changes, desertification, and wind as the major parameters threatening earthen heritage. In the Western Himalaya, Sikka et al. (2009) observed that changing climatic conditions necessitate modifications to traditional building materials to enhance moisture resistance, reflecting a broader need to integrate adaptation into vernacular traditions. The vulnerability of earthen heritage to wind and moisture is further illustrated by research at Suoyang, China, where Findlay (2020) found that increased wind speed significantly heightens deterioration risks, underscoring the need for collaborations between climate and heritage scientists. Richards et al. (2020) employed cellular automaton models to simulate deterioration processes over a 100-year horizon, demonstrating the challenges of addressing conservation considering uncertainties in climate projections. Expanding on this, Richards et al. (2022) showed that higher-density earthen materials in dryland environments could be more vulnerable to frost damage than lower-density equivalents, highlighting the complex interactions between material properties and environmental stressors. In Egypt, Tawab (2013) evaluated authenticity attributes of earthen heritage and concluded that non-material values often contribute more to perceptions of authenticity than the material itself, raising critical questions about conservation priorities under climate stress. Shao et al. (2022), drawing on the Chinese principle of "water and earth," emphasized the value of traditional ecological knowledge, advocating its integration into modern adaptation frameworks as a means of ensuring sustainable conservation practices while strengthening local cultural ties.

2.3. Climate change and World Heritage properties

World Heritage properties face particularly acute risks under climate change, with research showing that traditional management frameworks are insufficient to address the scale of threats. Weber et al. (2021) found that in Northern Queensland, climate change threatens Outstanding Universal Value (OUV), while conventional regulatory tools fail to mitigate risks effectively. This aligns with Khalaf (2021), who argues that conservation assessment standards must be rethought considering escalating threats, proposing to treat heritage as evolving "processes" rather than fixed "things." Day et al. (2019) tested the Climate Vulnerability Index (CVI) in Scotland, concluding that hazards are expected to persist and intensify, while Phillips (2014) observed that vulnerability assessments, climate impact monitoring, and adaptation planning have yet to be systematically applied across most UK WHSs. Daly (2014) further highlights methodological issues, questioning what to monitor, how to monitor, and how to

interpret collected data. Similarly, Guzman et al. (2020) promote a landscape-based approach for conserving OUV, recognizing the importance of managing broader environmental contexts under climate uncertainty. O'Neill et al. (2022), applying high-resolution climate models in Edinburgh, project a three- to fourfold increase in annual damage to cultural properties by the end of the 21st century due to extreme weather events. Meanwhile, Lafrenz and Platts (2020) underscore the communicative power of heritage in mobilizing stakeholders for climate action, emphasizing the role of WHSs in shaping climate discourse.

2.4. The World Heritage Convention and climate change

The World Heritage Convention provides a critical legal framework for protecting WHSs under climate threats. Huggins (2007) argues that the Convention imposes strong obligations on States Parties, including commitments to significant greenhouse gas mitigation strategies. Similarly, Thorson (2007) stresses that States Parties are obliged to adopt aggressive climate-change mitigation strategies to ensure the safeguarding of WHSs. UNESCO (2017), through Decision 41 COM 7, explicitly requested the World Heritage Centre and Advisory Bodies to prioritize building climate resilience within the limits of available resources. Shearing (2008) emphasizes the necessity of aligning the Convention's mechanisms with broader international climate agreements to address shared risks, while Gruber (2011) notes that effective adaptation requires integrated application of environmental law across scales. These perspectives highlight both the strengths and limitations of the Convention in delivering climate resilience for heritage.

2.5. Hazard and vulnerability assessment in earthen heritage

Hazard and vulnerability assessment methodologies are central to evaluating risks to earthen heritage. Nakhaei (2022a), in a study on Persepolis, advocates for low-cost early warning systems as essential tools for hazard detection and future risk reduction. Richards et al. (2019) developed portable wind and rain erosion simulation devices for the Suoyang Ancient City, finding that wind plays a key role in accelerating deterioration. Similarly, Trizio et al. (2022), studying Quito's Historic Centre, demonstrated that intrinsic vulnerabilities and visible weathering damages amplify risks of material loss. Other studies have emphasized the need for integrated frameworks. Beckett et al. (2020) proposed an assessment model based on water exposure routes, noting that durability rather than strength is the key factor in earthen deterioration. Hart et al. (2021), examining untreated adobe walls in the American Southwest,

stressed the need for managers to adapt strategies to account for increasingly frequent high-intensity rainfall.

2.6. Intangible cultural heritage, adaptation, and mitigation

The integration of intangible heritage and traditional knowledge is increasingly recognized as critical to adaptation. Crowley et al. (2022) criticize most current methods for failing to engage local community values and knowledge, while Carmichael et al. (2018, 2020) present methodologies for community-scale climate risk assessments that combine cultural value with hazard sensitivity and exposure. Sacko (2021), drawing from African contexts, highlights traditional methods in Djenné as valuable resources that could be revalorized to support contemporary conservation. Adaptation at the material level has also received attention. Oliver (2000), through the Getty Adobe Project, demonstrated the potential of protective coatings and wall treatments, while Wang et al. (2020, 2022) examined grouts and weather-resistant treatments for earthen materials in China, showing significant differences in environmental adaptability. Trizio et al. (2020), studying Alzira, argue that past knowledge of flood adaptation remains critical for developing modern measures. At a policy level, barriers to adaptation are significant. Fatorić and Biesbroek (2020) identified the lack of adaptation policies, vulnerability assessments, and risk assessment tools as major constraints, particularly in the Netherlands. Sesana et al. (2018) similarly emphasizes the need for more research to identify adaptation measures suitable for specific heritage types. Perry (2015) stresses that ecosystem-based adaptation is preferable under uncertainty, while Hemeda (2021) highlights the importance of short-term, cost-effective mitigation measures in Egypt.

2.7. Summary of Key Issues

This chapter has established the broader conceptual and contextual foundation for understanding the complex interactions between climate change and cultural heritage. It has shown that climate change is not only an environmental issue but also a cultural and social challenge that threatens the material fabric, authenticity, and meaning of heritage worldwide. The review demonstrated that heritage sites, both tangible and intangible, are increasingly exposed to diverse climatic hazards, including temperature fluctuations, flooding, droughts, and wind erosion, all of which accelerate decay processes and alter the environmental equilibrium that supports heritage stability. Special attention was given to earthen heritage, which represents one of the most vulnerable categories due to the sensitivity of its materials to

moisture variation, thermal stress, and erosive forces. The discussion highlighted that despite its global prevalence, particularly in arid and semi-arid regions, earthen heritage remains underrepresented in international climate adaptation frameworks. This gap underscores the urgent need for site-specific vulnerability assessments and adaptive conservation approaches that respect cultural significance while enhancing physical resilience. The chapter also examined the evolution of international policy responses, including the role of the World Heritage Convention and initiatives by UNESCO, ICOMOS, and the IPCC, which have gradually recognized the interdependence between heritage conservation and climate action. However, existing strategies often remain reactive rather than proactive, focusing on post-damage interventions instead of integrated risk reduction and long-term adaptation planning. This chapter also emphasized that effective climate risk management requires bridging the divide between scientific assessment and cultural values, integrating both tangible and intangible dimensions of heritage. Recognizing the adaptive potential embedded in traditional knowledge, community practices, and local building systems is essential for achieving resilience.

Building upon this conceptual background, the next chapter shifts the focus from global understanding to empirical analysis, exploring how climate change manifests in specific earthen heritage sites. It examines the physical impacts, observed vulnerabilities, and contextual factors influencing deterioration, laying the groundwork for the vulnerability assessment and adaptation framework developed later in the thesis.

References

Beckett, C. T. S., Jaquin, P. A., & Morel, J. C. (2020). Weathering the storm: A framework to assess the resistance of earthen structures to water damage. *Construction and Building Materials*, *242*, 118098.

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Brockwell, S., Webb, B., Hunter, F., & Bird, D. (2018). Local and Indigenous management of climate change risks to archaeological sites. *Mitigation and Adaptation Strategies for Global Change*, *23*, 231-255.

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Cahill, J., Brockwell, S., Webb, B., Bird, D., & Daly, C. (2020). A Methodology for the Assessment of Climate Change Adaptation Options for Cultural Heritage Sites. *Climate*, *8*(8), Article 8. https://doi.org/10.3390/cli8080088

Crowley, K., Jackson, R., O'Connell, S., Karunarthna, D., Anantasari, E., Retnowati, A., & Niemand, D. (2022). Cultural heritage and risk assessments: Gaps, challenges, and future research directions for the inclusion of heritage within climate change adaptation and disaster management. *Climate Resilience and Sustainability*, *1*(3), e45. https://doi.org/10.1002/cli2.45

Daly, C. (2014). A Framework for Assessing the Vulnerability of Archaeological Sites to Climate Change: Theory, Development, and Application. *Conservation and Management of Archaeological Sites*, *16*(3), 268–282. https://doi.org/10.1179/1350503315Z.00000000086

Dastgerdi, A. S., Sargolini, M., & Pierantoni, I. (2019). Climate change challenges to existing cultural heritage policy. *Sustainability*, *11*(19), 5227.

Day, J. C., Heron, S. F., Markham, A., Downes, J., Gibson, J., Hyslop, E., Jones, R and Lyall, A. (2019). Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site.

Erdogan, B. G. (2022) A study on Risks of Earthen Architecture due to Climate Change. *Kerpic'22, Re-Thinking Earthen Architecture for Sustainable Development 9th International Conference, İstanbul Turkey*, 30 June –3 July/2022.

Fatorić, S., & Biesbroek, R. (2020). Adapting cultural heritage to climate change impacts in the Netherlands: Barriers, interdependencies, and strategies for overcoming them. *Climatic Change*, *162*(2), 301–320. https://doi.org/10.1007/s10584-020-02831-1

Findlay, A. (2020). Conservation under climate change. *Nature Climate Change*, *10*(12), 1069-1069. https://doi.org/10.1038/s41558-020-00961-z.

Gruber, S. (2011). The Impact of Climate Change on Cultural Heritage Sites: Environmental Law and Adaptation Thematic Focus: Climate Change Governance - The International Regime Complex. *Carbon & Climate Law Review*, *2011*(2), 209–219.

Guzman, P., Fatorić, S., & Ishizawa, M. (2020). Monitoring climate change in world heritage properties: evaluating landscape-based approach in the state of conservation system. *Climate*, *8*(3), 39.

Hart, S., Raymond, K., Williams, C. J., Johnson, J., DeGayner, J., & Guebard, M. C. (2021). Precipitation impacts on earthen architecture for better implementation of cultural resource management in the US Southwest. *Heritage Science*, *9*, 1-18.

Hemeda, S. (2021). Geotechnical modelling of the climate change impact on world heritage properties in Alexandria, Egypt. *Heritage Science*, *9*(1), 1-32.

Huggins, A. (2007). What Obligations Do States Parties to the World Heritage Convention Have to Protect World Heritage Sites from the Adverse Impacts of Climate Change?. *Australian International Law Journal*, *14*, 121-136.

ICOMOS, CCHWG. (2019). The future of our past: engaging cultural heritage in climate action. *Outline of Climate Change and Cultural Heritage, Paris, France*.

Khalaf, R. W. (2021). A proposal to operationalise the concept of compatibility in World Heritage Climate Change Policy. *The Historic Environment: Policy & Practice*, *12*(3-4), 313-335.

Lafrenz Samuels, K., & Platts, E. J. (2020). An ecolabel for the world heritage brand? Developing a climate communication recognition scheme for heritage sites. *Climate*, *8*(3), 38.

Nakhaei, M. (2022a). Disaster Risk Management of Persepolis World Heritage Site (Multi-hazard and place approach). *Institute of Disaster Mitigation for Urban Cultural Heritage, Ritsumeikan University*. ITC 2022, 16th year.

Nakhaei, M. (2022b). Community Engagement as a Tool for Managing Climate Change Risks: Challenges and Problems. Climate, Culture and Peace conference, case studies, 24 - 28 January 2022.

Oliver, Anne, Getty Adobe Project, Getty Conservation Institute, and Museum of New Mexico. 2000. *Fort Selden Adobe Test Wall Project: Phase I: Final Report*. Los Angeles, CA: Getty Conservation Institute. http://hdl.handle.net/10020/gci_pubs/fort_selden_project.

O'Neill, S., Tett, S. F., & Donovan, K. (2022). Extreme rainfall risk and climate change impact assessment for Edinburgh World Heritage sites. *Weather and Climate Extremes*, *38*, 100514.

Perry, J. (2015). Climate change adaptation in the world's best places: A wicked problem in need of immediate attention. *Landscape and Urban Planning*, *133*, 1–11. https://doi.org/10.1016/j.landurbplan.2014.08.013

Phillips, H. (2014). Adaptation to Climate Change at UK World Heritage Sites: Progress and Challenges. *The Historic Environment: Policy & Practice*, *5*(3), 288–299. https://doi.org/10.1179/1756750514Z.00000000062

Phillips, H. (2015). The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. *Environmental Science & Policy*, *47*, 118–125. https://doi.org/10.1016/j.envsci.2014.11.003

Richards, J., Bailey, R., Mayaud, J., Viles, H., Guo, Q., & Wang, X. (2020). Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty. *Scientific Reports*, *10*(1), 16419. https://doi.org/10.1038/s41598-020-73456-8

Richards, J., Guo, Q., Viles, H., Wang, Y., Zhang, B., & Zhang, H. (2022). Moisture content and material density affects severity of frost damage in earthen heritage. *Science of the Total Environment*, *819*, 153047.

Richards, J., Zhao, G., Zhang, H., & Viles, H. (2019). A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain. *Heritage Science*, *7*, 1-13.

Sacko, O. (2021). The involvement of local communities in the conservation process of earthen architecture in the Sahel-Sahara region–the case of Djenné, Mali. *Built Heritage*, *5*(1), 1-20.

Sesana, E., Gagnon, A. S., Bertolin, C., & Hughes, J. (2018). Adapting Cultural Heritage to Climate Change Risks: Perspectives of Cultural Heritage Experts in Europe. *Geosciences*, *8*(8), Article 8. https://doi.org/10.3390/geosciences8080305

Sesana, E., Gagnon, A. S., Bonazza, A., & Hughes, J. J. (2020). An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *Journal of Cultural Heritage*, *41*, 211–224. https://doi.org/10.1016/j.culher.2019.06.013

Sesana, E., Gagnon, A. S., Ciantelli, C., Cassar, J., & Hughes, J. J. (2021). Climate change impacts on cultural heritage: A literature review. *WIREs Climate Change*, *12*(4), e710. https://doi.org/10.1002/wcc.710

Shao, Y., Chen, Y., & Su, J. (2022). Understanding of the settlements with coexisting water and earth under the background of climate change—the case of Liang Village in Pingyao County, China. *Built Heritage*, *6*(1), 1-20.

Shearing, S. (2008). Here today, gone tomorrow? Climate change and world heritage. *Australasian Journal of Natural Resources Law and Policy*, *12*(2), 161-200.

Sikka, S., Chaudhry, C., & Valletta, M. (2009). Climate change in western himalaya impacts, mitigation and adaptation of historic earthen structures. In COMOS Scientific Symposium–Malta.

Tawab, A. G. A. (2013). Evaluating the authenticity of earthen heritage: The case of Ramses Wissa Wassef art centre in Egypt. *Alexandria Engineering Journal*, *52*(3), 489-498.

Thorson, E. J. (2007). The World Heritage Convention & climate change: the case for climate-change mitigation strategy beyond the Kyoto Protocol.

Trizio, F., Garzón-Roca, J., Eguibar, M. Á., Bracchi, P., & Torrijo, F. J. (2022). Above the Ravines: Flood Vulnerability Assessment of Earthen Architectural Heritage in Quito (Ecuador). *Applied Sciences*, *12*(23), 11932.

Trizio, F., Mileto, C., Torrijo, F. J., & Lidón de-Miguel, M. (2020). Preliminary analysis of earthen architecture response to floods: The case of Alzira (Spain). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (Online)*, *44*, 713-717.

UNESCO. (2018). Convention concerning the protection of the World Cultural and Natural Heritage World Heritage Committee. Forty-second session. Manama, bahrain. 24 june – 4 july 2018.

Wang, X. D., Zhang, B., Pei, Q. Q., Guo, Q. L., Chen, W. W., & Li, F. J. (2020). Experimental studies on sacrificial layer in conservation of earthen sites. *Journal of Cultural Heritage*, *41*, 74-83.

Wang, X., Zhang, B., Guo, Q., & Pei, Q. (2022). Discussion on the environmental adaptability of weather-resistant measures for earthen sites in China. *Built Heritage*, *6*(1), 1-13.

Weber, E. T., Catterall, C. P., Locke, J., Ota, L. S., Prideaux, B., Shirreffs, L., Talbot, L., & Gordon, I. J. (2021). Managing a World Heritage Site in the Face of Climate Change: A Case Study of the Wet Tropics in Northern Queensland. *Earth*, *2*(2), Article 2. https://doi.org/10.3390/earth2020015.

3. Chapter 3 - Impacts of climate change on earthen heritage

This chapter translates the general understanding of climate heritage interactions into the specific context of earthen archaeological sites. It investigates the physical and environmental processes, such as erosion, moisture fluctuations, temperature extremes, and wind abrasion, that threaten the integrity of earthen materials. The chapter also integrates findings from field observations and existing documentation of Iranian sites to characterize the nature and severity of these impacts.

Climate change poses a growing threat to the preservation of earthen heritage, requiring an integrated approach that considers its physical, social, and cultural dimensions. This article presents a comprehensive assessment to evaluate the impacts of climate change on earthen heritage sites in Iran. Earthen sites are particularly vulnerable to climate change due to their sensitivity to environmental conditions, cultural significance value threat, and age. Various features of earthen heritage are examined and used as a conceptual model to evaluate climate change hazards, vulnerability, impacts, and risks at four sites in Iran. Our findings indicate that climate change is expected to have significant consequences for these sites, including erosion, structural deterioration, as well as the loss of cultural landscape and value. The study emphasizes the need of interdisciplinary collaboration and the engagement of local communities in the safeguarding of earthen heritage when facing climate change. The proposed framework offers a valuable tool for heritage managers, policymakers, and researchers in comprehending and mitigating the impacts of climate change on earthen heritage.

3.1. Introduction

Earthen heritage is one of the most ancient and important expressions of human creativity. It can be traced in all continents and reveals the ability of communities to use local available materials in the surrounding built environment. Its cultural significance can be observed throughout history in archaeological sites, historical centres, religious dwellings, and cultural landscapes around the world.

The tangible and intangible values of this unique earthen heritage are at risk due to the impacts of climate change, requiring focused efforts to mitigate and adapt to these risks. Earthen heritage is vulnerable to the effects of climate change that increases the risk of extreme weather events and natural hazards, leading to both direct and indirect impacts on built structures, archaeology, and landscapes (Brimblecombe et al., 2011; Phillips, 2015; Nakhaei and Correia, 2020). The impact of climate change on cultural heritage has been widely reviewed in recent

years, encompassing various research methods and diverse disciplines for risk assessment, disaster risk reduction, and resilience. However, the majority of studies on climate change impacts have focused on stone monuments, with a relatively narrow geographic reach, mainly in Europe, China, North America, and Australia (Fatorić and Seekamp, 2017; Orr et al., 2021). In contrast, climate data has revealed a clear trend towards global warming, with many regions experiencing its impacts, particularly the Middle East (Asian Development Bank, 2017; Rahmasary et al., 2019; Vakulchuk et al., 2023). Furthermore, according to the WHEAP programme, in 2011, 10% of sites of the World Heritage List incorporated earthen structures (WHEAP at https://whc.unesco.org/en/earthen-architecture/) and 14% were inscribed on the World Heritage in Danger List (Correia, 2016).

The lack of research on climate change impacts in earthen architecture is a concerning reality. The most significant climate parameters believed to pose major threats to earthen dwellings include atmospheric humidity change, temperature change, cloudburst rain events, and wind (Gokmen Erdogan, 2022). These phenomena will potentially expose earthen heritage to a range of pressures, risks, conflicts, and disasters not experienced before. The need of existing climate risk assessment standards must be reassessed in light of this challenge (Khalaf, 2021; Weber et al., 2021). Moreover, climate change impacts are a threat to the authenticity and integrity of earthen World Heritage properties, as well as to their Outstanding Universal Value (OUV) attributes. Legislative protection, traditional regulations and management approaches are inadequate to address this threat (Khalaf, 2021; Weber et al., 2021). Decision 41 COM 7 emphasized the need of examining the repercussions of climate change, as well as formulating and executing climate adaptation strategies for properties, vulnerable to climate change (UNESCO WHC, 2017).

Iran, a country with mostly arid and semi-arid climates, has also experienced significant effects of climate changes that have been compounded by management-related issues. As a result, Iran has faced various climatic-related disasters, ranging from droughts to land subsidence, floods, and the shrinking of lakes and rivers (Vaghefi et al., 2019; IMF, 2023). The present study focuses on the assessment of climate change impacts in four earthen sites in different arid and semi-arid climates regions in Iran. Two of these are archaeological sites, namely Persepolis and Tchogha Zanbil, while the other two are living heritage sites, namely Sistan and Yazd. In the four case studies, the sites were built in adobe masonry and cob (Sadeghi, 2018; Askari Chaverdi et al., 2016; Sajjadi and Moradi, 2014; Garshasbi and Motamedinasab, 2013). Also relevant, is the fact that three of these four sites are listed as World Heritage properties.

The aim of this research is to understand how climate change can affect different forms of earthen heritage, including archaeological sites, historic monuments and vernacular architecture, which represent different aspects of cultural heritage in Iran. These sites are located in different climatic zones and have experienced different climate extremes, such as drought, heavy rainfall, and dust storms, providing a diverse set of case studies to evaluate the impacts of climate change on earthen heritage. Studying climate change impacts on earthen sites contributes to a broader scientific knowledge and understanding of climate change and its effects on cultural heritage.

3.2. Methodology

The methodology employed in this study adopts a systematic approach to assess the impacts of climate change on earthen heritage sites. To develop a comprehensive understanding of these impacts, a literature review was conducted to gather relevant information on climate change's effects on cultural heritage. This review served as the foundation for identifying key concepts, frameworks, and methodologies as a base for the development of a conceptual model. The methods used for evaluating hazards in the selected case studies focused on a combination of quantitative and qualitative assessments to identify and understand the risks posed by climate variability and extreme weather events to earthen heritage sites. The conceptual model encompasses several essential components, which were derived from the risk assessment guideline for cultural heritage (UNESCO et al. 2010, 2013), climate change impact and vulnerability (IPCC 2022), and applying the methodological approach identified through the literature review (e.g., Yıldırım Esen, S., & Bilgin Altınöz 2018, Valagussa et al. 2021, Cacciotti et al. 2024). The model used in this research involves the identification and analysis of climate change hazards and relevant climate variables specific to each earthen site under study. Data were analysed to assess patterns of climate variability, including precipitation, temperature changes, and extreme weather events. The specific hazards relevant to each site were identified based on local climate conditions. This step helps to understand the potential climatic risks faced by these sites. To evaluate the vulnerability of earthen heritage, a comprehensive vulnerability assessment was conducted, by considering multiple factors including:

- *Exposure* - The degree to which a site is exposed to climate change hazards;
- *Sensitivity* - The site’s susceptibility to these hazards based on its characteristics;
- *Adaptive capacity* - The ability of the site and local communities to adapt to and to mitigate the impacts of climate change (UNESCO et al. 2010; Cacciotti et all. 2024).

For evaluating the overall vulnerability, the formula used was:

$$Vulnerability = (Exposure \times Sensitivity) - Adaptive\ capacity$$

For each factor, three degrees were proposed such as High (=3), Medium (=2) and Low (=1). Following the formula, the overall vulnerability was categorized in five levels of Very High (=6 to 8), High (=4 to 6), Medium (=2 to 4), Low (=0 to 2) and Very Low (less than 0).

Direct field observations were conducted to examine the physical impacts of identified hazards on the sites. This included observing structural damage, erosion patterns, and environmental degradation caused by extreme weather events. Interviews and consultations with local experts, heritage managers, and community members provided qualitative insights into the hazards' impacts. The model also incorporates site-specific factors that play a crucial role in determining the impacts of climate change on earthen sites. These factors include site morphology, construction techniques, historical significance, and the socio-economic condition of the regions. The relationships and interactions between the various components of the model were established to highlight the influence of climate change hazards on vulnerability and subsequent impacts. This allowed for a comprehensive analysis of climate change impacts on each earthen site, estimating potential consequences such as erosion, structural damage, and loss of cultural significance. The data collection for this study involved multiple sources and methods, including meteorological data analysis, literature review, field observations, and oral interviews with local communities and site experts.

3.3. Climate change in the study areas

Iran has experienced significant impacts from global warming (Fig 3.1), leading to detrimental consequences for its rich earthen architectural heritage, characterized by ancient cities, historical sites, and traditional dwellings, particularly vulnerable to the adverse effects of climate change. Sistan, Yazd, Persepolis, and Tchogha Zanbil were chosen as specific sites for this study due to various considerations and factors. Firstly, these sites hold significant importance in the context of earthen heritage, with Tchogha Zanbil and Persepolis being archaeological sites that highlight remarkable historical earthen architecture and provide valuable insights into ancient civilizations. On the other hand, Sistan represents vernacular heritage characterized by traditional earthen construction building cultures, while Yazd is an earthen city renowned for its unique urban fabric and architectural heritage. The study focuses on a selection of diverse sites to gain a comprehensive understanding of how climate change

affects different forms of earthen heritage (Fig 3.2). Each site experiences unique climatic events and hazards, which allows for a thorough analysis of the impacts of climate change.

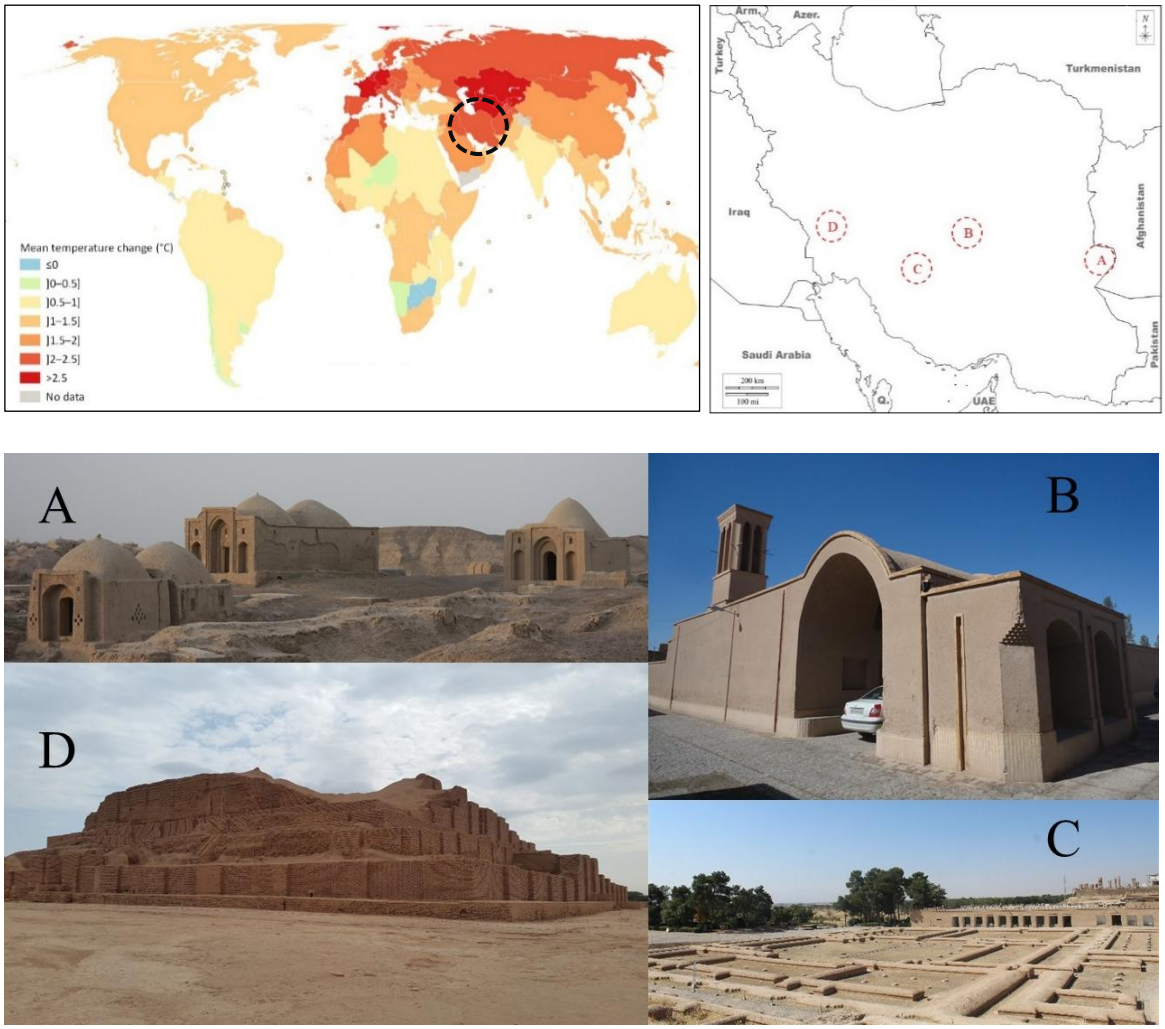


Fig 3.1: The status of Iran in relation to climate change on a global scale (Source: FAO, 2023)

Fig 3.2: Location of study areas (A) Sistan, (B) Yazd, (C) Persepolis, (D) Tchogha Zanbil (Source: Authors' owns work).

3.3.1. Sistan

The Sistan region in southeastern Iran (A in Fig 3.1) is known for its historical use of earthen construction and its population concentration around the Hamoun Lake and delta wetlands of the Hirmand River. The region is home to remarkable ancient sites like Shahr-i Sokhta WHS and Kuh-e Khwaja archaeological site, which hold great archaeological importance (Sajjadi and Moradi, 2014). Agriculture is the primary occupation (Sharifikia, 2013), and the inhabitants live in dome-shaped adobe houses that harmonize with the natural surroundings (Fig 3.3). Notably, the region features ancient wind catchers known as Asbads, highlighting the

ingenuity of the local population in adapting to the prevailing winds and limited water resources.

The region experiences low annual rainfall (Karimi and Ataei, 2022), and climate change together with the obstruction of the Hirmand River by Afghanistan has led to prolonged drought and the drying up of the Hamoun lakes, resulting in dust storms (Sharifikia, 2013). The Levar wind, a notable atmospheric phenomenon, contributes to dust activation (Rami et al., 2022; Rashki et al., 2015). The severe drought and reduced precipitation have caused the lakes to shrink, making the exposed silt and clay material susceptible to erosion and facilitating frequent dust storms (Maleki et al., 2018; Miri et al., 2021). The average annual wind speed in the Sistan region has been increasing by approximately 4.7 meters per second from 1989 to the end of 2018 (Hosseini and Jafarizadeh, 2023).

Fig 3.3: Abandoned earthen heritage in Sistan (Source: Authors' own work)

3.3.2. Yazd

The historic city of Yazd (B in Fig 3.1) exemplifies a traditional human settlement that has adapted to the harsh desert environment through an intricate system of earthen architecture and the clever management of scarce resources such as water, through the Qanat system (Bolouhari et al., 2020). Yazd's buildings (B in Fig. 3.2) are predominantly made of adobe, including walls and roofs built with vaults and domes (Sadeghi, 2018). In contrast with the too many traditional earthen cities destroyed by modernization trends, Yazd has retained its traditional districts (Fig 3.4), the Qanat system, the traditional houses, the bazars, the water cisterns, and the historic gardens (WHC, 2018).

This region has a warm and arid climate with low average annual rainfall and high temperatures (Dargahian et al., 2021). The region is predominantly affected by strong northwest winds carrying abrasive particles (Ebrahimikhusfi and Dargahian, 2018). Over the years, there has

been a decreasing trend in annual precipitation, with a more significant decline in the last decade. The winter season receives the highest amount of rainfall, followed by spring and autumn, while summer has very minimal precipitation (Shirgholami and Masoodian, 2023). This decreasing precipitation trend, coupled with increased evapotranspiration, has led to an increase in drought occurrences since 1966 (Zarch and Amin, 2017).

Fig 3.4: Earthen heritage in Yazd (Source: Courtesy of Mohammad Hosseini, 2023)

3.3.3. Persepolis

Situated in southwestern Iran (C in Fig 3.1), Persepolis was the ceremonial capital of the Achaemenid Empire. Featuring impressive ruins (C in Fig 3.2) that dominate the surrounding fertile landscape (Aminzadeh and Samani, 2006), Persepolis was built on an artificial terrace. Founded by Darius in 518 B.C (Mousavi, 2012), the city had adobe walls, stone for vertical elements like columns (Fig 3.5), and wood for horizontal load-bearing components (Askari Chaverdi et al., 2016). Recognized as a UNESCO World Heritage Site in 1979, Persepolis is a witness to the cultural traditions of a vanished civilization and has significantly influenced ancient artistic and architectural styles (WHC, 2012).

This area is renowned for its wide-ranging climates, which span from arid and cold to semi-arid and moderate (Javadinejad et al., 2020). Nevertheless, recent shifts in climate patterns have resulted in a reduction in yearly rainfall by 10mm, coupled with a rise in average annual temperature by 1°C and evaporation by 230mm (Mozafari, 2022; Hematian et al., 2019). The agricultural sector, the main economic activity, has been severely impacted by the drought, leading to land abandonment and a shift towards less water-intensive crops (Ghazali et al., 2021). This has resulted in decreased agricultural productivity and income (Khalili et al., 2021). Additionally, water scarcity has caused rivers and water sources to dry up, further impacting the natural environment and the site's landscape (Heydari and Jabbari, 2022).

Fig 3.5: Remains of ancient earthen walls in Persepolis (Source: Authors' own work)

3.3.4. Tchogha Zanbil

Tchogha Zanbil, also known as Dur-Untash, is an ancient site situated in the southwestern region of Iran (D in Fig 3.1). It was built during the 13th century BCE under the patronage of King Untash-Napirisha to serve as a place of worship for Inshushinak, a prominent deity during the Elamite era (Neghahban, 1994). The complex consisted of a towering ziggurat made primarily of adobe (D in Fig 3.2), adorned with baked bricks and cuneiform inscriptions (Garshasbi and Motamedinasab, 2013). Although it originally stood at 53 meters, only 24.75 meters of the ziggurat remain intact today (Ghirshman, 1966) (Fig 3.6). Today, Tchogha Zanbil is a UNESCO World Heritage site, offering insights into Elamite engineering, architecture, and religious practices (Hosseini et al., 2020; Niroumand et al., 2012).

The region has a semi-arid to arid climate with low precipitation and high evaporation rates. It faces frequent high-intensity rainfall in short periods, leading to destructive flash floods, especially in the summer (Nakhaei and Correia, 2020). Climate change has amplified the frequency and intensity of heavy rainfall and flash floods. This trend is expected to continue, resulting in more frequent and severe flooding events (Malekshahi and Farhadpoor, 2014). In addition to the increased frequency of dust storms, the region is also witnessing more frequent and intense heat waves (MalAmiri et al., 2022). Long-term meteorological data indicates that for the future, the region is likely to continue with encounter severe heatwaves, but also droughts, and floods (Eskandari Damaneh et al., 2021; Masoudi and Elhaeesahar, 2016).

Fig 3.6: Aerial photo of Tchogha Zanbil (Source: Authors' own work)

3.4. Results

3.4.1. Climate change hazards & Climate variables

The concept of hazard refers to potential sources or events that pose a risk to earthen sites because of climate variability and extreme weather events (Ravankhah et al., 2019). The hazard assessment helps to identify and evaluate these potential risks and their consequences for the earthen heritage (Bosher et al., 2019). The hazard assessments conducted for the four case studies (Table 3.1) have revealed the substantial risks that climate variability and extreme weather events pose to earthen sites.

Table 3.1: Hazard assessment of representative earthen sites in arid and semi-arid regions (Source: Authors' own work)

Case Study	**Hazard Assessment**
Sistan	Prolonged hydrological and meteorological drought (Karimi and Ataei, 2022).
	Severe soil erosion and frequent dust storms (Sharifikia, 2013).
	Economic losses and respiratory diseases due to dust storms (Maleki et al., 2018; Miri et al., 2021).
	Migration from the region due to environmental hazards (Hosseini and Jafarizadeh, 2023).
Yazd	Decreasing trend in precipitation and increasing potential for evapotranspiration (Zarch and Amin, 2017).
	Drought occurrence and increasing risk of droughts (Dargahian et al., 2021).
	Flash floods caused by heavy precipitation (Shirgholami and Masoodian, 2023).

	Unprincipled city development (Sharif et al., 2023).
Persepolis	Droughts and rising temperatures (Javadinejad et al., 2020).
	Soil erosion and degradation (Heydari and Jabbari, 2022).
	Reduced agricultural productivity and income of locals (Khalili et al., 2021).
	Land subsidence and water scarcity (Mirassi et al., 2013).
Tchogha Zanbil	High-intensity rainfall (Nakhaei and Correia, 2020).
	Increased frequency and intensity of dust storms (Dargahian et al., 2023).
	Increased frequency and intensity of heatwaves (MalAmiri et al., 2022).
	Extreme weather events (Malekshahi and Farhadpoor, 2014).

3.4.2. Vulnerability assessment

The concept of vulnerability refers to the susceptibility of a system or entity to harm, damage, or negative impacts (Shah et al., 2023). In the context of climate change, vulnerability encompasses the degree to which a particular system or site is likely to be affected by climate-related hazards and the capacity of that system or site to cope with and recover from those impacts (ICOMOS, CCHWG, 2019). The vulnerability assessment of earthen heritage sites in Sistan, Yazd, Persepolis, and Tchogha Zanbil employed a comprehensive approach combining sensitivity analysis of materials, exposure assessment using climate data, the evaluation of adaptive capacity through infrastructure, and management practices. Community engagement and expert consultations provided qualitative insights into local and regional contextual factors. An integrated vulnerability framework was developed, highlighting the unique vulnerabilities of each site, influenced by specific climate conditions, cultural significance, and socioeconomic characteristics. On this research, the selected case studies include adobe structures demonstrating that despite their apparent similarities to each other, each of these examples exhibits different vulnerabilities that are determined by the local climate and socio-economic characteristics of the region (Table 3.2). Although the earthen material used in these structures appears to demonstrate a similar level of sensitivity, it should be noted that their vulnerability is not solely related to their inherent sensitivity, but rather, to various other factors at local and regional scale which contribute to the susceptibility of these sites.

Table 3.2: Vulnerability assessment of case studies to the impacts of climate change (Source: Authors' own work)

Case study site	Exposure to climate change	Sensitivity to climate change	Adaptive capacity	Overall vulnerability
Sistan	High exposure to droughts, heatwaves, and dust storms (Miri et al., 2021; Shiravand and Bayat, 2023)	Highly sensitive due to impact on water resources, agriculture, and instability of ancient sites (Karimi and Ataei, 2022; Sardar Shahraki et al., 2020)	Low adaptive capacity, need for significant improvements in infrastructure and adaptation strategies	Very High
Yazd	High exposure to flash floods and, heatwaves (Shirgholami and Masoodian, 2023)	Moderately sensitive due to the historical context and pressures of modernization (Sharif et al., 2023)	Moderate adaptive capacity, need for improved disaster risk management and adaptation strategies	Moderate
Persepolis	High exposure to droughts, rising temperatures, and extreme weather events (Javadinejad et al., 2020)	Highly sensitive due to impact on cultural heritage and agricultural sector (Khalili et al., 2021)	Moderate adaptive capacity, need for improved water management in the region and adaptation strategies	High
Tchogha Zanbil	High exposure to heavy precipitation,	Highly sensitive due to ancient structures'	Moderate adaptive capacity due to the existence of ancient	High

	floods, and dust storms (Nakhaei and Correia, 2021; Dargahian et al., 2023)	fragility Masoudi and Elhaeesahar, 2016)	knowledge, need for improved adaptation strategies	

3.4.3. Climate change impacts

Climate change, defined as long-term alterations in climatic patterns spanning at least a decade (IPCC, 2022), exerts a detrimental influence on earthen heritage. However, the wide complexity of climate change impacts on each site, even within a particular climatic zone, varies depending on the severity and type of hazard, as well as the level of sensitivity and exposure of each site. Therefore, climate change impacts differ from site to site, and is assessed based on site specific characteristics (Table 3.3). The assessment of climate change impacts on the four earthen heritage sites was conducted using Site-Specific Climate Data Analysis and Field Observations. The evaluation ranges were determined by assessing the intensity (how strong the impact is), frequency (how often the impact occurs), and severity (the extent of the damage or disruption caused by the impact) of climate change effects at each site. The combination of these factors for each specific hazard led to the categorization of the impacts as "high," "moderate," or other appropriate levels.

Table 3.3: Assessment of climate change impacts in the 4 case studies (Source: Authors' own work)

Case study	Impact	Description	Severity
Sistan	Drought and Water Resources	Severe and prolonged drought due to reduced precipitation and obstruction of water flow from Afghanistan; Drying up of Hamoun lakes and its impact on the ecosystem and livelihood of the locals (Karimi and Ataei, 2022; Sardar Shahraki et al., 2020).	High
	Wind and dust Storms	Frequent and severe dust storms caused by strong winds and soil erosion; Increasing intensity of the Levar wind and its impact on the ecosystem and locals' health (Miri et al., 2021).	High

	Cultural heritage impact	Deterioration of earthen archaeological sites due to sandstorms and wind erosion (Kaskaoutis et al., 2019).	High
	Socio-Economic Impact	Large-scale rural migration due to economic losses and environmental hazards; Loss of traditional knowledge related to the conservation and restoration of earthen sites (Hosseini and Jafarizadeh, 2023).	High
Yazd	Temperature and water resources	High temperature fluctuations, hot and dry climate; decreasing trend, increasing potential for drought and water scarcity (Shirgholami and Masoodian, 2023).	Moderate (Temperature), High (Precipitation)
	Wind and evaporation	Dominant wind carrying abrasive particles, impacting health and contributing to migration; physical and chemical damage to heritage buildings due to high evapotranspiration (Zarch and Amin, 2017).	Moderate (Wind), High (Evapotranspiration)
	Flooding and Infrastructure	Flooding causing significant damage to safety in traditional districts, infrastructure, and financial problems (Sharif et al., 2023).	High
	Cultural Heritage	Damage to build heritage due to heavy precipitation and inadequate city development (Sharif et al., 2023).	High
Persepolis	Temperature and precipitation	Rising temperatures exacerbating hot summers and cool winters, impacting the stability of archaeological structures; droughts affecting the agricultural sector and natural environment, leading to land subsidence and instability of heritage buildings (Javadinejad et al., 2020).	Moderate (Temperature), High (Precipitation)
	Natural Environment	Deforestation, land-use changes, and agriculture leading to soil erosion and degradation; drying up of nearby rivers affecting the landscape and natural environment (Khalili et al., 2021).	Moderate
	Cultural Heritage	The impacts of climate change, particularly droughts and rising temperatures, are affecting the stability of the archaeological structures at Persepolis, causing damage and instability (Mirassi et al., 2013).	Moderate

	Socio-Economic Impacts	Economic impacts due to the drought significantly reducing productivity and income for farmers, affecting the regional economy (Javadinejad et al., 2020).	High
Tchogha Zanbil	Flooding and water resources	High-intensity rainfall during summer causing flash floods, increased frequency and severity of floods due to climate change (Nakhaei and Correia, 2021).	High
	Wind and dust Storms	More frequent and intense dust storms causing damage to ancient structures (Dargahian et al., 2023).	Moderate
	Temperature and heat Waves	Increased frequency and intensity of heat waves, making the region highly vulnerable to extreme weather events (Dargahian et al., 2023).	High
	Droughts and cultural heritage	More frequent and severe droughts expected, impacting the livelihood of locals and the heritage value of the region (Masoudi and Elhaeesahar, 2016).	Moderate (Droughts), High (Heritage value)

3.5. Discussion

Climate change is having a multifaceted and varied impact on earthen heritage, which is especially vulnerable due to its distinctive features (Nakhaei, 2020). These sites are frequently situated in areas with specific climatic conditions, such as arid or semi-arid regions, where changes in precipitation patterns, extreme weather events, and rising temperatures can significantly impact their stability, integrity, and overall preservation (Richards et al., 2020; Nakhaei and Correia, 2021). Furthermore, socio-economic factors, such as limited resources for conservation and inadequate communication between stakeholders, can exacerbate the vulnerability of heritage sites (Bushozi, 2014). Accordingly, indirect elements play a significant role in increasing the susceptibility of these sites to damage. The studied regions known as climate change hotspots, face a variety of climate-related challenges, including rising temperatures, changing precipitation patterns, a growing frequency of extreme weather events, and water scarcity (Motamedi et al., 2023). The detrimental consequences of climate change pose a direct and indirect threat to the structural integrity, material preservation, and cultural significance of the studied earthen sites, as it is the case of Sistan, Yazd, Persepolis and Tchogha Zanbil.

3.5.1. Comparative vulnerability assessment in the studied sites

The vulnerability assessment of the four case study sites provides a detailed understanding of how each location is uniquely affected by climate change. Each site exhibits distinct combinations of exposure, sensitivity and adaptive capacity, which together determine their overall vulnerability.

3.5.1.1. Exposure and sensitivity

Sistan and Tchogha Zanbil both face high exposure to extreme weather events, but the nature of these exposures differs significantly. Sistan is primarily challenged by droughts, heatwaves, and dust storms, which directly affect water resources, agriculture and the stability of ancient sites. In contrast, Tchogha Zanbil is highly exposed to heavy precipitation and floods, which pose a severe risk to its fragile ancient structures. This distinction is crucial, as it highlights that while both sites are highly exposed, the specific climate risks they face are quite different in nature, necessitating tailored adaptive strategies.

Persepolis shares a high exposure to droughts and rising temperatures like Sistan but is also sensitive to extreme weather events, which threaten its cultural heritage and agricultural sector. Yazd, on the other hand, is exposed to flash floods and heatwaves but has a lower sensitivity due to its historical context and ongoing modernization efforts. This suggests that Yazd's vulnerabilities are somewhat mitigated by its more developed urban infrastructure compared to the rural and more isolated settings of Sistan and Tchogha Zanbil.

3.5.1.2. Adaptive capacity and vulnerability:

Sistan exhibits very high vulnerability due to its low adaptive capacity, inadequate infrastructure, and socio-economic challenges, including migration. Yazd and Persepolis have moderate adaptive capacities but differ in vulnerability; Yazd faces moderate vulnerability, while Persepolis has high vulnerability due to cultural and agricultural impacts. Tchogha Zanbil also has high vulnerability due to its fragile structures and moderate adaptive capacity. The assessment highlights the diverse impacts of climate change on these sites and stresses the need for improved adaptive capacity, the preservation of traditional knowledge, and tailored, site-specific strategies integrating both modern and ancient practices.

3.5.1.3. Impacts in the studied sites

Sistan faces significant challenges impacting its cultural heritage, health, and ecosystem. Severe drought, exacerbated by reduced precipitation and restricted water flow from

Afghanistan, has led to the drying of the Hamoun lakes (Karimi and Ataei, 2022; Sardar Shahraki et al., 2020). Intensifying Levar winds cause dust storms, leading to soil erosion and threatening earthen archaeological sites (Miri et al., 2021). The drought has also prompted migration, resulting in the loss of traditional adobe construction knowledge, vital for maintaining heritage sites (Hosseini and Jafarizadeh, 2023; Molanaei and Soleimani, 2016; Nakhaei, 2020). Sandstorms, lasting 120 days annually, further damage adobe structures by carrying salts that cause deterioration after rainfall (Kaskaoutis et al., 2019). Immediate action is needed to mitigate these challenges.

Yazd and its local community are facing significant challenges and vulnerabilities due to the impact of climate change (Zarch and Amin, 2017). One notable impact of climate change on Yazd is the occurrence of severe rainfall events, which pose a significant risk to the region's EH (Shirgholami and Masoodian, 2023). The city is home to a wealth of earthen houses built in adobe and cob, to innovative wind catchers, and ancient structures (Bolouhari et al., 2020). These architectural features, along with Qanats, have historically played a vital role in the well-being of the residents, supplying water for agricultural and permanent settlements, as well as collecting rainwater. However, many of these ancient management systems have lost their functionality over the years due to urban development and modernization. Recent flooding, such as the rare summer monsoon rains and subsequent floods in Yazd's World Heritage Site, has had devastating consequences for the earthen houses in the historical core of the city (Sharif et al., 2023). More than 200 historical houses in the city's historical texture have suffered partial or complete damage, largely attributed to inadequate urban management and unregulated interventions. Despite efforts to reinforce roofs and slopes to withstand rainfall, numerous buildings collapsed following the summer monsoon rains.

Persepolis and its local community are experiencing significant impacts from climate change, particularly in relation to rising temperatures, droughts, and the resulting effects on the agricultural sector and the natural environment (Javadinejad et al., 2020). The agricultural sector, which plays a vital role in the local economy, is facing challenges due to reduced productivity and income for farmers. The region's vulnerability to climate change is exacerbated by additional factors such as deforestation, land-use changes, and agricultural practices that have resulted in soil erosion and degradation (Khalili et al., 2021). One notable impact of climate change on Persepolis and its surroundings is the decline in annual precipitation. The reliance on various water sources, including wells, rivers, and rainfall, for irrigation has become increasingly challenging due to the significant decline in precipitation

and groundwater levels (Javadinejad et al., 2020). The uncontrolled exploitation of groundwater resources through the construction of new, deeper wells has resulted in a gradual decrease in the water table over time. This unsustainable use has led to land subsidence in several areas, including the buffer zone of the world heritage site, due to increased agricultural activities, and farmers' reliance on groundwater as surface water sources diminish (Mirassi et al., 2013).

Tchogha Zanbil, like many other ancient sites, is facing notable impacts of climate change, with increasing occurrences of heavy rainfall being a significant concern. This rise in intense precipitation events poses a threat to the authenticity and preservation of the adobe structures that make up the ziggurat (Nakhaei and Correia, 2021). The vulnerability of this construction material to the erosive effects of heavy rains has led to structural deterioration and the potential loss of original building materials. In response to this challenge, efforts are being made to implement protective measures aimed at mitigating the immediate damage caused by heavy rainfall. However, the long-term exposure to intense precipitation events raises concerns about the need for restoration materials, which could compromise the authenticity and overall integrity of the site. Finding a delicate balance between preserving Tchogha Zanbil's cultural value and ensuring its structural stability and conservation becomes a complex challenge in the face of climate change impacts. In addition to heavy rainfall, the region is also experiencing more frequent and intense dust storms, further endangering physical integrity of ancient structures and well-being of local communities (Dargahian et al., 2023).

3.6. Adaptation in the studied sites

This research emphasizes the significant to moderate effects of climate change in earthen heritage located in arid to semi-arid areas. To mitigate climate change adverse impacts, it is essential to develop appropriate adaptation strategies. This includes integrating indigenous and traditional knowledge into adaptation efforts and conducting studies on the strength of the local material components, in this case adobe masonry and cob. Additionally, promoting sustainable land use practices, water conservation, reforestation, and implementing early warning systems can help minimize the negative impacts of climate hazards.

It is crucial to preserve and transmit traditional knowledge related to the maintenance, conservation and restoration of these sites and to develop training programs for skilled workers. Addressing the challenges posed by climate change in Sistan requires measures to control the consequences of wind speeds, address the drought crisis, and ensure the sustainability of the

Hamoun wetlands. In Yazd, a multi-faceted approach integrating climate change adaptation into urban planning and heritage conservation efforts is crucial. Effective surface water management, preservation of traditional water management infrastructure, and sustainable urban development practices are essential. Persepolis requires sustainable water resource management and adaptation strategies that prioritize cultural heritage preservation and community well-being. Tchogha Zanbil needs comprehensive strategies that integrate short-term protection and long-term sustainability through adaptive management approaches.

3.7. Summary of Key Issues

Climate change is having a multifaceted and varied impact on earthen sites from arid and semi-arid territories, specifically in the regions of Sistan, Yazd, Persepolis and Tchogha Zanbil. These sites are particularly vulnerable due to their distinctive features and the specific climatic conditions they are situated in. Changes in precipitation patterns, extreme weather events, rising temperatures, and water scarcity pose significant threats to the stability, integrity, and preservation of these sites. Socioeconomic factors, including limited resources for conservation and inadequate communication between stakeholders, further exacerbate their vulnerability. In Sistan, severe drought and the drying up of lakes, exacerbated by intense winds, lead to dust storms and soil erosion that threaten archaeological sites. The loss of traditional adobe and cob knowledge due to population migration, adds to the challenges of preserving traditional built heritage. In Yazd, severe rainfall events, combined with inadequate urban management, have caused significant damage to the city's earthen heritage, highlighting the need for comprehensive climate change adaptation plans. In Tchogha Zanbil, heavy rainfall events are causing the deterioration of adobe structures, compromising their authenticity. Dust storms and heat waves further endanger both the ancient structures and local communities. Persepolis is facing impacts from rising temperatures, droughts, and changes in groundwater level, resulting in land subsidence and jeopardizing archaeological structures and agricultural productivity. The urgency of addressing these issues underscores the need for interdisciplinary approaches, effective governance, and community engagement. Preserving earthen historical sites in the face of climate change is a global responsibility, and it requires collaboration, funding, and support from governments, heritage organizations, and the public. The development of effective assessment and adaptation strategies is also vital to ensure the resilience and longevity of these cultural heritage sites, amidst an unpredictable climate future.

By highlighting the direct and indirect mechanisms through which climatic stressors damage earthen heritage, this chapter establishes the empirical basis for assessing vulnerability. The next chapter advances from impacts to solutions by reviewing existing strategies for adaptation and risk reduction.

References

Aman, F. (2016). Water dispute escalating between Iran and Afghanistan. Atlantic council, South Asia Center. Http://www.jstor.com/stable/resrep03471

Aminzadeh, B., & Samani, F. (2006). Identifying the boundaries of the historical site of Persepolis using remote sensing. *Remote Sensing of Environment*, *102*(1), 52–62. https://doi.org/10.1016/j.rse.2006.01.018

Asian Development Bank (2017). *A Region at Risk: The Human Dimensions of Climate Change in Asia and the Pacific*. Asian Development Bank. https://doi.org/10.22617/TCS178839-2

Askari Chaverdi, A., Callieri, P., Laurenzi Tabasso, M., & Lazzarini, L. (2016). The Archaeological Site of Persepolis (Iran): Study of the Finishing Technique of the Bas-Reliefs and Architectural Surfaces. *Archaeometry*, *58*(1), 17–34. https://doi.org/10.1111/arcm.12153

Bolouhari, S., Barbera, L. V., & Etessam, I. (2020). Learning Traditional Architecture for Future Energy-Efficient Architecture in the Country; Case Study: Yazd City. *Naqshejahan-Basic Studies and New Technologies of Architecture and Planning*, *10*(2), 85–93.

Bosher, L., Kim, D., Okubo, T., Chmutina, K., & Jigyasu, R. (2019). Dealing with multiple hazards and threats on cultural heritage sites: An assessment of 80 case studies. *Disaster Prevention and Management: An International Journal*, *29*(1), 109–128. https://doi.org/10.1108/DPM-08-2018-0245

Brimblecombe, P., Bonazza, A., Brooks, N., Sampedro, G., Harris, I., & Sabbioni, C. (2011). Impact of climate change on earthen buildings. In *Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architectural Heritage* (p. 278). Getty Publications.

Bushozi, P. M. (2014). Towards Sustainable Cultural Heritage Management in Tanzania: A Case Study of Kalenga and Mlambalasi Sites in Iringa, Southern Tanzania. *The South African Archaeological Bulletin*, *69*(200), 136–141.

Cacciotti, R., Sardella, A., Drdácký, M., & Bonazza, A. (2024). A Methodology for Vulnerability Assessment of Cultural Heritage in Extreme Climate Changes. *International Journal of Disaster Risk Science*, 1-17.

Correia, M. R. A. R. (2016). *Conservation in Earthen Heritage: Assessment and Significance of Failure, Criteria, Conservation Theory, and Strategies*. Cambridge Scholars Publishing.

Dargahian, F., Heidarnejad, S., & Razavizadeh, S. (2021). *Investigating the trend of changes in the heat wave properties Related to climate change in arid regions (Case Study: Yazd City)*. *28*(3), 564–577. https://doi.org/10.22092/ijrdr.2021.125020

Dargahian, F., Mousivand, Y., Razavizadeh, S., & Lotfinasabasl, S. (2023). Identifying Dust Sources Affecting Southwestern Iran (Khuzestan Province) Using Remote Sensing Techniques and HYSPLIT Model. *Journal of the Indian Society of Remote Sensing*, *51*(3), 565–583. https://doi.org/10.1007/s12524-022-01648-y

Ebrahimikhusfi, Z., & Dargahian, F. (2018). Investigation of the Climatic parameters Effect on the Concentration Change of Particles Matter less than 10 μm and its Relation to Wind Erosion Occurrence in Arid Regions. *Journal of Arid Regions Geographics Studies*, *9*(34), 76–92.

Eskandari Damaneh, H., Jafari, M., Eskandari Damaneh, H., Behnia, M., Khoorani, A., & Tiefenbacher, J. P. (2021). Testing Possible Scenario-Based Responses of Vegetation Under Expected Climatic Changes in Khuzestan Province. *Air, Soil and Water Research*, *14*, 11786221211013332. https://doi.org/10.1177/11786221211013332

Fatorić, S., and Seekamp, E. (2017). Are cultural heritage and resources threatened by climate change? A systematic literature review. *Climatic Change*, *142*(1), 227–254. https://doi.org/10.1007/s10584-017-1929-9

Garshasbi, R., & Motamedinasab, A. (2013). Physical Consideration of the Water Filtration in Choghazanbil Ziggurat. *Journal of Novel Applied Sciences*.

Ghazali, S., Azadi, H., Kurban, A., Ajtai, N., Pietrzykowski, M., & Witlox, F. (2021). Determinants of farmers' adaptation decisions under changing climate: The case of Fars province in Iran. *Climatic Change*, *166*(1), 6. https://doi.org/10.1007/s10584-021-03088-y.

Ghirshman, R., (1966). Tchoga Zanbil (Dur-Untash). Volume I: La Ziggurat. Librairie Orientaliste Paul Geuthner. Paris.

Gokmen Erdogan, B. (2022). A study on Risks of Earthen Architecture due to Climate Change. *Kerpic'22 – Re-Thinking Earthen Architecture for Sustainable Development 9th International Conference*. Istanbul Turkey, 30 June –3 July / 2022.

Hematian, F., Morbi Harvi, H., & Badam Firoz, J. (2019). Investigation of changes in weather patterns caused by climate changes in Iran, *the second international congress on agricultural and environmental development with emphasis on the development of nations*, Tehran.

Heydari, A., & Jabbari, I. (2022). Modelling the subsidence development of Marvdasht plain in relation to groundwater abstraction. *Journal of Natural Environmental Hazards*, *11*(34), 17–34. https://doi.org/10.22111/jneh.2022.38867.1815

Hosseini, A., & Jafarizadeh, A. (2023). Investigation of the effects of dust storms caused by wind speed on the migration of rural population in the Sistan region. *Journal of Natural Environmental Hazards*, *12*(36), 1–1. https://doi.org/10.22111/jneh.2022.41858.1885

Hosseini, S., Niroumand, H., Burcu Gültekin, A., Barceló, J. A., Osmadi, A., & Mahdavi, F. (2020). Structural analysis of earth construction's vaults: Case of underground tombs of Chogha Zanbil. *Revista de La Construcción*, *19*(3), 366–380. https://doi.org/10.7764/rdlc.19.3.366.

ICOMOS, CCHWG. (2019). *The Future of Our Pasts: Engaging cultural heritage in climate action Outline of Climate Change and Cultural Heritage* (International Council on Monuments and Sites - ICOMOS and H. Wilson, Eds.). International Council on Monuments and Sites - ICOMOS. https://openarchive.icomos.org/id/eprint/2459/IMF. (2023). Trend in number of climate-related natural disasters (Climate-related Disasters Frequency). *Climate Change Indicators Dashboard*.

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009325844.

Javadinejad, S., Dara, R., & Jafary, F. (2020). How groundwater level can predict under the effect of climate change by using artificial neural networks of NARX. *Resources Environment and Information Engineering*, *2*(1), Article 1. https://doi.org/10.25082/REIE.2020.01.005

Karimi, H., & Ataei, P. (2022). Farmers' Cultural Biases and Adaptation Behavior towards Drought: A Case in Sistan Plain. *Journal of Agricultural Science and Technology*, *24*(4), 793–809.

Kaskaoutis, D. G., Francis, D., Rashki, A., Chaboureau, J.-P., & Dumka, U. C. (2019). Atmospheric Dynamics from Synoptic to Local Scale During an Intense Frontal Dust Storm over the Sistan Basin in Winter 2019. *Geosciences*, *9*(10), Article 10. https://doi.org/10.3390/geosciences9100453

Khalaf, R. W. (2021). World Heritage on the Move: Abandoning the Assessment of Authenticity to Meet the Challenges of the Twenty-First Century. *Heritage*, *4*(1), Article 1. https://doi.org/10.3390/heritage4010023

Khalili, N., Arshad, M., Kächele, H., Farajzadeh, Z., & Müller, K. (2021). Drought shocks and farm household consumption behaviour: Insights from Fars province of Iran. *International Journal of Disaster Risk Reduction*, *66*, 102625. https://doi.org/10.1016/j.ijdrr.2021.102625

MalAmiri, N., Rashki, A., Hosseinzadeh, S. R., & Kaskaoutis, D. G. (2022). Mineralogical, geochemical, and textural characteristics of soil and airborne samples during dust storms in Khuzestan, southwest Iran. *Chemosphere*, *286*, 131879.

Maleki, S., Miri, A., Rahdari, V., & Dragovich, D. (2021). A method to select sites for sand and dust storm source mitigation: Case study in the Sistan region of southeast Iran. *Journal of Environmental Planning and Management*, *64*(12), 2192–2213. https://doi.org/10.1080/09640568.2020.1862770

Maleki, S., Soffianian, A. R., Koupaei, S. S., Pourmanafi, S., & Saatchi, S. (2018). Wetland restoration prioritizing, a tool to reduce negative effects of drought; An application of multicriteria-spatial decision support system (MC-SDSS). *Ecological Engineering*, *112*, 132–139. https://doi.org/10.1016/j.ecoleng.2017.12.031

Malekshahi, H., & Farhadpoor, M. (2014). Cooperation project of Sardar-Abad natural and historical protected area. *Tchogha Zanbil World Heritage Research Center* [In Farsi].

Masoudi, M., & Elhaeesahar, M. (2016). *Trend assessment of climate changes in Khuzestan Province, Iran*. *2*, 143–152.

Mirassi, S., Rahnema, H., & Elyasi, M. (2013). *Groundwater level dropping and occurrence land subsidence phenomenon in Marvdasht Plains, Fars*.

Miri, A., Maleki, S., & Middleton, N. (2021). An investigation into climatic and terrestrial drivers of dust storms in the Sistan region of Iran in the early twenty-first century. *Science of The Total Environment*, *757*, 143952. https://doi.org/10.1016/j.scitotenv.2020.143952

Molanaei, S., & Soleimani, S. (2016). Insight into the valuable elements of Sistan local architecture in relation to climatic factors of sustainable architecture. *The Monthly Scientific Journal of Bagh-e Nazar*, *13*(41), 57–66.

Motamedi, A., Gohari, A., & Haghighi, A. T. (2023). Three-decade assessment of dry and wet spells change across Iran, a fingerprint of climate change. *Scientific Reports*, *13*(1), Article 1. https://doi.org/10.1038/s41598-023-30040-0

Mousavi, A. (2012). *Persepolis: Discovery and Afterlife of a World Wonder*. Walter de Gruyter.

Mozafari, M. (2022). The effect of climate change and dam construction on the drying up of Kor and Sivand rivers. *The fifth national conference on climate change and its impact on agriculture and environment*, Urmia.

Nakhaei, M. (2020). Facing climate change: the importance of protecting earthen heritage traditional knowledge. *In 2020 ICOMOS 6 ISCS joint meeting proceedings* (vol. 68).

Nakhaei, M., & Correia, M. (2020). *Water-risk management in Tchogha Zanbil World Heritage Site in Iran, with a focus on the Ancient Management System*. https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-683-2020

Nakhaei, M., & Correia, M. (2021). Assessment of vulnerability and site adaptive capacity to the risk of climate change: The case of Tchogha Zanbil World Heritage earthen site in Iran. *Journal of Cultural Heritage Management and Sustainable Development*, *12*(2), 107–125. https://doi.org/10.1108/JCHMSD-06-2021-0108

Neghahban, E., (1994). Excavation in Haft Tappeh and Khuzestan Plain. *Iranian Cultural Heritage Organization Publications,* Tehran.

Niroumand, H., Zain, M. F. M., & Jamil, M. (2012). The Important Role of Chogha Zanbil in Earth Architecture Based on Material, Structural and Architectural Aspects. *Advanced Materials Research*, *457–458*, 395–398. https://doi.org/10.4028/www.scientific.net/AMR.457-458.395

Orr, S. A., Richards, J., & Fatorić, S. (2021). Climate Change and Cultural Heritage: A Systematic Literature Review (2016–2020). *The Historic Environment: Policy and Practice*, *12*(3–4), 434–477. https://doi.org/10.1080/17567505.2021.1957264

Phillips, H. (2015). The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. *Environmental Science and Policy*, *47*, 118–125. https://doi.org/10.1016/j.envsci.2014.11.003

Rahmasary, A. N., Robert, S., Chang, I.-S., Jing, W., Park, J., Bluemling, B., Koop, S., & Van Leeuwen, K. (2019). Overcoming the Challenges of Water, Waste and Climate Change in Asian Cities. *Environmental Management*, *63*(4), 520–535. https://doi.org/10.1007/s00267-019-01137-y

Rami, A., Hamidi, M., & Navayi Neya, B. (2022). Atmospheric analysis of dust storms in Sistan region. *Journal of Atmospheric and Solar-Terrestrial Physics*, *227*, 105800. https://doi.org/10.1016/j.jastp.2021.105800

Rashki, A., Kaskaoutis, D. G., Francois, P., Kosmopoulos, P. G., & Legrand, M. (2015). Dust-storm dynamics over Sistan region, Iran: Seasonality, transport characteristics and affected areas. *Aeolian Research*, *16*, 35–48. https://doi.org/10.1016/j.aeolia.2014.10.003

Ravankhah, M., de Wit, R., Argyriou, A. V., Chliaoutakis, A., Revez, M. J., Birkmann, J., Žuvela-Aloise, M., Sarris, A., Tzigounaki, A., & Giapitsoglou, K. (2019). Integrated Assessment of Natural Hazards, Including Climate Change's Influences, for Cultural Heritage Sites: The Case of the Historic Centre of Rethymno in Greece. *International Journal of Disaster Risk Science*, *10*(3), 343–361. https://doi.org/10.1007/s13753-019-00235-z

Richards, J., Bailey, R., Mayaud, J., Viles, H., Guo, Q., & Wang, X. (2020). Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty. *Scientific Reports*, *10*(1), 16419. https://doi.org/10.1038/s41598-020-73456-8

Sadeghi, N. H. (2018). *Conservation and Safety Assessment of Vaulted Adobe Architecture in Yazd, Iran* [Ph.D., Universidade do Minho (Portugal)]. https://www.proquest.com/docview/2585392399/abstract/1E508CDE12504F4FPQ/1

Sajjadi, S. M. S., & Moradi, H. (2014). Excavation at Buildings Nos.1 and 20 at Shahr-i-Sokhta. *International Journal of the Society of Iranian Archaeologists*, Vol. 1, No.1, Winter-Spring.

Sardar Shahraki, A., Hashemi Tabar, M., & Aliahmadi, N. (2020). Assessment the Effects of Drought on Economic Development and Planning Optimal Strategy for Sustainable Livelihood in Sistan. *Regional Planning*, *10*(38), 51–64.

Shah, A. A., Khan, N. A., Gong, Z., Ahmad, I., Naqvi, S. A. A., Ullah, W., & Karmaoui, A. (2023). Farmers' perspective towards climate change vulnerability, risk perceptions, and adaptation measures in Khyber Pakhtunkhwa, Pakistan. *International Journal of*

Environmental Science and Technology, *20*(2), 1421–1438. https://doi.org/10.1007/s13762-022-04077-z

Sharif, M., Heidari, S., & Hosseini, S. M. (2023). MAPPING OF URBAN FLOOD INUNDATION USING 3D DIGITAL SURFACE MODEL AND SENTINEL-1 IMAGES. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *X-4-W1-2022*, 715–720. https://doi.org/10.5194/isprs-annals-X-4-W1-2022-715-2023

Sharifikia, M. (2013). Environmental challenges and drought hazard assessment of Hamoun Desert Lake in Sistan region, Iran, based on the time series of satellite imagery. *Natural Hazards*, *65*(1), 201–217. https://doi.org/10.1007/s11069-012-0353-8

Shiravand, H., & Bayat, A. (2023). Vulnerability and drought risk assessment in Iran based on fuzzy logic and hierarchical analysis. *Theoretical and Applied Climatology*, *151*(3), 1323–1335. https://doi.org/10.1007/s00704-022-04323-x

Shirgholami, M., & Masoodian, S. A. (2023). *Journal of Natural Environmental Hazards*, *12*(35), 95–114. https://doi.org/10.22111/jneh.2022.40681.1862

UNESCO, ICCROM, ICOMOS, IUCN. 2010. Managing disaster risks for World Heritage, World Heritage Resource Manual, UNESCO, Paris, 1–6. http://whc.unesco.org/en/news/630/

UNESCO, ICCROM, ICOMOS, IUCN. 2013. Managing cultural world heritage, World heritage resource manual, Paris. http://whc.unesco.org/en/news/1078

UNESCO. (2018). Convention concerning the protection of the World Cultural and Natural Heritage World Heritage Committee. Forty-second session. Manama, bahrain. 24 june – 4 july 2018.

UNESCO. W. H. C. (2018). *41 COM 7—Decision*. UNESCO World Heritage Centre. Retrieved 29 March 2023, from https://whc.unesco.org/en/decisions/6940/

Vaghefi, S. A., Keykhai, M., Jahanbakhshi, F., Sheikholeslami, J., Ahmadi, A., Yang, H., & Abbaspour, K. C. (2019). The future of extreme climate in Iran. *Scientific Reports*, *9*(1), Article 1. https://doi.org/10.1038/s41598-018-38071-8

Vakulchuk, R., Daloz, A. S., Overland, I., Sagbakken, H. F., & Standal, K. (2023). A void in Central Asia research: Climate change. *Central Asian Survey*, *42*(1), 1–20. https://doi.org/10.1080/02634937.2022.2059447

Valagussa, A., P. Frattini, G. Crosta, D. Spizzichino, G. Leoni, and C. Margottini. 2021. Multi-risk analysis on European cultural and natural UNESCO heritage sites. *Natural Hazards* 105: 2659–2676.

Weber, E. T., Catterall, C. P., Locke, J., Ota, L. S., Prideaux, B., Shirreffs, L., Talbot, L., & Gordon, I. J. (2021). Managing a World Heritage Site in the Face of Climate Change: A Case Study of the Wet Tropics in Northern Queensland. *Earth*, *2*(2), Article 2. https://doi.org/10.3390/earth2020015.

World Heritage Centre (2012). Periodic Reporting Cycle 2, Section II. Persepolis (114). https://whc.unesco.org/en/list/114/documents/

Yıldırım Esen, S., & Bilgin Altınöz, A. G. (2018). Assessment of risks on a territorial scale for archaeological sites in Izmir. *International Journal of Architectural Heritage*, *12*(6), 951-980.

Zarch, A., & Amin, M. (2017). Analyzing climate change effects on drought occurrence in Yazd province, Iran. *Desert Management*, *5*(9), 74–90. https://doi.org/10.22034/jdmal.2017.27980

4. Chapter 4 - Adaptation of cultural heritage to climate change: A literature review

Following the analysis of climate-induced deterioration, this chapter explores how the heritage sector has responded to climate change through adaptation frameworks, policies, and conservation strategies. It synthesizes global scholarship on resilience-building, traditional knowledge, and institutional responses, identifying both progress and persistent gaps in implementation.

Climate change poses escalating threats to cultural heritage worldwide, yet systematic understanding of how adaptation is conceptualized and implemented in this field remains limited. This study applies a systematic literature review following PRISMA guidelines to identify, evaluate, and synthesize research on climate change adaptation in cultural heritage published between 2000 and 2025. A total of 359 records were retrieved from the Web of Science Core Collection and complemented by policy and guidance documents from UNESCO, ICOMOS, IPCC, and UNFCCC. After rigorous screening and eligibility assessment, 143 studies were included for in-depth analysis. Publications were thematically coded into eight major categories, ranging from adaptive management and sustainable conservation to community engagement, Indigenous knowledge, and policy frameworks, and classified according to the IPCC AR6 adaptation action types. Results reveal a predominance of research from Europe and the Americas, with emerging contributions from Asia and Oceania, and a sharp increase in adaptation-focused publications after 2015. The findings underscore persistent institutional, financial, and knowledge barriers that hinder the integration of cultural heritage into broader climate adaptation and disaster risk reduction frameworks. Despite growing attention to adaptive management and local participation, adaptation policies often remain fragmented and Eurocentric, with limited engagement from the Global South. The review highlights the potential of combining traditional knowledge systems with technological innovation to enhance resilience and calls for interdisciplinary, community-based, and policy-oriented research to advance effective adaptation strategies.

4.1. Introduction

Climate change has become one of the most significant threats to both natural and cultural systems, with its impacts visible through rising global temperatures, accelerated sea-level rise, and more frequent extreme weather events. Since the first World Climate Conference (1979) and the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988, international policy frameworks such as the UN Framework Convention on Climate Change

(UNFCCC, 1992), the Kyoto Protocol (1997), and the Paris Agreement (2015) have progressively recognized the urgency of the crisis (Jim & Charlie, 2014; Ford et al., 2016). While mitigation remains crucial, the IPCC's Sixth Assessment Report (2023) emphasizes that certain degrees of change are now inevitable, making adaptation, the process of adjusting human and natural systems to moderate harm or exploit beneficial opportunities, an equally urgent priority (El-Ashry, 2009; IPCC, 2023).

Within this global context, cultural heritage has emerged as both vulnerable to and instrumental in adaptation. Cultural heritage encompasses tangible and intangible expressions of human creativity, from monuments and archaeological sites to oral traditions and knowledge systems that shape community identity (ICOMOS, 2019; Boro et al., 2020). These assets face increasing exposure to climatic hazards such as flooding, erosion, temperature fluctuations, and biological decay, threatening not only their material integrity but also their cultural meaning. In IPCC terms, vulnerability reflects the exposure, sensitivity, and adaptive capacity of these systems (IPCC, 2023). In heritage studies, this aligns with the concept of resilience, the capacity to endure, adjust, and recover from adverse impacts while maintaining essential identity and function (Germanà & Bagnato, 2019).

Recent scholarship increasingly reframes cultural heritage not as a passive victim of climate change but as an active agent in adaptation, offering models for sustainable design, resource management, and community resilience. Fluck and Dawson (2021) describe heritage as a "cultural toolkit" for addressing environmental change, while UNESCO (2023) and ICOMOS (2019) emphasize its role in fostering locally grounded, cross-generational knowledge for resilience building.

The Paris Agreement (Article 7) explicitly recognizes the importance of Indigenous and traditional knowledge systems in guiding effective adaptation, thereby expanding the scope of climate governance beyond purely technical solutions (UNFCCC, 2015). Building on this foundation, the Glasgow–Sharm el-Sheikh Work Programme on the Global Goal on Adaptation has further institutionalized the role of culture in adaptation planning. At COP27, "tangible cultural heritage" was included as a thematic area within this framework, marking a significant step toward acknowledging heritage as a sector of adaptation strategy rather than merely collateral to environmental change (UNFCCC, 2022; Climate Heritage Network, 2022).

Many experts and researchers in the field also believe that adapting heritage to climate change is feasible. However, the delay in taking action now may limit future adaptation possibilities

for cultural heritage resources (Shirvani Dastgerdi et al., 2020). Continued exposure to intensifying climatic stressors, such as extreme rainfall, temperature shifts, and biological decay, can cause irreversible material damage, surpassing the limits of repair. Postponing action also weakens institutional and financial capacities while increasing the costs and complexity of future interventions. Moreover, delays risk the loss of traditional knowledge vital for context-specific adaptation (Shirvani Dastgerdi et al., 2020). The persistence of delayed action underscores a broader policy gap: while the risks are increasingly recognized, the integration of adaptation into cultural heritage governance remains inconsistent and fragmented.

This paper critically reviews how climate change adaptation has been conceptualized and implemented in cultural heritage policy and governance, identifying trends, barriers, and opportunities for mainstreaming. It analyses 223 studies and policy documents (2000–2025) to explore how adaptation concepts, resilience, inclusivity, and adaptive governance, are translated into heritage management. The paper argues that, despite increasing awareness, adaptation in the heritage sector remains fragmented. It concludes by identifying pathways to embed cultural heritage more systematically within climate adaptation policy, emphasizing interdisciplinary collaboration, equity, and the co-production of knowledge.

4.2. Method

4.2.1. Overall Approach

This study employed a systematic literature review in accordance with the PRISMA guidelines to ensure transparency, rigor, and reproducibility. The review aimed to identify, evaluate, and synthesize research addressing climate change adaptation within the context of cultural heritage across global regions. A PRISMA flow diagram was used to record and visualize the selection process, including the identification, screening, eligibility, and inclusion phases.

4.2.2. Data Sources and Search Strategy

A comprehensive literature search was performed using the Web of Science Core Collection, covering the period 2000–2025. The final search was conducted on 30 October 2025. To complement peer-reviewed literature, relevant policy and guidance documents were retrieved from international organizational repositories, including UNESCO, the World Heritage Centre, ICOMOS, and major climate policy sources such as the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC).

The Boolean search strategy combined terms related to cultural heritage with those about climate change adaptation, while explicitly excluding mitigation-focused or risk-only studies. The Web of Science query was as follows:

4.2.3. Title-abs-key:

("climate change adaptation" or "adaptation to climate change" or "adaptive management" or "resilience to climate change" or "adaptation strategy" or "adaptation planning" or "adaptive capacity") and ("cultural heritage" or "built heritage" or "archaeological site*" or "historic building*" or "heritage site*" or "monument*" or "world heritage" or "museum*" or "heritage conservation" or "heritage management") not ts=("mitigation" or "carbon emission*" or "vulnerability assessment" or "impact*" or "risk assessment" or "hazard*" or "damage*" or "exposure" or "sensitivity")

The initial query retrieved 359 records: 352 in English, 3 in Spanish, 2 in Turkish, 1 in German, and 1 in Russian. Only English-language publications were retained for the analysis, resulting in a refined sample of 352 records. After removing duplicates and applying relevance screening, 143 studies were selected for detailed review. The temporal coverage of the dataset spans from 2000 to 2025, capturing a period of accelerated international attention to cultural heritage and climate change adaptation particularly following the adoption of the Paris Agreement (2015) and the inclusion of culture in climate resilience agendas under UNESCO and IPCC frameworks.

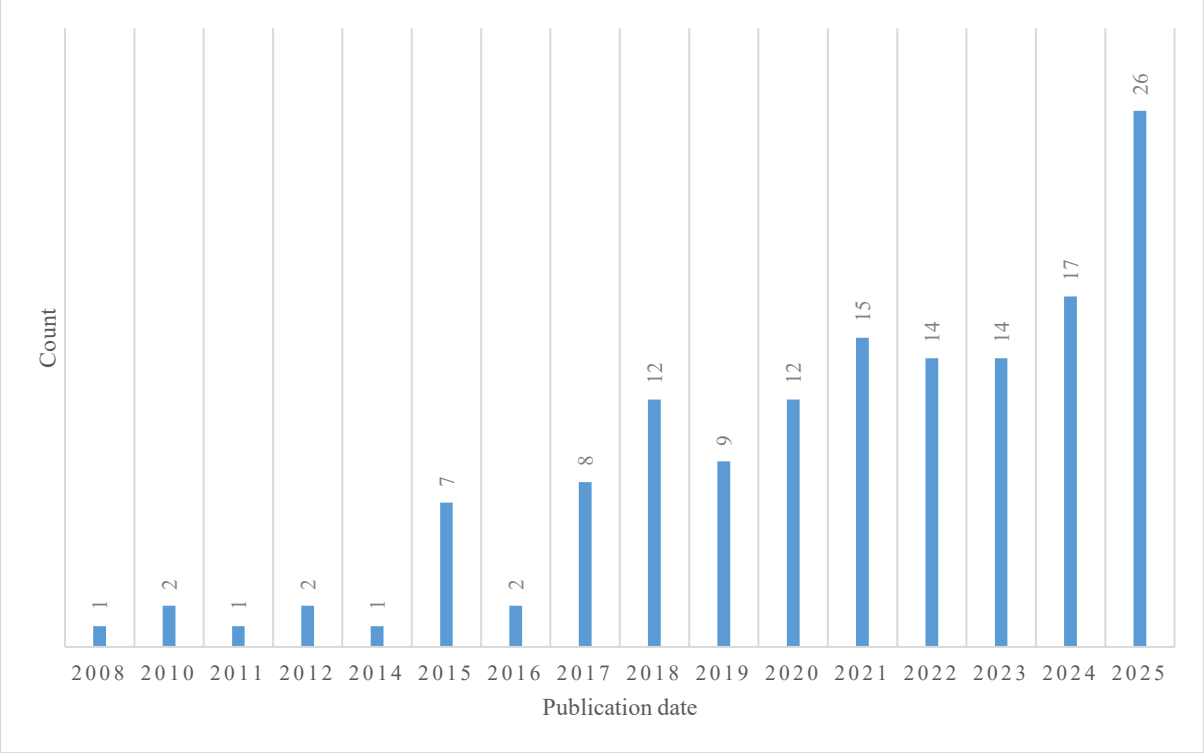


Fig. 4.1: Temporal distribution of publications on cultural heritage adaptation to climate change (2000–2025)

The reviewed studies encompassed a global geographic distribution, with research conducted across all inhabited continents and a pronounced concentration in Europe America. This distribution reflects both the regional density of World Heritage sites and the uneven research capacity across countries.

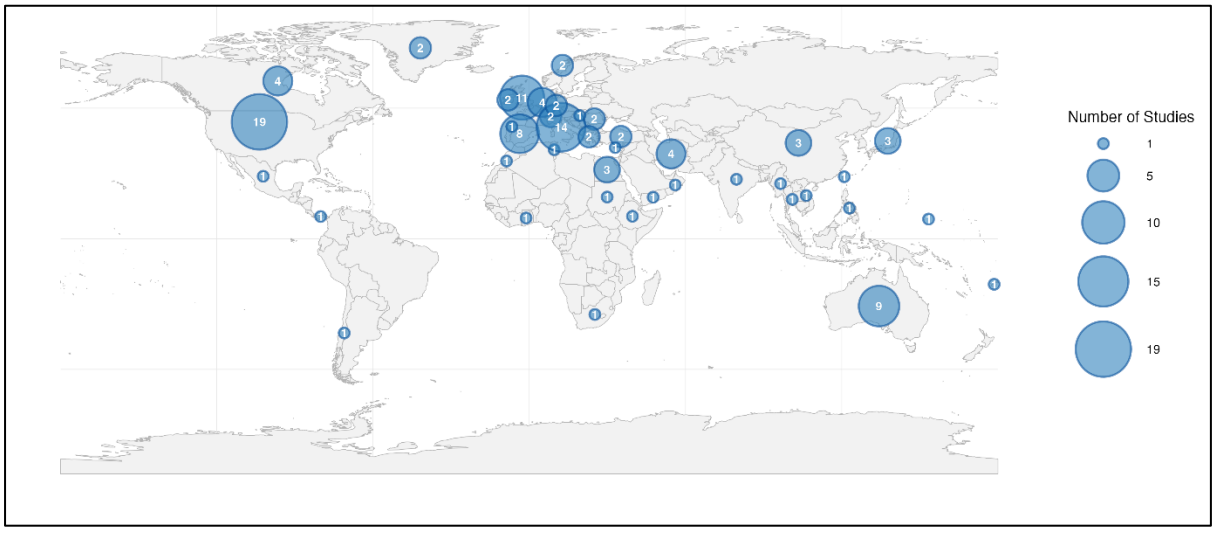


Fig. 4.2: Geographic distribution of studies on cultural heritage adaptation to climate change by country

4.2.4. Thematic Coding

Each publication was reviewed in full and coded into one or more thematic categories according to its main research objectives and discussion focus. The coding combined keyword analysis, abstract reading, and inductive thematic review. Eight thematic categories were identified, reflecting dominant trends in cultural heritage adaptation research:

1. Climate-change impacts on cultural heritage and risk/vulnerability assessment
2. Adaptive management and planning
3. Sustainable conservation techniques
4. Community engagement and Indigenous knowledge
5. Policy and legal frameworks
6. Technological innovations
7. Ancient knowledge as adaptive capacity
8. Barriers to climate change adaptation

4.2.5. Adaptation action type classification (AR6 framework)

To deepen the understanding of adaptation mechanisms, each publication was additionally classified according to the IPCC AR6 typology of adaptation actions, reflecting the nature of responses to climate change within the cultural heritage sector. The classification was based on an interpretive coding framework derived from the abstract, methodology, and discussion sections.

Each study was assessed using diagnostic questions and key-phrase matching as shown below:

Table 4.1: Diagnostic framework for identifying adaptation action types in cultural heritage studies based on IPCC AR6 categories

Diagnostic Question	AR6 Adaptation Type	Example Keywords / Phrases
Are they building or modifying something?	Structural / Physical	“retrofit”, “restoration”, “construction”, “engineering solution”

Are they developing policies or plans?	Institutional	“planning”, “policy”, “framework”, “governance”, “management strategy”
Are they involving communities or changing practices?	Behavioural	“community participation”, “local practices”, “behavioural change”, “awareness”
Are they using new tools, models, or monitoring technologies?	Technological	“monitoring system”, “digital”, “remote sensing”, “modelling”, “innovation”
Are they relying on nature or landscapes for protection?	Ecosystem-based	“ecosystem services”, “nature-based solution”, “green infrastructure”
Are they providing funding, incentives, or economic analysis?	Economic	“funding”, “economic valuation”, “incentive mechanism”, “cost-benefit”
Are they educating or transferring knowledge?	Educational / Knowledge-based	“capacity building”, “training”, “knowledge exchange”, “education”

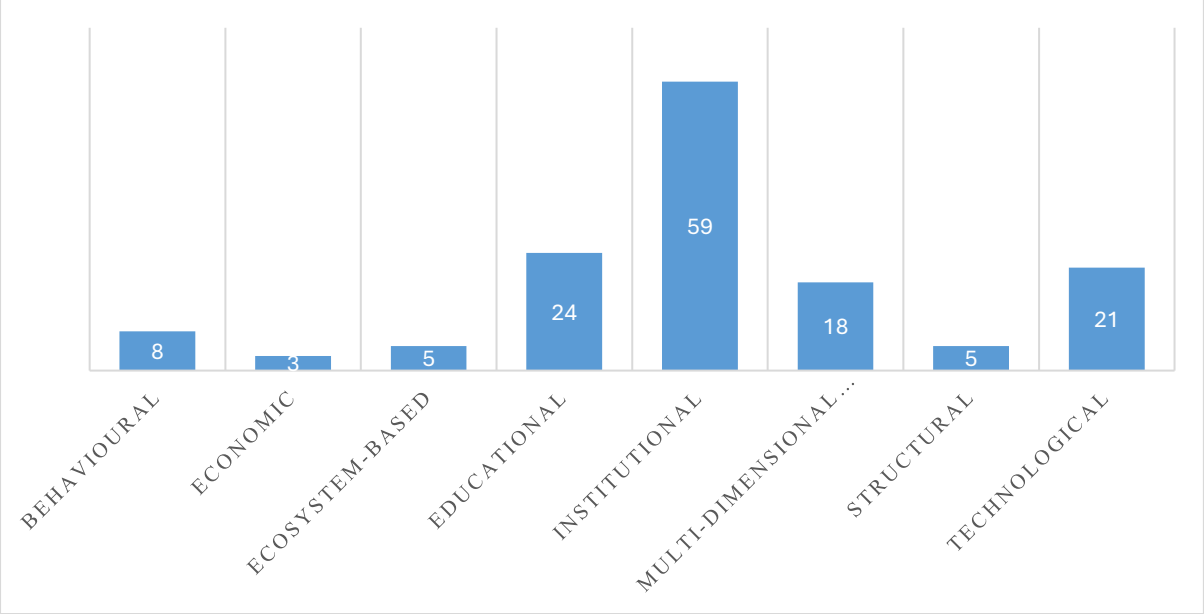


Fig. 4.3: Classification of adaptation actions in cultural heritage studies according to the IPCC AR6 typology

4.3. Climate change impacts, risk, and vulnerability assessment for cultural heritage

Climate change exerts increasing pressure on cultural heritage, prompting a growing body of research focused on understanding, assessing, and mitigating its impacts. Studies consistently underscore the urgency of developing integrated approaches to preserve and adapt heritage resources in the face of climatic stressors (Sesana et al., 2018; Fatorić & Seekamp, 2017a). The impacts are multifaceted ranging from structural degradation caused by temperature and humidity fluctuations to flooding, coastal erosion, and biological deterioration (Horowitz et al., 2016; Orr et al., 2021). Archaeological sites, historic buildings, and cultural landscapes are particularly vulnerable, with long-term monitoring and scientific research identified as critical needs for understanding these impacts comprehensively (Hollesen, 2022; Daly, 2011).

UNESCO's focus on World Heritage properties emphasizes the need for geographically diverse studies, interdisciplinary collaboration, and the integration of intangible heritage within adaptation strategies (Nguyen & Baker, 2023). At the same time, local-scale research in Europe highlights the necessity of site-specific and forward-looking adaptation measures for architectural structures (Brimblecombe et al., 2011; Vyshkvarkova & Sukhonos, 2023). Methodological advances increasingly combine high-resolution climate projections, building simulations, and geospatial analysis to model risk and anticipate future impacts (Rajčić et al., 2018; Leissner et al., 2015). However, these approaches are often concentrated in the Global North, leaving many heritage contexts, especially in Africa, Asia, and Latin America, underrepresented (Crowley et al., 2022).

The need for inclusive and participatory approaches is increasingly recognized. Incorporating Indigenous and local knowledge into adaptation planning enhances the contextual understanding of risk, particularly in coastal and rural communities facing sea-level rise and climatic variability (Pearson et al., 2021). Values-based frameworks (Simpson, et al., 2022; Carmichael et al., 2017) and participatory models such as the Adapt Northern Heritage Toolkit (Boro et al., 2020) demonstrate how community perspectives and cultural significance can be embedded into vulnerability assessments. This represents a shift from purely technical evaluations toward socially grounded and holistic assessments that respect diverse knowledge systems.

Methodologically, risk and vulnerability assessment for cultural heritage has evolved from conceptual frameworks to integrative, data-driven, and participatory models (Dapilah et al., 2025). Early works, such as Daly's (2014a, 2014b) vulnerability framework for Ireland's World

Heritage Sites, emphasized the importance of preliminary assessments before adaptation planning (Daly, 2014a; Daly, 2014b). More recent approaches combine hazard mapping, geospatial tools, and multi-criteria decision analysis (Bonazza et al., 2021; Nicu, 2016; Gandini et al., 2017), offering more nuanced ways to evaluate exposure and prioritize interventions. Comprehensive projects such as Noah's Ark and CARRA have produced vulnerability atlases and decision-support tools for policymakers (Sabbioni et al., 2010; Pollard-Belsheim et al., 2014).

These methodologies reveal both progress and persistent challenges. While climate projection-based modelling quantifies long-term risk, it is often limited by data availability and uncertainty (Leissner et al., 2015). GIS-based analyses enhance visualization and prioritization but may neglect intangible or community-defined values (Nicu, 2016). Participatory and values-based approaches enrich legitimacy and social relevance but remain time-intensive and difficult to standardize (Simpson, et al., 2022).

4.4. Adaptation in Response to Climate Change

According to the IPCC's Sixth Assessment Report (AR6, 2022), adaptation is defined as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects." AR6 conceptualizes adaptation as a multidimensional and iterative process involving social, institutional, ecological, and behavioral adjustments to climate risks. Within the cultural heritage sector, this perspective extends adaptation beyond physical protection to include governance, community participation, and the safeguarding of intangible values. It also introduces the notions of adaptation limits and maladaptation, which are particularly relevant where interventions risk eroding authenticity or reinforcing social inequities. Effective heritage adaptation should therefore align with AR6 principles of inclusivity, equity, and transformative change.

This adaptive process depends on the active involvement of diverse stakeholders across multiple levels (UNFCCC 2023). The Paris Agreement (Article 7) established a global goal on adaptation to enhance adaptive capacity, strengthen resilience and reduce vulnerability to climate change while contributing to sustainable development. More recent frameworks, such as the Glasgow-Sharm el-Sheikh work programme (2021-2023) and the COP28 UAE outcome, through the UAE Framework for Global Climate Resilience, reinforce the need for robust

governance, climate-proof investments, and knowledge-based planning that safeguard both ecosystems and human well-being. Importantly, adaptation action under Article 7.5 of the Paris Agreement must be “based on and guided by the best available science and, as appropriate, traditional knowledge, knowledge of Indigenous peoples and local knowledge systems.” For the cultural heritage sector, this underscores the need to integrate scientific and traditional knowledge systems into adaptation planning to ensure context-specific and culturally grounded resilience strategies.

Adaptation strategies are typically structural, institutional, ecological, or behavioral, integrating nature-based and ecosystem-based approaches alongside technological and policy measures (IPCC, AR6 Glossary, 2022). This updated classification extends beyond the earlier typology of technological, behavioral, managerial, and policy measures (IPCC, 2014), acknowledging the importance of ecological and nature-based (green) solutions as integral components of adaptation. For cultural heritage, this broader framing highlights opportunities to align conservation and adaptation goals through ecosystem-based management, sustainable landscape planning, and the revitalization of traditional ecological knowledge. Adaptation in the context of cultural heritage emphasizes specialized planning for climate risk and the reinforcement of monitoring and maintenance of cultural heritage while transitioning from reactive to proactive and planned adaptation is critical. Proactive adaptation demands specialized planning and government support to enhance the monitoring and maintenance of cultural heritage (Quintero, 2014; Wang et al., 2022). The adaptive process for cultural heritage primarily focuses on 'moderating harm' through the management of, and response to, risks arising from climate change (Daly, 2017).

Two primary approaches to climate change adaptation can be identified: hazard-oriented and vulnerability-oriented. In developed economies, adaptation efforts often concentrate on specific climate-related risks (According to the IPCC, risk results from the interaction of hazard, exposure, and vulnerability) through hazard-oriented approaches that rely on climate models and long-term projections to raise awareness and guide planning. In contrast, regions facing poverty and climate injustice emphasize vulnerability-oriented approaches, which focus on the social and environmental factors that shape exposure and adaptive capacity (Daly et al., 2020). Adaptation strategies to address climate change can also be categorized as 'resist,' 'retreat,' or 'rebuild' strategies (Higgins, 2022). These strategies are influenced by societal values and understanding. Scientific information and insights from local communities play a role in establishing the basis for determining the degree of climate change that is deemed

"damaging" (Huq & Reid, 2004). However, it's crucial to note the potential consequences of maladaptation. Adapting to environmental changes can sometimes lead to maladaptive outcomes, as witnessed in historical collapses of societies and modern-day examples. Adaptations, such as building levees to cope with flooding, can initially assist in managing climate impacts but might lead to unintended consequences, like increased vulnerability to severe floods and hurricanes due to decreased flood-storage capacity. This highlights the importance of considering and minimizing the unintended consequences of adaptations, ensuring they effectively address environmental challenges (Fazey et al., 2010). Adaptation remains a dynamic process that encompasses societal, ecological, and economic adjustments to address climate change impacts and capitalize on potential opportunities. Collaborative efforts and transparent frameworks guided by science and traditional knowledge are integral in safeguarding ecosystems, livelihoods, and communities against the challenges posed by climate change (UNFCC, 2023).

4.5. Policy and legal frameworks

Climate change policy has long struggled to incorporate cultural heritage within its adaptation agenda. As Daly (2019) notes, uncertainty, political inertia, and financial instability continue to undermine long-term planning. Within heritage policy, the UNESCO World Heritage Centre increasingly emphasizes adaptation over mitigation, calling for corrective measures that strengthen resilience and revive traditional building knowledge (UNESCO, Decision 32 COM 7A.32). Yet, as Phillips (2014) observes, integrating adaptation into World Heritage management plans remains limited by data gaps, uneven resources, and competing priorities.

Internationally, efforts to align heritage protection with global adaptation frameworks reveal growing recognition of cultural and Indigenous knowledge as adaptive capacity. Kim (2011) and the IPCC (AR6, 2022) both highlight that resilience depends not only on safeguarding physical assets but also on sustaining cultural practices and governance systems. This reflects a shift toward rights-based and community-led approaches, consistent with wider adaptation discourse emphasizing equity, inclusion, and local agency (UNFCCC, 2013; Ford et al., 2016). However, translating these principles into enforceable policy remains uneven, exposing a persistent gap between rhetorical commitments and operational frameworks across the heritage sector.

The UNFCCC has been central to global adaptation governance, supporting countries through knowledge sharing, capacity building, and financial and technological assistance (UNFCCC,

2013). Yet, translating this international guidance into effective national policies for cultural heritage remains limited. While the Convention promotes institutional coordination and stakeholder engagement (UNFCCC, 2014), heritage adaptation often lacks integration within national adaptation plans. For instance, Antonson et al. (2021) highlight Sweden's insufficient preparedness and weak inter-agency cooperation in addressing heritage-related climate risks, reflecting broader institutional fragmentation across the sector.

Daly et al. (2020) highlight Ireland's National Adaptation Framework as one of the few examples where climate adaptation has been systematically embedded in heritage policy. Their work illustrates how linking heritage management with national adaptation planning can clarify governance responsibilities and funding priorities, issues that remain fragmented elsewhere. In follow-up research, Daly et al. (2022) show that in low- and middle-income countries, cultural heritage is still marginal in adaptation agendas, revealing a persistent gap between recognition and implementation. Similarly, Fluck (2016) underscores the need for institutional capacity building within organizations such as Historic England to maintain the mainstream adaptation across projects. These examples indicate that while awareness of climate risks has grown, adaptation in the heritage sector largely operates through ad hoc or project-based initiatives rather than coordinated policy frameworks. As Schipper (2006) notes, the global policy discourse still privileges mitigation over adaptation, and heritage governance reflects this imbalance. Although the 1972 World Heritage Convention laid the groundwork for shared responsibility, it remains insufficiently aligned with the post-Paris Agreement adaptation agenda, where cross-sectoral coordination and measurable adaptation outcomes are expected.

The UNFCCC's Nairobi Work Program promotes cross-sectoral collaboration, integration of adaptation into national policies, and the recognition of Indigenous and local knowledge as key components of resilience building (UNFCCC, 2023). However, while this framework has advanced adaptation thinking in sectors such as agriculture and water management, its influence on the cultural heritage domain remains limited. Heritage adaptation strategies often lack the participatory and knowledge-sharing mechanisms envisioned by the Program, reflecting broader governance gaps in translating high-level adaptation principles into sector-specific action (Fatorić & Seekamp, 2017).

Policy and legal frameworks linking climate change and cultural heritage remain fragmented despite growing recognition of their interdependence. Scholars argue for integrated and cross-sectoral approaches where adaptation is embedded in heritage governance rather than treated

as an external concern (Gruber, 2011; Rockman, 2016). Recent work highlights persistent research and policy gaps, including limited attention to decolonial and justice-oriented perspectives within adaptation agendas (Ballard et al., 2022; Simpson et al., 2022). Broader climate policy literature reinforces that effective adaptation depends on political coordination, sustained funding, and international cooperation (Burton et al., 2006; Bouwer & Aerts, 2006; Bakhtiari, 2018). Yet, as Huq et al. (2004) and Cassar & Pender (2005) note, these mechanisms are weakest in Least Developed Countries where heritage institutions lack access to adaptation finance. Case studies from Ireland to the Cayman Islands, reveal that implementation remains uneven, constrained by administrative silos, regulatory rigidity, and scarce resources (Daly et al., 2020; Johnston & Cooper, 2022). Despite calls for integrated legal frameworks and adaptive regulation (Gruber, 2011; Mualam, 2020), heritage governance continues to lag the broader climate policy discourse. This reflects a structural tension: adaptation requires locally grounded action, yet heritage policy is often framed through universal conventions. The ongoing difficulty in operationalizing the World Heritage Climate Action framework underscores how consensus at the international level rarely translates into coherent national or local adaptation practice.

Recent research highlights that adaptive and integrative governance is essential to bridge the divide between climate policy and heritage management. Analyses of World Heritage documents show persistent regional inequalities and weak operational alignment between adaptation discourse and implementation, exposing the limited prioritization of adaptation within heritage policy (Chen et al., 2025). Emerging work also demonstrates that innovative financing mechanisms, such as cross-sectoral approaches in tourism, agriculture, and forestry, can enhance policy coherence and resource mobilization for heritage adaptation (Salpina et al., 2025). National examples, including Egypt's policy reforms, illustrate how regulatory integration and institutional coordination can embed resilience into heritage governance (Khater. et al., 2024). Yet, evidence from historic cities suggests that rigid or outdated legislation continues to constrain sustainable energy transitions, revealing the need for more flexible, forward-looking frameworks (Pérez-Pérez & Chacón-Linares, 2025). Furthermore, the incorporation of traditional ecological knowledge depends on inclusive legal structures that empower local communities and recognize plural governance models (Dastgerdi & De Luca, 2025). At the transnational level, initiatives such as the UNESCO City Labs and the Global Stocktake enable policy learning and multilevel collaboration, though their influence on local implementation remains limited (Nicolini, 2024).

The studies and reports presented in this section underscore the complexities involved, including uncertainties, financial instability, and differing levels of interest. The integration of climate change adaptation into heritage policies faces obstacles such as data reliability, resource constraints, and cooperation challenges. The role of international organizations like UNESCO and the UNFCCC is crucial, emphasizing the need for collaboration, access to skills and resources, and mainstreaming adaptation into existing agendas. The legal perspective stresses the importance of a "rights-based" system, recognizing the vital role of indigenous communities in adaptation efforts. National adaptation plans, as highlighted in the case of Ireland, are essential for addressing the unique challenges posed by climate change to cultural heritage resources. Additionally, the emphasis on institutional arrangements at the national level, as advocated by the UNFCCC, is crucial for effective coordination and integration across sectors.

4.6. Adaptive management and planning

Adaptive management and planning translate climate adaptation policies into practice through iterative learning, monitoring, and adjustment (Holling, 1978; IPCC, 2022). In the heritage sector, these frameworks are crucial for linking strategic policy goals with on-the-ground conservation, yet their application remains fragmented and often reactive (Sesana et al., 2021; ICOMOS, 2019). While some studies, such as Jernæs and Granberg (2020), emphasize integrating historical adaptation knowledge at municipal levels to strengthen urban and heritage resilience, most initiatives remain project-based rather than embedded in long-term governance structures. Urban transformation and the relocation of heritage buildings in Arctic mining towns illustrate how climate change forces difficult choices about what and where to preserve (Luciani & Sjöholm, 2020). These cases highlight the limits of traditional conservation and the need for adaptive management that anticipates change rather than merely responding to damage. The wider adaptation literature reinforces this view: short-term coping often increases long-term vulnerability if underlying social and ecological drivers are ignored (Fazey et al., 2010). Effective adaptation requires iterative, learning-based governance that builds local capacity and flexibility within broader development frameworks (Smit & Wandel, 2006). Within heritage policy, this translates to linking cultural and natural systems, integrating biodiversity and Indigenous knowledge into planning, and developing context-specific tools for resilience (Jacobs et al., 2019). Yet few studies evaluate how such adaptive principles are implemented in heritage management, revealing a persistent gap between theoretical adaptation models and practical governance mechanisms in the sector.

The integration of cultural heritage into climate adaptation policies increasingly emphasizes participatory and flexible planning approaches (Daly, 2017). Recent studies highlight the need for proactive and anticipatory strategies rather than reactive conservation. For example, relocation of archives and heritage collections from vulnerable regions has been proposed as a necessary though controversial form of adaptation (Tansey, 2015). Landscape-based approaches, such as those by Dupont and Van Eetvelde (2013), demonstrate how spatial analysis can guide adaptive planning, while projects like Newcastle's Coal River reinterpret heritage as a living and evolving landscape rather than a static monument (Roberts & Eklund, 2012). At the policy level, Ireland's National Adaptation Framework (Daly, 2019) stands out for integrating cultural heritage into national climate planning through measures that enhance adaptive capacity and stakeholder participation.

Integrating the European Landscape Convention with territorial planning has been proposed to enhance coherence in climate adaptation frameworks for heritage management (Shirvani Dastgerdi et al., 2020). Yet, heritage policies often remain fragmented, with limited coordination between cultural and environmental planning. While case studies offer practical guidance for site-specific adaptation (Jim & Charlie, 2014; Perry, 2015), the sector lacks mechanisms for continuous learning and monitoring, despite calls for iterative, adaptive management (O'Brien et al., 2015). Challenges persist in translating adaptation principles, flexibility, equity, and resilience into heritage policy and practice, particularly in balancing preservation with sustainability goals such as energy efficiency (Sesana et al., 2018). Recent frameworks and tools (Fatorić & Seekamp, 2017; Aktürk & Fatorić, 2021; Xiao et al., 2019) attempt to bridge this gap, but evidence of their policy uptake remains limited, revealing a broader disconnection between adaptation theory and heritage governance.

Recent scholarship demonstrates efforts to align heritage conservation with adaptive planning and climate resilience. Frameworks such as those applied in Catania (Privitera & Jelo, 2025) and UNESCO coastal buffer zones (Psoma & Pyla, 2025) exemplify a shift from reactive protection toward anticipatory, scenario-based planning rooted in Nature-based Solutions. Initiatives like the Eco-Wisdom Laboratory (Zhao et al., 2025) and the Netherlands' adaptive water management culture (Cheang et al., 2025) illustrate the potential for integrating traditional ecological knowledge and long-term governance into adaptation practice. Large-scale programs, SHELTER, ARCH, and OptiPres, seek to operationalize resilience through cross-sectoral coordination and evidence-based tools (Ripp et al., 2024; Xiao et al., 2024). Yet,

as Melbourne-Thomas et al. (2024) and Magni et al. (2024) note, the translation of these models into policy remains uneven, constrained by institutional silos and limited monitoring capacity.

Adaptive management and planning are increasingly recognized as essential for translating climate adaptation principles into actionable heritage conservation strategies. Yet, much of this work remains descriptive, focusing on process rather than evaluating outcomes or institutional effectiveness. Few studies critically assess how adaptive management is embedded within governance systems or whether it genuinely supports long-term resilience rather than short-term coping.

4.7. Sustainable conservation techniques

Sustainable conservation is increasingly framed as a key pathway for adapting cultural heritage to climate change. Rather than merely preserving the past, contemporary practice emphasizes adaptive reuse and environmentally responsive design that enhance resilience while maintaining heritage values (Germanà & Bagnato, 2019; Pintossi et al., 2023; Köpeczi-Bócz et al., 2025). Adaptive reuse is increasingly framed as both a conservation and adaptation strategy, offering pathways to enhance the resilience of heritage buildings while supporting sustainable development goals. However, tensions persist between energy efficiency and preservation principles, revealing a policy and technical gap in aligning heritage values with climate adaptation imperatives (Fiorani et al., 2017; Miran & Husein, 2023). Studies highlight reuse as a dynamic process that adds new layers of meaning to historic structures (Fiorani et al., 2017) and call for decision-making frameworks, such as multi-criteria analyses and lifecycle tools to evaluate adaptive options (Della Spina, 2021; Prieto et al., 2019). Yet, these approaches often remain site-specific and technocratic, with limited integration into broader climate adaptation planning (Li et al., 2022). Research in Italy, Australia, and Croatia demonstrates the importance of stakeholder participation and governance support to balance heritage integrity with energy transition goals (De Medici et al., 2020; Yazdani Mehr & Wilkinson, 2020; Pintossi et al., 2021). Such approaches align with broader adaptation principles of flexibility and transformation (IPCC, 2022), positioning heritage conservation within sustainability and circular-economy agendas. However, while adaptive reuse and maintenance-based strategies, such as rainwater harvesting and passive climate control are widely promoted, their effectiveness depends on integrating risk assessment and long-term monitoring, areas still underdeveloped in heritage adaptation research (Fatorić & Seekamp, 2017; Cassar, 2016). Furthermore, the concept of Ecosystem-based Adaptation (EbA) emerges as a cost-effective and flexible strategy in combating climate change impacts on heritage sites

(Munang et al., 2013). This approach considers the environmental elements surrounding heritage buildings, such as climate, topography, and vegetation, as highlighted by Chang et al. (2021) in their exploration of cultural ecology in heritage building adaptation, particularly in tropical cities. Integrating these environmental factors into conservation strategies becomes crucial for long-term sustainability and resilience.

Sedova (2021) argues that sustainability must guide decision-making for heritage buildings, while Saleem Beg (2016) highlights the adaptive value of vernacular techniques that align with local climates and materials. Integrating such knowledge into modern conservation practice strengthens both environmental and cultural resilience. Similarly, framing heritage within the circular economy underscores its potential as a renewable resource for sustainable development (Fusco Girard & Vecco, 2021). Yet, research remains fragmented: case studies from Indonesia (Soewarno, 2020) and the Arab world (Alghazawi et al., 2015) reveal limited institutional capacity and uneven regional expertise. Moreover, climate-induced maintenance challenges, such as material degradation and increased costs (Grøntoft, 2011), are rarely linked to policy-level adaptation frameworks.

Studies highlight the integration of disaster risk reduction and sustainability principles as essential for building resilience in heritage areas (Santangelo et al., 2022; Martens, 2017). Innovative methodologies such as the LegIT monitoring tool (Daly, 2017) and the adaptSTAR model for adaptive reuse (Conejos et al., 2017) illustrate efforts to operationalize adaptation through data-driven assessment and design flexibility. Case studies from China and Taiwan demonstrate the potential of regenerative and hybrid planning to reconcile historic and modern urban fabrics (Sun et al., 2022; Shih & Qiu, 2023). Similarly, the integration of green and grey infrastructure points to a more ecosystem-oriented adaptation paradigm (Vojinovic et al., 2021).

These studies suggest that implementation of sustainable conservation techniques in preserving cultural heritage involves a multidimensional approach, incorporating adaptive reuse, Ecosystem-based Adaptation, consideration of traditional knowledge, and the integration of heritage within sustainability frameworks.

4.8. Technological innovations

Technological innovation is increasingly recognized as a key enabler of adaptation of climate change in the heritage sector. Rather than focusing solely on documentation or preservation, emerging tools are now being used to enhance resilience and inform adaptive management. For

instance, the GBC Historic Building tool integrates energy efficiency into conservation practices (Boarin, 2016), while the OptiPres Model supports climate adaptation planning by balancing heritage value with vulnerability and cost-effectiveness (Li et al., 2022). Beyond technical optimization, digital and data-driven approaches, such as remote sensing, AI modeling, and participatory digital platforms, are expanding how communities engage with and manage heritage under changing climatic conditions (Bertacchini, 2017).

Furthermore, Projects such as STORM and VIADUC illustrate how predictive modelling, non-invasive monitoring, and regional climate projections can inform risk assessment and adaptive planning for cultural sites (Resta et al., 2019; Brum et al., 2018; Corre et al., 2015). More recently, digital and AI-based tools, ranging from augmented reality systems for interpretation to machine learning for predictive conservation, demonstrate the sector's growing engagement with data-driven adaptation (Bousbahi & Boreggah, 2018; Budiman et al., 2019; Xiao et al., 2023). Low-cost drone and sensor technologies further enhance real-time monitoring and preventive conservation (Bakirman et al., 2023; Tringa et al., 2024).

Emerging research shows that when digital tools are co-designed with local communities, they enhance adaptive capacity by linking cultural identity with environmental monitoring (Hearn & Fagerholm, 2025; Silva-Ávila et al., 2025). Participatory GIS, digital archives, and transdisciplinary data platforms have proven effective in translating Indigenous practices into adaptive governance, as seen in Myanmar and Chile (Bawi, 2025; Silva-Ávila et al., 2025). Such approaches echo broader adaptation literature emphasizing co-production, social learning, and knowledge hybridity as drivers of resilience. However, most applications remain project-based and unevenly integrated into formal policy, revealing a gap between technological potential and institutional uptake (López Campos et al., 2024; Gatiso et al., 2025).

While these innovations advance anticipatory and resilience-oriented adaptation, the literature remains largely instrumental, focusing on technical efficiency rather than examining how digital tools reshape governance, and participation in heritage adaptation. Few studies assess whether technologies are embedded within adaptive governance or ecosystem-based adaptation frameworks. This reflects a persistent gap between technological potential and institutional integration. Future research should therefore critically evaluate how innovation mediates decision-making and inclusivity, ensuring that digital approaches support

transformative and socially grounded adaptation pathways rather than functioning as isolated technical fixes.

4.9. Community engagement and indigenous knowledge

Community engagement and Indigenous knowledge are increasingly recognized as vital components of climate change adaptation for cultural heritage. Rather than viewing heritage as a static entity, recent literature stresses its potential as a living resource for resilience and community empowerment. However, heritage management still tends to prioritize material conservation over socio-cultural continuity, limiting adaptive capacity and local participation (Landorf, 2009). Participatory and Indigenous-led approaches, such as those involving Indigenous rangers in Australia (Carmichael et al., 2020) or community-based climate responses in the Pacific (Kundra et al., 2023), demonstrate how traditional knowledge enhances contextual understanding of climate risks and fosters place-based adaptation. Yet, many policies still treat Indigenous knowledge as supplementary to science rather than as a parallel knowledge system (Ford et al., 2016; Negi et al., 2017). This reflects a broader gap: heritage adaptation frameworks rarely institutionalize Indigenous agency, echoing wider critiques in adaptation studies on the marginalization of local voices (Perkins & Krause, 2018).

Studies emphasize their role in interpreting environmental change and guiding community-based responses (Henderson & Seekamp, 2018; Ayers & Forsyth, 2009). Integrating such knowledge into policy frameworks enhances cultural relevance and local ownership of adaptation measures. Examples such as the Mongolian Ger (Paddock & Schofield, 2017) and vernacular adaptation in heritage reuse (Plevoets & Sowińska-Heim, 2018) demonstrate how traditional practices can strengthen resilience while maintaining authenticity. However, despite increasing policy rhetoric, the practical integration of Indigenous knowledge remains limited, often constrained by top-down governance and lack of institutional support (Higgins, 2022; Pandey et al., 2018). This gap highlights the need for adaptive governance that bridges scientific and local systems, enabling proactive, community-led adaptation rather than reactive crisis responses (Füssel, 2007).

Van Dolah (2018) shows that heritage values can inform adaptive decision-making, while Williams and Hardison (2013) stress that equitable collaboration between researchers and Indigenous communities requires attention to legal, cultural, and governance contexts. These studies reveal that adaptation is not only technical but also social and ethical, demanding respect for local knowledge systems and community agency. Recent research emphasizes that

safeguarding intangible cultural heritage, particularly in contexts of climate-induced displacement is essential to maintaining cultural continuity and resilience (Aktürk & Lerski, 2021). Hiwasaki et al. (2014) outlined a process to merge local and indigenous knowledge with scientific methodologies to enhance adaptation efforts, acknowledging the value of these collective knowledge systems. Evidence from disaster risk reduction further illustrates this point: integrating Indigenous knowledge strengthens both participation and preparedness, as shown by Cuaton and Su (2020) in the Philippines and by Jigyasu (2019) in his call for proactive, knowledge-based adaptation planning.

Understanding place identity is central to climate change adaptation, as adaptation involves not only material responses but also the reconfiguration of how people relate to place. Fresque-Baxter and Armitage (2012) show that strong person place bonds can both enable and constrain adaptive behaviour, supporting commitment to conservation yet sometimes reinforcing resistance to change. In the heritage sector, this tension highlights the challenge of balancing authenticity with transformation. Stakeholders and community engagement emerge as recurring themes in adaptation literature and heritage practice. Studies such as Hermann et al. (2021) and Fatorić and Egberts (2020) demonstrate that inclusive participation enhances the legitimacy and sustainability of adaptation actions, aligning with broader adaptation governance principles that stress co-production and social learning. However, most heritage-focused initiatives remain project-based and lack mechanisms to embed participation into long-term policy frameworks. Evidence from diverse contexts including Hoi An (Bui et al., 2020) and the Solomon Islands (Leon et al., 2015) illustrates that linking local and scientific knowledge strengthens adaptive capacity, yet these examples are still exceptions rather than norms.

Studies emphasize that locally grounded, bottom-up approaches enhance both the relevance and resilience of interventions (Carmichael et al., 2017; Adetunji, 2025). Research in South Asia shows that Indigenous information systems evolve dynamically, integrating traditional and scientific knowledge to strengthen adaptive capacity (Jigyasu, 2002). Such approaches align with broader climate adaptation literature, which highlights co-production, local ownership, and social learning as key to effective and sustainable adaptation. However, the heritage field often underestimates the tensions between conservation values and adaptive change.

4.10. Ancient knowledge as adaptive capacity

Throughout history, human societies have demonstrated remarkable adaptive capacity to environmental and climatic variability foundation that contemporary climate change adaptation (CCA) efforts can build upon. Archaeological and historical evidence reveal long-term strategies of resilience, resource management, and social reorganization in response to shifting environments (Rockman, 2012; Varadzin et al., 2023). This historic adaptation perspective (Jernæs & Granberg, 2020) offers valuable insights for present-day CCA, emphasizing place-based learning and low-carbon practices rooted in traditional knowledge (Fluck & Dawson, 2021).

In arid zones such as Dhofar, Oman, early pastoral communities used monument construction as a collective mechanism for managing environmental uncertainty, an early expression of social adaptation (McCorriston et al., 2025). Similar ingenuity is evident in traditional water-harvesting systems in Turkey and hydraulic infrastructures in Sudan, which exemplify locally grounded forms of ecosystem-based adaptation (Gerçek et al., 2025; Minguez Garcia et al., 2024). Reviving earthen-building techniques and other low-carbon practices aligns with modern adaptation principles emphasizing nature-based and culturally embedded solutions (Nakhaei Ashtari et al., 2025). Yet, while these cases demonstrate the adaptive potential of heritage knowledge, current policy frameworks rarely integrate such practices into national or international adaptation agendas, reflecting a persistent gap between heritage preservation and climate governance (Elsayed et al., 2024).

Studies of pastoral and agrarian communities, from the Rabari in India to early civilizations in Armenia, Egypt, and the Fertile Crescent reveal locally grounded adaptive practices, such as flexible subsistence systems, selective breeding, and mobility (Salpeteur et al., 2017; Perello et al., 2021; Palmer et al., 2009; Lawrence et al., 2022). These examples highlight how adaptation was embedded in cultural, ecological, and social processes rather than driven by external policy or technology. Recent research emphasizes that ancient and Indigenous strategies can inform modern resilience thinking by integrating local knowledge, low-carbon practices, and ecosystem-based adaptation (Nunn, 2014; Smith, 2023; Orlove, 2005). However, heritage literature often treats such evidence descriptively rather than analytically, missing opportunities to examine how these historical adaptations could shape current climate policies and governance frameworks (Pei et al., 2019).

4.11. Barriers to climate change adaptation

Barriers to climate change adaptation in the cultural heritage sector remain a persistent challenge, limiting the translation of policy ambitions into practice. Research identifies four key categories, institutional, technical, socio-cultural, and financial, but most studies stop at describing these obstacles rather than analysing how and why they persist (Fatorić & Biesbroek, 2020). Institutional and technical limitations, such as fragmented governance and lack of expertise, often combine with short-term funding and reactive planning to undermine adaptation capacity (Casey & Becker, 2019). Drawing on broader climate adaptation literature, these challenges reflect what Biesbroek et al. (2013) call the "implementation gap," where adaptation is constrained by weak coordination, insufficient political will, and limited cross-sectoral integration. In heritage contexts, the problem is intensified by rigid regulatory frameworks and conservation ethics that prioritise preservation over transformation.

Research on barriers to cultural heritage adaptation reveals uneven geographical focus and limited analytical depth. Most studies concentrate on Europe, with gaps across the Middle East and North Africa, particularly in small and mid-sized municipalities where institutional and financial capacities are weakest (Fila et al., 2023). A recurring theme is the fragmentation of governance, heritage and climate policies often operate in silos, reducing coherence and accountability (Eisenack et al., 2014; Moser & Ekstrom, 2010). Actor-centered perspectives show that effective adaptation depends on the agency and coordination of multiple stakeholders, yet decision-making remains top-down in most contexts. Comparative analyses, such as Aktürk's (2022) review of polar regions, identify technical, regulatory, and behavioral barriers that mirror broader adaptation challenges across sectors. However, few studies critically assess why these barriers persist or how institutional learning could address them. Moreover, adaptation in heritage contexts often underestimates social and cultural dimensions, including resistance to change within local communities (Fatorić & Seekamp, 2017; Trõger, 2016).

Institutional fragmentation, political constraints, and inadequate funding mechanisms remain among the most critical challenges limiting the implementation of effective heritage adaptation strategies (Thuc et al., 2024). These issues are compounded by a lack of technical expertise and coordinated governance structures that can translate policies into actionable plans. Moreover, limited access to training and knowledge-sharing platforms exacerbates the gap between policy ambition and on-the-ground practice. Strengthening capacity-building initiatives and embedding heritage considerations into disaster risk reduction and adaptation programs have

therefore been identified as essential steps toward overcoming institutional and knowledge-related barriers (Bhatia & Shukla, 2024).

The challenges in identifying and categorizing barriers remain focal points, demanding comprehensive, integrated strategies to overcome these hurdles. The complexity of these barriers underscores the importance of collaborative efforts, compelling cases for investments, and an interdisciplinary approach to foster effective climate change adaptation for cultural heritage.

4.12. Gaps in research

The literature on climate change adaptation for cultural heritage reveals significant research gaps in developing effective strategies for safeguarding heritage sites and landscapes against the impacts of a changing climate. Despite an emerging understanding of the vulnerability of cultural heritage to climate change, there exists a dearth of comprehensive research on practical and successful adaptation strategies in this domain (Sesana et al., 2018). One reason contributing to this gap is the relatively recent recognition of the importance of cultural heritage in the context of climate change. The focus of climate change research has traditionally centered around environmental and ecological impacts, leaving limited room for addressing the social and cultural dimensions, particularly cultural heritage (Fatorić & Biesbroek, 2020). This historical bias might have led to the limited integration of cultural heritage concerns into mainstream climate change research and planning, delaying the development of specialized adaptation measures for heritage sites. Furthermore, the challenges of evaluating and quantifying the effectiveness of adaptation measures for diverse cultural heritage sites present another obstacle. Cultural heritage locations vary significantly and often have unique characteristics, making the application of standardized adaptation strategies challenging. These adaptation measures must be culturally sensitive, considering the local values and significance attached to these heritage sites. The complexity of this context could be a deterrent for researchers in exploring and developing specific adaptation approaches (Henderson & Seekamp, 2018). Another significant factor contributing to the research gap is the interdisciplinary nature of addressing climate change impacts on cultural heritage. Effective adaptation strategies require collaboration between experts from diverse fields such as climate science, archaeology, heritage conservation, architecture, community engagement, and policy development. Interdisciplinary research can be challenging due to differences in methodologies, terminologies, and perspectives among these different disciplines (Sesana et al., 2018). Moreover, there is a need for case studies and best practices that illustrate successful

adaptation measures for different types of cultural heritage sites and landscapes, providing practical guidance and insight into successful strategies (Sesana et al., 2018).

4.13. Summary of Key Issues

This review provides the first comprehensive synthesis of two decades of research on climate change adaptation in cultural heritage, revealing both the progress achieved and the significant gaps that remain. The findings highlight that adaptive management and planning dominate literature, reflecting a strong focus on integrating resilience thinking into heritage conservation and urban management. However, technological innovations and studies addressing barriers to adaptation remain underrepresented, exposing a crucial research frontier for developing more effective, data-driven, and context-sensitive solutions. The geographic distribution of studies reveals a pronounced Eurocentric bias, with limited contributions from Africa, Latin America, and the Pacific, regions that are among the most vulnerable to climate impacts yet least studied in heritage adaptation research.

A key insight emerging from this synthesis is that resilient heritage management depends on combining scientific knowledge, traditional practices, and community engagement within inclusive policy frameworks. Nevertheless, fragmented governance, limited funding, and disciplinary silos continue to impede the mainstreaming of cultural heritage within broader climate adaptation agendas. The review emphasizes that the integration of tangible and intangible values, as well as cross-sectoral collaboration, is essential to ensuring culturally appropriate and sustainable adaptation measures.

Future research must therefore prioritize interdisciplinary and transdisciplinary collaboration, capacity building, and the development of practical case studies that evaluate adaptation effectiveness across diverse heritage contexts. By bridging the gap between heritage conservation, climate science, and community practice, the sector can move toward a more equitable, inclusive, and actionable adaptation framework that aligns with global climate resilience goals. This review reveals that while adaptation concepts are increasingly embedded in heritage policy, practical applications remain fragmented, especially for earthen sites in developing and arid regions. These insights guide the subsequent examination of barriers that hinder effective adaptation at the local level.

References

Adetunji, O. (2025). *Social participation for climate change adaptation of cultural built heritage: a case study of Nigeria* (Doctoral dissertation, Open Research Newcastle).

Aktürk, G. (2022). A systematic overview of the barriers to building climate adaptation of cultural and natural heritage sites in polar regions. *Environmental Science & Policy*, *136*, 19-32.

Aktürk, G., & Fatorić, S. (2021). Roundtable III: Climate Change Adaptation of Cultural Heritage. In U. Pottgiesser, S. Fatoric, C. Hein, E. de Maaker, & A. Pereira Roders (Eds.), LDE Heritage Conference on Heritage and the Sustainable Development Goals: Proceedings (pp. 521-523). TU Delft Open.

Aktürk, G., & Lerski, M. (2021). Intangible cultural heritage: a benefit to climate-displaced and host communities. *Journal of Environmental Studies and Sciences*, *11*(3), 305-315.

Alghazawi, R., Waheeb, M., & Kraishan, D. (2015). Cultural heritage management adaptation in the Arab world: Review & Perspectives. *Mediterranean Archaeology and Archaeometry*, *15*(1), 11-11.

Antonson, H., Buckland, P., & Nyqvist, R. (2021). A society ill-equipped to deal with the effects of climate change on cultural heritage and landscape: a qualitative assessment of planning practices in transport infrastructure. *Climatic Change*, *166*(1), 18.

Ayers, J., & Forsyth, T. (2009). Community-based adaptation to climate change. *Environment: science and policy for sustainable development*, *51*(4), 22-31.

Bakirman, T., Kulavuz, B., & Bayram, B. (2023). Use of Artificial Intelligence Toward Climate-neutral Cultural Heritage. *Photogrammetric Engineering & Remote Sensing*, *89*(3), 163–171. https://doi.org/10.14358/PERS.22-00118R2

Ballard, C., Baron, N., Bourgès, A., Bucher, B., Cassar, M., Daire, M.-Y., Daly, C., Egusquiza, A., Fatoric, S., Holtorf, C., Kosian, M., & Lefevre, R.-A. (2022). Cultural Heritage and Climate Change: New challenges and perspectives for research.

Bawi, S. V. (2025). Revitalizing Ritual Performances for Environmental Conservation and Climate Change Adaptation: A Case Study of Ecotourism in Khaw Nu M'cung National Park, Myanmar. *Forest and Society*, *9*(1), 48–69. https://doi.org/10.24259/fs.v9i1.33163

Bertacchini, E. (2017). Cultural heritage in a changing world. *Journal of Cultural Economics*, *41*(3), 337–340. https://doi.org/10.1007/s10824-017-9301-5

Bhatia, S., & Shukla, N. (2024). Integrating traditional knowledge and cultural heritage with climate adaptation and disaster risk reduction: The role of training and tools. *Journal of Cultural Heritage Management and Sustainable Development*, *14*(5), 773–776. https://doi.org/10.1108/JCHMSD-05-2024-0095

Biesbroek, G. R., Klostermann, J. E. M., Termeer, C. J. A. M., & Kabat, P. (2013). On the nature of barriers to climate change adaptation. *Regional Environmental Change*, *13*(5), 1119–1129. https://doi.org/10.1007/s10113-013-0421-y

Boarin, P. (2016). Bridging the gap between environmental sustainability and heritage preservation: towards a certified sustainable conservation, adaptation and retrofitting of historic buildings. *Revisiting the role of architectural science in design and practice*, 28-30.

Bonazza, A., Sardella, A., Kaiser, A., Cacciotti, R., De Nuntiis, P., Hanus, C., Maxwell, I., Drdácký, T., & Drdácký, M. (2021). Safeguarding cultural heritage from climate change related hydrometeorological hazards in Central Europe. *International Journal of Disaster Risk Reduction*, *63*, 102455. https://doi.org/10.1016/j.ijdrr.2021.102455

Boro, M., Flyen, A. C., Bain, R., & Bexelius, J. (2020). Adapt Northern Heritage Toolkit: Adaptation stories Examples of risk assessment, adaptation planning and conservation management of northern historic places. Historic Environment Scotland.

Bousbahi, F., & Boreggah, B. (2018). Mobile Augmented Reality Adaptation through Smartphone Device Based Hybrid Tracking to Support Cultural Heritage Experience. *Proceedings of the 2nd International Conference on Smart Digital Environment*, 48–55. https://doi.org/10.1145/3289100.3289109

Brimblecombe, P., Grossi, C. M., & Harris, I. (2011). Climate change critical to cultural heritage. In *Survival and sustainability: environmental concerns in the 21st century* (pp. 195-205). Berlin, Heidelberg: Springer Berlin Heidelberg.

Brum, P., Neto, F., Revez, M. J., Vaz Pinto, I., & Magalhães, A. P. (2018). *STORM: Safeguarding Cultural Heritage through Technical and Organizational Resources*. ICOMOS 19th General Assembly and Scientific Symposium 'Heritage and Democracy', New Delhi, India. https://openarchive.icomos.org/id/eprint/2037/

Budiman, E., Wati, M., & Norhidayat. (2019). The 5R adaptation framework for cultural heritage management information system of the Dayak tribe Borneo. *Journal of Physics: Conference Series*, *1341*(4), 042016. https://doi.org/10.1088/1742-6596/1341/4/042016

Bui, H. T., Jones, T. E., Weaver, D. B., & Le, A. (2020). The adaptive resilience of living cultural heritage in a tourism destination. *Journal of Sustainable Tourism*, *28*(7), 1022-1040.

Burton, I., Diringer, E., & Smith, J. (2006). *Adaptation to climate change: international policy options*. Arlington: Pew Center on Global Climate Change.

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Cahill, J., & Bird, D. (2017). Testing the scoping phase of a bottom-up planning guide designed to support Australian Indigenous rangers manage the impacts of climate change on cultural heritage sites. *Local Environment*, *22*(10), 1197-1216.

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Cahill, J., Brockwell, S., ... & Daly, C. (2020). A methodology for the assessment of climate change adaptation options for cultural heritage sites. *Climate*, *8*(8), 88.

Casey, A., & Becker, A. (2019). Institutional and Conceptual Barriers to Climate Change Adaptation for Coastal Cultural Heritage. *Coastal Management*, *47*(2), 169–188. https://doi.org/10.1080/08920753.2019.1564952

Cassar, J. (2016). Climate change and archaeological sites: Adaptation strategies. Edipuglia.

Cassar, M., & Pender, R. (2005). The impact of climate change on cultural heritage: evidence and response. In *ICOM Committee for Conservation: 14th Triennial Meeting The Hague, Preprints* (Vol. 2, pp. 610-616). James & James.

Chang, B., Hasanah, A., & Caesarina, H. M. (2021, May). Cultural ecology of heritage building adaptation in tropical cities. In *IOP Conference Series: Earth and Environmental Science* (Vol. 780, No. 1, p. 012058). IOP Publishing.

Cheang, K., Bai, N., & Pereira Roders, A. (2025). Unveiling Climate-Adaptive World Heritage Management Strategies: The Netherlands as a Case Study. *Sustainability*, *17*(12), 5555. https://doi.org/10.3390/su17125555

Chen, Y., Wang, D., Zhang, L., Wang, C., Sun, C., & Dong, Q. (2025). World Heritage documents reveal persistent gaps between climate awareness and local action. *Nature Climate Change*, 1-7.

Conejos, S., Chew, M. Y., & Yung, E. H. (2017). The future adaptivity of nineteenth century heritage buildings. *International Journal of Building Pathology and Adaptation*, *35*(4), 332-347.

Corre, L., Dandin, P., L'Hôte, D., & Besson, F. (2015). The VIADUC project: Innovation in climate adaptation through service design. *Advances in Science and Research*, *12*(1), 199–205. 14th EMS Annual Meeting & 10th European Conference on Applied Climatology (ECAC) -. https://doi.org/10.5194/asr-12-199-2015

Crowley, K., Jackson, R., O'Connell, S., Karunarthna, D., Anantasari, E., Retnowati, A., & Niemand, D. (2022). Cultural heritage and risk assessments: Gaps, challenges, and future research directions for the inclusion of heritage within climate change adaptation and disaster management. *Climate Resilience and Sustainability*, *1*(3), e45. https://doi.org/10.1002/cli2.45

Cuaton, G. P., & Su, Y. (2020). Local-indigenous knowledge on disaster risk reduction: Insights from the Mamanwa indigenous peoples in Basey, Samar after Typhoon Haiyan in the Philippines. *International Journal of Disaster Risk Reduction*, *48*, 101596.

Daly, C. (2011). Climate Change and the Conservation of Archaeological Sites: A Review of Impacts Theory. *Conservation and Management of Archaeological Sites*, *13*(4), 293–310. https://doi.org/10.1179/175355212X13315728646058

Daly, C. (2014a). *A Cultural Heritage Management Methodology for Assessing the Vulnerabilities of Archaeological Sites to Predicted Climate Change Focuing on Ireland's Two World Heritage Sites*. https://doi.org/10.21427/D76G65

Daly, C. (2014b). A Framework for Assessing the Vulnerability of Archaeological Sites to Climate Change: Theory, Development, and Application. *Conservation and Management of Archaeological Sites*, *16*(3), 268–282. https://doi.org/10.1179/1350503315Z.00000000086

Daly, C. (2017). Archaeological and Built Heritage Climate Adaptation Sectoral Plan Background Study. Report prepared for Department of Arts, Heritage, Regional, Rural and Gaeltacht Affairs of Ireland. School of History and Heritage, College of Arts, University of Lincoln.

Daly, C. (2019, September 30). *Built & Archaeological Heritage Climate Change Sectoral Adaptation Plan* [Paper or Report]. Department of Culture, Heritage and the Gaeltacht. https://assets.gov.ie/75639/a0ad0e1d-339c-4e11-bc48-07b4f082b58f.pdf

Daly, C., Engel Purcell, C., Donnelly, J., Chan, C., MacDonagh, M., & Cox, P. (2020). Climate change adaptation planning for cultural heritage, a national scale methodology. *Journal of Cultural Heritage Management and Sustainable Development*, *11*(4), 313–329. https://doi.org/10.1108/JCHMSD-04-2020-0053

Daly, C., Fatorić, S., Carmichael, B., Pittungnapoo, W., Adetunji, O., Hollesen, J., Nakhaei, M., & Diaz, A. H. (2022). Climate change adaptation policy and planning for cultural heritage in low-and middle-income countries. *Antiquity*, *96*(390), 1427-1442.

Dapilah, F., Bedigbee, B. A., & Bonye, S. Z. (2025). Adaptation to climate change in nature-based tourist destination in northern Ghana. *Journal of Outdoor Recreation and Tourism*, *51*, 100918. https://doi.org/10.1016/j.jort.2025.100918

Dastgerdi, A. S., & De Luca, G. (2025). Harmonizing Cultural Landscape with Resilience: Climate Adaptation Strategies in the Arno and Hudson River Basins. *Sustainability*, *17*(13), 6058. https://doi.org/10.3390/su17136058

De Medici, S., De Toro, P., & Nocca, F. (2019). Cultural heritage and sustainable development: Impact assessment of two adaptive reuse projects in Siracusa, Sicily. *Sustainability*, *12*(1), 311.

Della Spina, L. (2021). Cultural heritage: A hybrid framework for ranking adaptive reuse strategies. *Buildings*, *11*(3), 132.

Eisenack, K., Moser, S. C., Hoffmann, E., Klein, R. J. T., Oberlack, C., Pechan, A., Rotter, M., & Termeer, C. J. A. M. (2014). Explaining and overcoming barriers to climate change adaptation. *Nature Climate Change*, *4*(10), Article 10. https://doi.org/10.1038/nclimate2350

El-Ashry, M. (2009). Adaptation to climate change: Building resilience and reducing vulnerability. *Climate Change Policy*, 58.

Elsayed, A. S., El Siedy, R., & Mustafa, I. K. (2024). Burj Rashid: A tale of two tides – rising waters and changing traditions. *Journal of Cultural Heritage Management and Sustainable Development*, *14*(5), 782–786. https://doi.org/10.1108/JCHMSD-06-2024-0158

Fatorić, S., & Biesbroek, R. (2020). Adapting cultural heritage to climate change impacts in the Netherlands: Barriers, interdependencies, and strategies for overcoming them. *Climatic Change*, *162*(2), 301–320. https://doi.org/10.1007/s10584-020-02831-1

Fatorić, S., & Egberts, L. (2020). Realising the potential of cultural heritage to achieve climate change actions in the Netherlands. *Journal of Environmental Management*, *274*, 111107.

Fatorić, S., & Seekamp, E. (2017). Are cultural heritage and resources threatened by climate change? A systematic literature review. *Climatic Change*, *142*(1), 227–254. https://doi.org/10.1007/s10584-017-1929-9

Fazey, I., Gamarra, J. G., Fischer, J., Reed, M. S., Stringer, L. C., & Christie, M. (2010). Adaptation strategies for reducing vulnerability to future environmental change. *Frontiers in Ecology and the Environment*, *8*(8), 414–422. https://doi.org/10.1890/080215

Fila, D., Fünfgeld, H., & Dahlmann, H. (2023). Climate change adaptation with limited resources: Adaptive capacity and action in small- and medium-sized municipalities. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-023-02999-3

Fiorani, D., Kealy, L., Musso, S. F., Houbart, C., PLEVOETS, B., & Van Cleempoel, K. (2017). *Conservation-Adaptation. Keeping alive the spirit of the place. Adaptive reuse of heritage with symbolic value*. EAAE.

Fluck, H. (2016). Climate change adaptation report. *Historic England report*, *28*, 2016.

Fluck, H., & Dawson, M. (2021). Climate Change and the Historic Environment. *The Historic Environment: Policy & Practice*, *12*(3–4), 263–270. https://doi.org/10.1080/17567505.2021.1990492

Ford, J., Maillet, M., Pouliot, V., Meredith, T., Cavanaugh, A., Lwasa, S., Llanos, A., Berrang-Ford, L., Carcamo, C., Namanya, D. B., Harper, S., & IHACC Research Team. (2016). Adaptation and Indigenous peoples in the United Nations Framework Convention on Climate Change. *Climatic Change*, *139*(3), 429–443. https://doi.org/10.1007/s10584-016-1820-0

Fresque-Baxter, J. A., & Armitage, D. (2012). Place identity and climate change adaptation: a synthesis and framework for understanding. *Wiley Interdisciplinary Reviews: Climate Change*, *3*(3), 251-266.

Fusco Girard, L., & Vecco, M. (2021). The “intrinsic value” of cultural heritage as driver for circular human-centered adaptive reuse. *Sustainability*, *13*(6), 3231.

Füssel, H. M. (2007). Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustainability science*, *2*(2), 265-275.

Gandini, A., Garmendia, L., & San Mateos, R. (2017). Towards sustainable historic cities: Mitigation climate change risks. *Entrepreneurship and Sustainability Issues*, *4*(3), 319–327. https://doi.org/10.9770/jesi.2017.4.3S(7)

Gatiso, T. T., Greenhalgh, S., Korovulavula, I., Fong, T., & Radikedike, R. P. (2025). Climate change-induced relocation dilemma between preserving cultural heritage and embracing modern infrastructure: Insights from Fijian coastal villages. *Climatic Change*, *178*(7), 131. https://doi.org/10.1007/s10584-025-03972-x

Gerçek, D., Yüceer, H., Özcan Gönülal, Y., Uştuk, O., Uzelli, T., Güler, S., & Baba, A. (2025). *Traditional Water Harvesting Systems In Climate Change Adaptation: Insights From A Semi-Arid Mediterranean Village*. https://doi.org/10.4305/METU.JFA.2025.1.8

Germanà, M., & Bagnato, V. (2019). Adaptation vs fragility, rule vs exception: antinomies of the architectural heritage. *STUDI E PROGETTI*, 33-38.

Grøntoft, T. (2011). Climate change impact on building surfaces and façades. *International Journal of Climate Change Strategies and Management*, *3*(4), 374-385.

Gruber, S. (2011). The impact of climate change on cultural heritage sites: environmental law and adaptation. *Carbon & Climate Law Review*, 209-219.

Hearn, K. P., & Fagerholm, N. (2025). The characterisation and future sustainability of a rural landscape: Using integrated approaches for temporal heritage landscape analysis in Northwest Spain. *Landscape Ecology*, *40*(4), 76. https://doi.org/10.1007/s10980-025-02083-3

Henderson, M., & Seekamp, E. (2018). Battling the Tides of Climate Change: The Power of Intangible Cultural Resource Values to Bind Place Meanings in Vulnerable Historic Districts. *Heritage*, *1*(2), Article 2. https://doi.org/10.3390/heritage1020015

Hermann, C., Glindmeier, V., Boro, M., Haugen, A., Sigurðarson, G. S., & Sonehag, T. (2021, October). Raising awareness and training professionals to assess climate risks to historic buildings and commence adaptation planning-Experiences from Adapt Northern Heritage. In *IOP Conference Series: Earth and Environmental Science* (Vol. 863, No. 1, p. 012029). IOP Publishing.

Higgins, N. (2022). Changing Climate; Changing Life—Climate Change and Indigenous Intangible Cultural Heritage. *Laws*, *11*(3), Article 3. https://doi.org/10.3390/laws11030047

Hiwasaki, L., Luna, E., & Shaw, R. (2014). Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. *International journal of disaster risk reduction*, *10*, 15-27.

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

Holling, C. S. (1978). *Adaptive environmental assessment and management*. John Wiley & Sons.

Horowitz, A. D., Lopez, M. F., Ross, S. M., & Sparenberg, J. A. (2016). *CLIMATE CHANGE AND CULTURAL HERITAGE CONSERVATION - A LITERATURE REVIEW* [Monograph]. APT Technical Committee on Sustainable Preservation's Education and Research focus group. http://www.apti.org/clientuploads/Technical%20Committees/2015-2016/APT%20TC-SP%20Literature%20Review%20Climate%20Change%20%20Cultural%20Heritage%20Conservation%202016June30.pdf

Huq, S., & Reid, H. (2004). Mainstreaming Adaptation in Development. *IDS Bulletin*, *35*(3), 15–21. https://doi.org/10.1111/j.1759-5436.2004.tb00129.x

ICOMOS. (2019). *The Future of Our Pasts: Engaging cultural heritage in climate action Outline of Climate Change and Cultural Heritage* (- International Council on Monuments and Sites - ICOMOS & H. Wilson, Eds). International Council on Monuments and Sites - ICOMOS. https://openarchive.icomos.org/id/eprint/2459/

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White, Eds.). Cambridge University Press. https://doi.org/10.1017/CBO9781107415379

Intergovernmental Panel on Climate Change (IPCC). (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009325844

Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team: H. Lee & J. Romero, Eds.). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

Jacobs, B., Boronyak, L., & Mitchell, P. (2019). Application of risk-based, adaptive pathways to climate adaptation planning for public conservation areas in NSW, Australia. *Climate*, *7*(4), 58.

Jernæs, N., & Granberg, M. (2020). *A retrospective approach to managing cultural heritage in a changing climate*. *79*.

Jigyasu, R. (2002). *Reducing Disaster Vulnerability through Local Knowledge and Capacity. The Cace of Earthquake Prone Rural Communities in India and Nepal*. Fakultet for arkitektur og billedkunst.

Jigyasu, R. (2019). Managing cultural heritage in the face of climate change. *Journal of International Affairs*, *73*(1), 87-100.

Jim, P., & Charlie, F. (2014). *Climate change adaptation for natural World Heritage sites: A practical guide*. UNESCO.

Johnston, W., & Cooper, A. (2022). Small islands and climate change: analysis of adaptation policy in the Cayman Islands. *Regional Environmental Change*, *22*(2), 45.

Kim, H. E. (2011). Changing climate, changing culture: adding the climate change dimension to the protection of intangible cultural heritage. *International Journal of Cultural Property*, *18*(3), 259-290.

Kundra, S., Nabobo-Baba, U., Kundra, N., Gabriel, M., Alam, M. A., Takiveikata, S., & Toga, K. (2023). Assessment of the Local Traditional Knowledge and Practices of Flood Risk Identification Techniques: A Case Study of Nadaro Village, Tailevu, Fiji. In *Indigenous Knowledge and Disaster Risk Reduction: Insight Towards Perception, Response, Adaptation and Sustainability* (pp. 127-151). Cham: Springer International Publishing.

Landorf, C. (2009). A framework for sustainable heritage management: A study of UK industrial heritage sites. *International Journal of Heritage Studies*, *15*(6), 494-510.

Lawrence, D., Philip, G., & de Gruchy, M. W. (2022). Climate change and early urbanism in Southwest Asia: A review. *Wiley Interdisciplinary Reviews: Climate Change*, *13*(1), e741.

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

Leon, J. X., Hardcastle, J., James, R., Albert, S., Kereseka, J., & Woodroffe, C. D. (2015). Supporting local and traditional knowledge with science for adaptation to climate change: lessons learned from participatory three-dimensional modeling in BoeBoe, Solomon Islands. Coastal Management, 43(4), 424-438.

Li, P., Xiao, X., & Seekamp, E. (2022). Climate adaptation planning for cultural heritages in coastal tourism destinations: A multi-objective optimization approach. *Tourism Management*, *88*, 104380. https://doi.org/10.1016/j.tourman.2021.104380

López Campos, L. I., Prestileo, F., Stella, E. M., Mascitelli, A., Aruffo, E., Chiacchiaretta, P., Di Carlo, P., & Dietrich, S. (2024). Heritage Resilience and Identity: Lesson from Trabocchi Coast about Climate Change Adaptation Strategies. *Sustainability*, *16*(14), 5848. https://doi.org/10.3390/su16145848

Luciani, A., & Sjöholm, J. (2020). Adaptation and relocation of built heritage: what can we learn from the urban transformations of Swedish mining towns?. In *Adapt Northern Heritage Conference, Virtual, May 5-6, 2020* (pp. 188-195). Northern Periphery and Arcitc Programme.

Magni, F., Lucertini, G., & Federico, K. (2024). *From the lagoon-city to the lagoon of adaptive cities*. https://air.iuav.it/handle/11578/342749

Martens, V. V. (2017). Mitigating climate change effects on cultural heritage?.

McCorriston, J., Ball, L., Harrower, M. J., Hamilton, I. M., Ivory, S. J., Senn, M. J., Steimer-Herbet, T., Buffington, A. F., Al-Kathiri, A. A., & Al-Mahri, A. M. (2025). South Arabia's prehistoric monument landscape shows social resilience to climate change. *PLOS ONE*, *20*(5), e0323544. https://doi.org/10.1371/journal.pone.0323544

Melbourne-Thomas, J., Lin, B. B., Hopkins, M., Hill, R., Dunlop, M., MacGregor, N., Merson, S. D., Vertigan, C., Donegan, L., Sheppard, M., Meyers, J., Thomas, L., Visschers, L., McNeair, B., Syme, L., Grant, C., Pedrocchi, N., Oakley, P., Stevens, A., … Ireland, T. (2024). Building capacity for climate adaptation planning in protected area management: Options and challenges for World Heritage. *Biological Conservation*, *290*, 110459. https://doi.org/10.1016/j.biocon.2024.110459

Minguez Garcia, B., Saif Alislam Abdulgadir Ahmed, M., Elgadi, E. O., & Elkhalifa, A. A. (2024). Sudan's climate-culture story: A project with HEART – Heritage Empowered Action for Risk in Tuti. *Journal of Cultural Heritage Management and Sustainable Development*, *14*(5), 793–797. https://doi.org/10.1108/JCHMSD-03-2024-0053

Miran, F. D., & Husein, H. A. (2023). Introducing a conceptual model for assessing the present state of preservation in heritage buildings: Utilizing building adaptation as an approach. *Buildings*, *13*(4), 859.

Moser, S. C., & Ekstrom, J. A. (2010). A framework to diagnose barriers to climate change adaptation. *Proceedings of the national academy of sciences*, *107*(51), 22026-22031.

Mualam, N. (2020). Tracing the Effectiveness of Land Use Regulation: The Case of Heritage Protection Measures, Flexibility, and Adaptations. In *Measuring the Effectiveness of Real Estate Regulation: Interdisciplinary Perspectives* (pp. 61-84). Cham: Springer International Publishing.

Munang, R., Thiaw, I., Alverson, K., Mumba, M., Liu, J., & Rivington, M. (2013). Climate change and Ecosystem-based Adaptation: A new pragmatic approach to buffering climate change impacts. *Current Opinion in Environmental Sustainability*, *5*(1), 67–71. https://doi.org/10.1016/j.cosust.2012.12.001

Nakhaei Ashtari, M., Della Ventura, G., & Correia, M. (2025). From drought to deluge: The complex impacts of climate change on earthen heritage. *Journal of Cultural Heritage Management and Sustainable Development*. https://doi.org/10.1108/JCHMSD-05-2024-0116

Negi, V. S., Maikhuri, R. K., Pharswan, D., Thakur, S., & Dhyani, P. P. (2017). Climate change impact in the Western Himalaya: People's perception and adaptive strategies. *Journal of Mountain Science*, *14*(2), 403–416. https://doi.org/10.1007/s11629-015-3814-1

Nguyen, K. N., & Baker, S. (2023). Climate Change and UNESCO World Heritage-Listed Cultural Properties: A Systematic Review, 2008–2021. *Heritage*, *6*(3), Article 3. https://doi.org/10.3390/heritage6030126

Nicolini, E. (2024). Climate change adaptation and mitigation and historic centers preservation. Underway and repeatable technological design solutions. *Cities*, *152*, 105174. https://doi.org/10.1016/j.cities.2024.105174

Nicu, I. C. (2016). Cultural heritage assessment and vulnerability using Analytic Hierarchy Process and Geographic Information Systems (Valea Oii catchment, North-eastern Romania). An approach to historical maps. *International Journal of Disaster Risk Reduction*, *20*, 103–111. https://doi.org/10.1016/j.ijdrr.2016.10.015

Nunn, P. D. (2014). Geohazards and myths: ancient memories of rapid coastal change in the Asia-Pacific region and their value to future adaptation. *Geoscience Letters*, *1*(1), 3.

Orlove, B. (2005). Human adaptation to climate change: A review of three historical cases and some general perspectives. *Environmental Science & Policy*, *8*(6), 589–600. https://doi.org/10.1016/j.envsci.2005.06.009

Orr, S. A., Richards, J., & Fatorić, S. (2021). Climate Change and Cultural Heritage: A Systematic Literature Review (2016–2020). *The Historic Environment: Policy & Practice*, *12*(3–4), 434–477. https://doi.org/10.1080/17567505.2021.1957264

Paddock, C., & Schofield, J. (2017). Authenticity and adaptation: the Mongol Ger as a contemporary heritage paradox. *International Journal of Heritage Studies*, *23*(4), 347-361.

Palmer, S. A., Moore, J. D., Clapham, A. J., Rose, P., & Allaby, R. G. (2009). Archaeogenetic Evidence of Ancient Nubian Barley Evolution from Six to Two-Row Indicates Local Adaptation. *PLOS ONE*, *4*(7), e6301. https://doi.org/10.1371/journal.pone.0006301

Pandey, R., Kumar, P., Archie, K. M., Gupta, A. K., Joshi, P. K., Valente, D., & Petrosillo, I. (2018). Climate change adaptation in the western-Himalayas: Household level perspectives on impacts and barriers. *Ecological Indicators*, *84*, 27-37.

Pearson, J., Jackson, G., & McNamara, K. E. (2021). Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, 20530196211005482. https://doi.org/10.1177/20530196211005482

Pei, S., Deng, C., de la Torre, I., Jia, Z., Ma, D., Li, X., & Wang, X. (2019). Magnetostratigraphic and archaeological records at the Early Pleistocene site complex of Madigou (Nihewan Basin): Implications for human adaptations in North China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *530*, 176–189. https://doi.org/10.1016/j.palaeo.2019.05.014

Perello, B., Badalyan, R., & Meliksetian, K. (2021). Ancient Armenia at the crossroads: Natural hazards and Adaptation Strategies in Armenia from 10 000 BCE onwards. *Quaternary International*, *579*, 1–5. https://doi.org/10.1016/j.quaint.2021.02.034

Pérez-Pérez, B., & Chacón-Linares, E. (2025). Energy Transition and Heritage in Anthropocene Era—Proposal for a Methodological Analysis at Local Scale. *Urban Science*, *9*(4), 112. https://doi.org/10.3390/urbansci9040112

Perkins, R. M., & Krause, S. M. (2018). Adapting to climate change impacts in Yap State, Federated States of Micronesia: The importance of environmental conditions and intangible cultural heritage. *Island Studies Journal*, *13*(1), 65–78. https://doi.org/10.24043/isj.51

Perry, J. (2015). Climate change adaptation in the world's best places: A wicked problem in need of immediate attention. *Landscape and Urban Planning*, *133*, 1-11.

Phillips, H. (2014). Adaptation to Climate Change at UK World Heritage Sites: Progress and Challenges. *The Historic Environment: Policy & Practice*, *5*(3), 288–299. https://doi.org/10.1179/1756750514Z.00000000062

Pintossi, N., Kaya, D. I., Van Wesemael, P., & Roders, A. P. (2023). Challenges of cultural heritage adaptive reuse: A stakeholders-based comparative study in three European cities. *Habitat International*, *136*, 102807.

Plevoets, B., & Sowińska-Heim, J. (2018). Community initiatives as a catalyst for regeneration of heritage sites: Vernacular transformation and its influence on the formal adaptive reuse practice. *Cities*, *78*, 128-139.

Pollard-Belsheim, A., Storey, M., Robinson, C., & Bell, T. (2014). The CARRA project: Developing tools to help heritage managers identify and respond to coastal hazard impacts on archaeological resources. *2014 Oceans - St. John's*, 1–5. https://doi.org/10.1109/OCEANS.2014.7003289

Prieto, A. J., Macías-Bernal, J. M., Silva, A., & Ortiz, P. (2019). Fuzzy decision-support system for safeguarding tangible and intangible cultural heritage. *Sustainability*, *11*(14), 3953.

Privitera, R., & Jelo, G. (2025). Built Heritage Preservation and Climate Change Adaptation in Historic Cities: Facing Challenges Posed by Nature-Based Solutions. *Sustainability*, *17*(13), 5693. https://doi.org/10.3390/su17135693

Psoma, A., & Pyla, P. (2025). Safeguarding heritage sites from climate change: UNESCO's 'buffer zones' as a tool for managing sea level rise in Cyprus. *Journal of Architectural Conservation*, *31*(1–2), 64–81. https://doi.org/10.1080/13556207.2025.2509463

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.

Resta, V., Rodrigues, J., Patrikakis, C., Zuvela-Aloise, M., Ravan, M., Proença, N., De Wit, R., Santamaria, U., Revez, M., Boi, S., Coghi, P., Capua, M., & Perossini, F. (2019). *Cultural Heritage Resilience Against Climate Change and Natural Hazards*.

Ripp, M., Egusquiza, A., & Lückerath, D. (2024). Urban Heritage Resilience: An Integrated and Operationable Definition from the SHELTER and ARCH Projects. *Land*, *13*(12), 2052. https://doi.org/10.3390/land13122052

Roberts, D. A., & Eklund, E. (2012). Australian convict sites and the heritage of adaptation: the case of Newcastle's Coal River Heritage Precinct. *Australian Historical Studies*, *43*(3), 363-380.

Rockman, M. (2012). The necessary roles of archaeology in climate change mitigation and adaptation. In *Archaeology in society: Its relevance in the modern world* (pp. 193-215). New York, NY: Springer New York.

Rockman, M. (2016). *Cultural resources climate change strategy*. National Park Service, US Department of the Interior.

Sabbioni, C., Brimblecombe, P., & Cassar, M. (2010). The atlas of climate change impact on European cultural heritage. *Scientific analysis and management strategies*.

Saleem Beg, M. (2016). Issues of conservation and adaptation in protecting Kashmir's vernacular heritage. *International Journal of Environmental Studies*, *73*(4), 524–532. https://doi.org/10.1080/00207233.2016.1178986

Salpeteur, M., Madella, M., Patel, H. R., & Reyes-García, V. (2017). Adaptation, Access to Resources and Mobility: From Contemporary Pastoral Systems to Ancient Societies. *Nomadic Peoples*, *21*(2), 191–213. https://doi.org/10.3197/np.2017.210203

Salpina, D., Casartelli, V., Marengo, A., & Mysiak, J. (2025). Financing strategies for the resilience of cultural landscapes. Lessons learned from a systematic literature and practice review. *Cities*, *162*, 105922. https://doi.org/10.1016/j.cities.2025.105922

Santangelo, A., Melandri, E., Marzani, G., Tondelli, S., & Ugolini, A. (2022). *Enhancing Resilience of Cultural Heritage in Historical Areas: A Collection of Good Practices. Sustainability 2022, 14, 5171*.

Schipper, E. L. F. (2006). Conceptual history of adaptation in the UNFCCC process. *Review of European Community & International Environmental Law*, *15*(1), 82-92.

Sedova, A. (2021). Cultural heritage adaptation is sustainable! *IOP Conference Series: Earth and Environmental Science*, *822*(1), 012006. https://doi.org/10.1088/1755-1315/822/1/012006

Sesana, E., Gagnon, A. S., Bertolin, C., & Hughes, J. (2018). Adapting Cultural Heritage to Climate Change Risks: Perspectives of Cultural Heritage Experts in Europe. *Geosciences*, *8*(8), Article 8. https://doi.org/10.3390/geosciences8080305

Sesana, E., Gagnon, A. S., Ciantelli, C., Cassar, J., & Hughes, J. J. (2021). Climate change impacts on cultural heritage: A literature review. *WIREs Climate Change*, *12*(4), e710. https://doi.org/10.1002/wcc.710

Shih, N. J., & Qiu, Y. H. (2023). Nested Fabric Adaptation to New Urban Heritage Development. *Remote Sensing*, *15*(10), 2694.

Shirvani Dastgerdi, A., Sargolini, M., Broussard Allred, S., Chatrchyan, A., & De Luca, G. (2020). Climate Change and Sustaining Heritage Resources: A Framework for Boosting Cultural and Natural Heritage Conservation in Central Italy. *Climate*, *8*(2), Article 2. https://doi.org/10.3390/cli8020026

Silva-Ávila, P., Rojas Hernández, J., & Barra, R. O. (2025). Knowledge Alliances for Global Change Adaptation: A Relational Approach Based on Traditional Ecological Knowledge, Territorial Management, and Community Practices in the Chilean Context. *Sustainability*, *17*(8), 3653.

Simpson, N. P., Orr, S. A., Sabour, S., Clarke, J., Ishizawa, M., Feener, R. M., Ballard, C., Mascarenhas, P. V., Pinho, P., Bosson, J.-B., Morrison, T., & Zvobogo, L. (2022). *ICSM CHC White Paper II: Impacts, vulnerability, and understanding risks of climate change for culture and heritage: Contribution of Impacts Group II to the International Co-Sponsored Meeting on Culture, Heritage and Climate Change*. ICOMOS & ISCM CHC. https://openarchive.icomos.org/id/eprint/2718/

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global environmental change*, *16*(3), 282-292.

Smith, M. E. (2023). How can research on past urban adaptations be made useful for sustainability science? *Global Sustainability*, *6*, e4. https://doi.org/10.1017/sus.2023.2

Soewarno, N. (2020). Adaptation of architectural style to preserve cultural heritage building. *Journal of Architectural Research and Education (JARE)(1)*, *2*, 46-54.

Sun, Y., Wang, Z., & Zheng, Y. (2022). Environmental adaptations for achieving sustainable regeneration: A conceptual design analysis on built heritage Fujian Tulous. *Sustainability*, *14*(18), 11467.

Tansey, E. (2015). Archival adaptation to climate change. *Sustainability: Science, Practice and Policy*, *11*(2), 45-56.

Thuc, L. D., Van Nguyen, M., Ha Duy, K., & Nguyen Van, D. (2024). Prioritizing barriers to the conservation of cultural heritage buildings in adaptation to urbanization and climate change. *Journal of Cleaner Production*, *473*, 143529. https://doi.org/10.1016/j.jclepro.2024.143529

Tringa, E., Kavroudakis, D., & Tolika, K. (2024). Microclimate-Monitoring: Examining the Indoor Environment of Greek Museums and Historical Buildings in the Face of Climate Change. *Heritage*, *7*(3), 1400–1418. https://doi.org/10.3390/heritage7030067

Trõger, S. (2016). Societal Transformation, Buzzy Perspectives Towards Successful Climate Change Adaptation: An Appeal to Caution. In W. Leal Filho, K. Adamson, R. M. Dunk, U. M. Azeiteiro, S. Illingworth, & F. Alves (Eds), *Implementing Climate Change Adaptation in Cities and Communities: Integrating Strategies and Educational Approaches* (pp. 353–365). Springer International Publishing. https://doi.org/10.1007/978-3-319-28591-7_19

United Nations Framework Convention on Climate Change (UNFCCC). (2015). *Paris Agreement*. United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (2022). *Glasgow–Sharm el-Sheikh work programme on the global goal on adaptation*. United Nations. https://unfccc.int/topics/adaptation-and-resilience/workstreams/glasgow-sharm-el-sheikh-work-programme

United Nations Framework Convention on Climate Change (UNFCCC). (2023). *Report on the global goal on adaptation under the Glasgow–Sharm el-Sheikh work programme*. United Nations. https://unfccc.int/documents/634808

Van Dolah, E. R. (2018). *Cultural heritage and climate change adaptation pathways* (Doctoral dissertation, University of Maryland, College Park).

Varadzin, L., Varadzinová, L., Abdallah, A., Abdallah, B. A., Mohammed, M. A., Ambrose, S. H., Burgert, P., Černý, M., D´Ercole, G., Fuller, D. Q., Garcea, E. A. A., Hošek, J., Hošková, K., Jones, M. B., Kapustka, K., Ahmed, I. M., McCool, J.-P., Hamdeen, H. M., Novák, J., … Unger, J. (2023). The Shaqadud Archaeological Project (Sudan): Exploring prehistoric cultural adaptations in the Sahelian hinterlands. *Antiquity*, *97*(391), e2. https://doi.org/10.15184/aqy.2022.148

Vojinovic, Z., Keerakamolchai, W., Torres, A. S., Weesakul, S., Meesuk, V., Alves, A., & Babel, M. S. (2021). Towards holistic and multifunctional design of green and blue infrastructure for climate change adaptation in cultural heritage areas. In *Water Security in Asia: Opportunities and Challenges in the Context of Climate Change* (pp. 381-390). Cham: Springer International Publishing.

Vyshkvarkova, E., & Sukhonos, O. (2023). Climate Change Impact on the Cultural Heritage Sites in the European Part of Russia over the Past 60 Years. *Climate*, *11*(3), Article 3. https://doi.org/10.3390/cli11030050

Wang, X., Li, H., Wang, Y., & Zhao, X. (2022). Assessing climate risk related to precipitation on cultural heritage at the provincial level in China. *Science of The Total Environment*, *835*, 155489.

Wang, X., Li, H., Wang, Y., & Zhao, X. (2022). Assessing climate risk related to precipitation on cultural heritage at the provincial level in China. *Science of The Total Environment*, *835*, 155489. https://doi.org/10.1016/j.scitotenv.2022.155489

Williams, T., & Hardison, P. (2013). Culture, law, risk and governance: contexts of traditional knowledge in climate change adaptation. In *Climate change and indigenous peoples in the United States: Impacts, experiences and actions* (pp. 23-36). Cham: Springer International Publishing.

Xiao, X., Li, P., & Seekamp, E. (2023). Sustainable adaptation planning for cultural heritage in coastal tourism destinations under climate change: A mixed-paradigm of preservation and conservation optimization. *Journal of Travel Research*, *63*(1), 215-233.

Xiao, X., Seekamp, E., van der Burg, M. P., Eaton, M., Fatorić, S., & McCreary, A. (2019). Optimizing historic preservation under climate change: Decision support for cultural resource adaptation planning in national parks. *Land Use Policy*, *83*, 379-389.

Yazdani Mehr, S., & Wilkinson, S. (2020). The importance of place and authenticity in adaptive reuse of heritage buildings. *International Journal of Building Pathology and Adaptation*, *38*(5), 689–701. https://doi.org/10.1108/IJBPA-01-2020-0005

Zhao, H., Fang, J., Lin, Z., Tang, J., Zhen, S., Shi, H., Hui, X., & Liu, Y. (2025). Living Inheritance of Traditional Knowledge and Practical Wisdom of Severe Cold-Region Traditional Villages: A Case Study of Jinjiang Chalet Village in the Changbai Mountain Area. *Sustainability*, *17*(9), 4225. https://doi.org/10.3390/su17094225

5. Chapter 5: Preserving archaeological sites in a changing climate: barriers to adaptation in earthen archaeological sites

This chapter bridges the theoretical and practical dimensions of adaptation by investigating the real-world constraints that limit implementation. Drawing on case studies from Iran, it identifies institutional, socio-economic, and technical barriers that shape the vulnerability and adaptive capacity of earthen archaeological sites.

Climate change poses significant challenges to the preservation and adaptation of archaeological sites, particularly in the context of earthen archaeological sites (EASs). These sites are highly vulnerable to the impacts of climate change, such as erosion, flooding, and extreme weather events. Adaptation to climate change is therefore essential for the preservation of these historical sites. However, several barriers hinder the adaptation of EASs to climate change. The aim of this article is to provide a systematic understanding of the main barriers to climate change adaptation in earthen sites, including limited knowledge and awareness, financial constraints, limited technical expertise and institutional capacity, conflicting conservation and development priorities, socio-cultural barriers, and lack of data and information. It also highlights the unique vulnerabilities of earthen sites and the need for effective adaptation strategies that balance preservation with resilience. To overcome these challenges, a coordinated effort involving stakeholders at all levels is required, including local communities, site managers, policymakers, conservation experts and archaeologists. The article recommends that recognizing and addressing these barriers is crucial for successful climate change adaptation in EASs.

5.1. Introduction

The failure to effectively mitigate global warming has raised concerns about the future of our planet, prompting the Intergovernmental Panel on Climate Change (IPCC) to call for urgent adaptation measures (Rama et al., 2022, p.20). Following the publication of the IPCC's fourth assessment report in 2007 (AR4), many sectors have adopted and implemented official adaptation policies. In recent years, archaeological sites around the world have also suffered extensive damage due to the effects of climate change (Nguyen and Baker, 2023, p 2404). The alterations in weather patterns and temperatures have increased the occurrence and intensity of various hazards, including droughts, floods, and landslides, which pose significant threats to these heritage sites (Sesana et al., 2020, p.211). Of particular concern are sites constructed with earthen materials, as they are not well-equipped to handle the current and future effects of the

changing climate (Nakhaei and Correia, 2021, p.118). These sites are facing a dual threat of natural hazards and degradation caused by maladaptation and the use of incompatible materials and techniques (Nakhaei, 2020, p.70). Looking ahead, it is evident that climate change will exert an even greater impact in the coming century (Rama et al., 2022, p.10). Therefore, it is imperative to develop effective adaptation strategies that ensure the preservation of these invaluable heritage sites. Despite the significant amount of research conducted on the effects of climate change on cultural heritage, there remains a substantial gap in our understanding of how to sustainably adapt EASs (Sesana et al., 2021, p.21). The urgency to take action in preserving these heritage sites has become increasingly apparent due to the alarming reality that a majority of World Heritage sites at risk are composed of vulnerable EASs (Correia, 2016, p.2). These sites face significant threats from the changing climate, necessitating immediate action. However, despite existing initiatives aimed at protecting EASs, there has been limited progress in improving their resilience and vulnerability. This situation underscores the crucial need for a more comprehensive understanding of the challenges and barriers that impede effective adaptation efforts. This study aims to contribute to the advancement of research about the climate change and future of EASs by providing a deeper understanding of barriers to their adaptation.

5.2. Vulnerabilities of EASs to climate change

EASs are highly vulnerable to climate change, posing a significant risk to their integrity and preservation. The vulnerability of these sites stems from two critical factors: the inherent weakness of earthen materials compounded by their deterioration over millennia and the presence of natural hazards (Richards et al., 2019, P.1). The organic composition and gradual degradation of earthen materials make them susceptible to deterioration over time. Furthermore, the loss of ancient risk management techniques, particularly those related to moisture control (Fig 5.1) has increased the vulnerability of these sites (Nakhaei and Correia, 2021, P.118). Additionally, natural hazards such as floods, windstorms, and climatic extremes pose significant risks to their stability and preservation (Richards et al., 2019, P.2). Unique vulnerabilities of earthen structures highlight the urgent need for proactive adaptation strategies to protect these invaluable cultural heritage sites from the impacts of climate change.

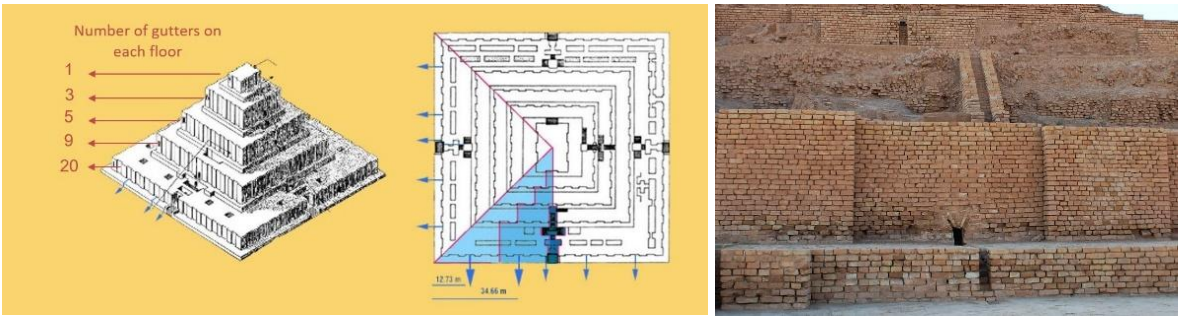


Fig 5.1: Ancient water risk management system in the Tchogha Zanbil (Source: Archive of Tchogha Zanbil research centre)

5.3. Adaptation of EASs to climate change

Adaptation is a crucial response to the challenges posed by climate change for sites constructed with earthen materials. IPCC defines adaptation as the process of adjusting to changing conditions in order to survive and thrive (Rama et al., 2022, p.5). In the context of EASs, adaptation becomes imperative for their preservation and effective management in the face of a range of environmental and socio-economic challenges posed by climate change. General adaptation strategies (Fig 5.2) encompass a range of measures aimed at reducing exposure to climate hazards, enhancing resilience to withstand adverse impacts, reducing vulnerability, and implementing effective mitigation strategies to minimize loss and decay (Fatorić and Biesbroek, 2020, P.302). Furthermore, place based approaches together with site-specific approaches are vital in addressing the unique challenges faced by individual earthen sites (Nakhaei and Correia, 2020, P.116). However, despite the urgent need for adaptation, numerous barriers hinder the effective implementation of climate change adaptation measures for EASs.

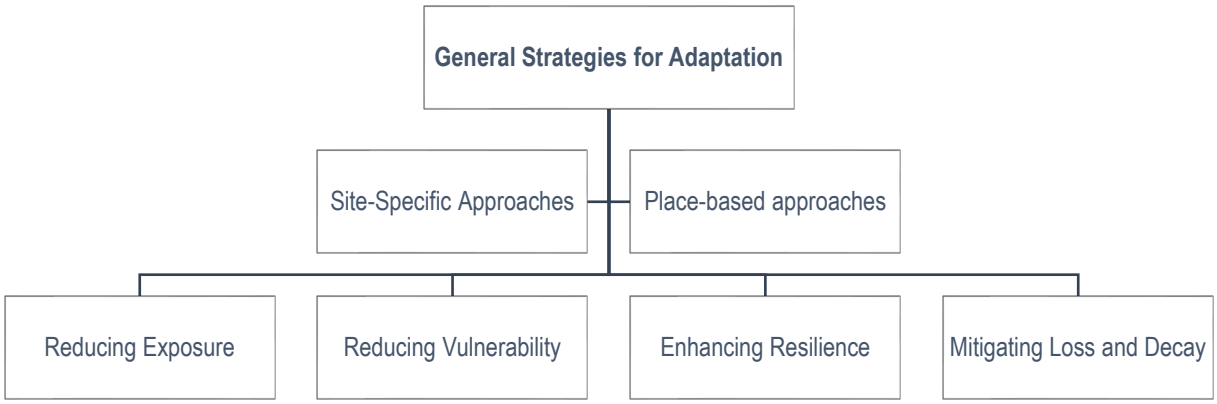


Fig 5.2: Adaptation Strategies for earthen Sites

5.4. Barriers to climate change adaptation in EASs

Barriers to climate adaptation of cultural heritage refer to obstacles that hinder or impede the creation or execution of specific measures aimed at reducing vulnerability or enhancing adaptive capacity of cultural heritage to cope with climate change (Fatorić and Biesbroek, 2020, P.304). These barriers encompass various factors such as knowledge, physical environment, biological tolerances, economic and social factors, human resources, and governance (Rama et al., 2022, P.978). Barriers occur throughout all stages of the adaptation process, encompassing the recognition of climate change impacts, the formulation of adaptation plans, the decision to take action, and the implementation of adaptation measures (Fatorić and Seekamp, 2017, P.3). Moreover, barriers often exhibit interdependence, where obstacles from various categories coincide or strengthen one another (Eisenack et al., 2014, p.869). In order to bridge the gap between climate change and adaptation planning for EASs, it is essential to recognize and classify the various types of barriers that emerge during the adaptation process.

5.4.1. Forgetting traditional knowledge and lack of awareness of climate change impacts

One significant barrier to climate change adaptation in EASs is the forgetting of traditional knowledge and a general lack of awareness regarding the impacts of climate change. Traditional knowledge, passed down through generations, holds valuable insights into local climate patterns, ecological interactions, and adaptive practices that were historically employed to protect and maintain EASs (Nakhaei, 2020, p.71). However, the consequences of climate change, such as the migration of the local population, are resulting in the loss of traditional Adobe knowledge. Consequently, the preservation and maintenance of existing adobe structures are becoming more challenging, and with the shortage of skilled labor, the conservation of these heritages will be negatively impacted. Moreover, local communities with traditional knowledge and historical experience often lack awareness of the risks they face due to inadequate communication and engagement from local governments (Nakhaei, 2022a, p.2). The decline of traditional knowledge and the resulting lack of awareness among communities living near EASs hinder proactive and timely responses to climate change impacts. Furthermore, the disconnect between scientific research on climate change and local communities exacerbates the awareness barrier. Findings from extensive studies often remain confined to scientific papers and reports, failing to reach the communities directly affected by climate change. This information gap between researchers, policymakers, and local communities persists, impeding effective adaptation efforts.

5.4.2. Socio-cultural barriers and limited community engagement

Socio-cultural barriers and limited community engagement pose significant challenges to climate change adaptation in EASs. These barriers manifest in various ways, including conflicts between authorities and local communities, inadequate community involvement in decision-making processes, and a loss of the sense of belonging (Khatibi et al., 2021, p.10). When conflicts arise, the affected communities may feel marginalized and excluded from decision-making processes, hindering their willingness to engage in preservation and adaptation efforts. Decision-making processes that overlook local perspectives and disregard community knowledge further impede effective preservation and adaptation. In some cases, decisions regarding the preservation and adaptation of EASs are made without consulting or involving the local communities. This top-down approach neglects the perspectives, knowledge, and needs of the people living in close proximity to these sites. As a consequence, local communities may feel excluded and disconnected from the decision-making process, leading to a loss of the sense of ownership and reduced motivation to participate in adaptation activities. Socio-economic conditions also influence the level of community susceptibility in climate change adaptation (Andrachuk and Smit, 2012, p.869). Disadvantaged communities facing poverty, limited access to resources, and competing development priorities may struggle to prioritize adaptation actions. Additionally, limited access to education and information about climate change hampers community understanding of risks and potential adaptation strategies (Lee et al., 2015, p.20).

5.4.3. Lack of data and information

The lack of data and information poses a significant barrier to informed decision-making for climate change adaptation in EASs. Insufficient information regarding vulnerability and behavior of earthen material in different climatic conditions, the absence of monitoring programs, and specific strategies that need to be developed hinders the development of effective adaptation and resource allocation (Richards et al., 2020, p.1; Traoré et al., 2023, p.9). One key challenge is the limited availability of data on the current condition of EASs and their susceptibility to climate change impacts. Many earthen sites lack comprehensive documentation, including detailed assessments of their structural integrity, vulnerability to erosion, and exposure to natural hazards. Without this crucial baseline information, it is difficult to assess the risks and prioritize adaptation measures effectively. In addition to the lack of data on the physical aspects of EASs, there is often a dearth of information on the socio-cultural significance and values associated with these sites (Daly et al., 2022, p.7).

Understanding the cultural importance and historical context of EASs is essential for developing adaptation strategies. However, this information may be scattered, incomplete, or not easily accessible, impeding informed decision-making. Another barrier is the unique vulnerability of each earthen site. The materials, location, and socio-cultural context in which these sites are situated contribute to their distinct vulnerabilities. However, due to limited data, there is often a lack of understanding of the specific adaptation needs of individual sites. This further complicates decision-making, as generic or blanket approaches may not be suitable for addressing the diverse challenges faced by different EASs. Furthermore, there is a lack of data on climate change projections and localized impacts specific to EASs (Rama et al., 2022, p.136). Climate models and projections often operate at broader scales, and the specific vulnerabilities and adaptation needs of earthen structures may not be adequately captured. This limits the ability to accurately anticipate and plan for the future climate conditions that will affect these sites.

5.4.4. Financial constraints and resource limitations

In the past century, the lack of adequate budget allocation for the protection and preservation of earthen sites has been a significant factor contributing to their destruction. This issue persists in many regions, where adobe structures, despite their value as well as high vulnerability to climate change, receive insufficient attention and budget allocation (Daly et al., 2022, p.7). Within countries possessing a wealth of historical sites, financial allocations frequently prioritize the conservation of architectural marvels built using materials like stone or brick, as well as the preservation of historical artifacts, while overlooking the importance of safeguarding earthen structures. Additionally, the specialized nature of earthen heritage conservation, the scarcity of qualified professionals, and the costs associated with their engagement further contribute to financial constraints. In addition to financial constraints, resource limitations pose another significant challenge to climate change adaptation in earthen sites (Nakhaei, 2020, p.72). Earthen structures require adequate resources such as suitable materials and tools to implement adaptation measures. However, the availability of these resources can be scarce, particularly in regions with poor infrastructure or remote locations. The costs associated with sourcing and transporting materials and equipment to these sites further restrict the implementation of adaptation measures. Furthermore, the lack of financial resources and resource limitations affect the capacity for data collection, analysis, and monitoring of climate change impacts on earthen sites. Data collection and monitoring are essential for understanding the specific vulnerabilities of these sites and informing adaptation

strategies. However, the costs associated with data collection equipment, remote sensing technologies, and the expertise required for data analysis and interpretation can be prohibitive, further exacerbating the financial constraints.

5.4.5. Limited institutional capacity and the lack of risk management plan

Limited institutional capacity and the absence of a risk management plan significantly impede the ability to adapt to climate change in EASs (Nakhaei, 2022b, p.97). The shortage of professionals with specialized knowledge in earthen heritage risk management hinders the effective implementation of adaptation measures, as the expertise required to assess vulnerabilities, develop suitable strategies, and monitor climate change impacts is often lacking. This deficiency leads to inadequate and suboptimal adaptation efforts, undermining the resilience of these sites. In addition, heritage management organizations and local communities often face challenges due to a lack of capacity, resources, and infrastructure necessary to address climate-related disasters (Nakhaei, 2022a, p.2). Insufficiently trained staff, limited funding, and inadequate technological resources restrict their ability to plan and execute effective adaptation measures. These limitations hamper the timely response and recovery from climate impacts, further exacerbating the vulnerability of EASs to damage. A key obstacle is the absence of comprehensive institutional frameworks and tailored risk management plans that specifically address the unique vulnerabilities of earthen heritage. Many heritage management organizations and authorities do not possess sufficient policies, guidelines, or protocols to tackle the specific challenges posed by climate change. Moreover, the integration of climate change considerations into existing heritage management practices and policies is frequently inadequate. Climate change adaptation necessitates a multidisciplinary approach that incorporates traditional and scientific knowledge, and community engagement (Rama et al., 2022, p.657). However, heritage management organizations may struggle to coordinate and collaborate with other sectors, such as climate science and local communities, due to their limited institutional capacity and established networks.

5.4.6. Conflicting conservation and development priorities

Balancing the preservation of EASs with the demands of development and economic growth can create tensions and challenges in implementing effective adaptation strategies. One of the primary conflicts arises from the competing interests between conservation and urban development (Mubaideen and Al Kurdi, 2017, p.1). In many cases, EASs are located in urban areas that are undergoing rapid expansion and urbanization. The pressure to accommodate growing populations and infrastructure needs often leads to conflicting priorities, where the

preservation of earthen sites may be overshadowed by the desire for urban development. Another aspect of conflicting priorities lies in the tension between preservation and modernization. The adaptive measures required to protect EASs from climate change impacts may conflict with modern construction practices and development standards. For instance, introducing modern materials and techniques, such as cement-based repairs or protective coatings, can have unintended consequences for the stability and authenticity of earthen structures (Correia, 2016, p.7).

Furthermore, the protection and conservation of earthen sites necessitate specialized knowledge and expertise. However, there is a prevailing lack of awareness regarding the vulnerability and unique values associated with these sites, leading to restoration specialists from other fields being tasked with their restoration and adaptation. This lack of specialization poses a significant threat to the integrity and authenticity of these structures. Earthen materials possess distinct characteristics and vulnerabilities that demand specialized knowledge for their preservation. The composition, structural properties, response to environmental factors and more importantly the unique value of earthen structures differ significantly from those of other construction materials. Without the requisite expertise, restoration specialists may inadvertently employ unsuitable conservation methods, use incompatible materials, or apply techniques that can lead to irreversible damage both to tangible and intangible values of earthen sites. This lack of specialized knowledge increases the risk of improper interventions, compromising the authenticity, historical value, and long-term stability of EASs.

5.4.7. The absence of frameworks, criteria, and legal reforms

The absence of frameworks, criteria, and legal reforms contributes to the complexity of addressing the matter effectively (Fatorić and Biesbroek, 2020, p.304). While there are regulations in place for intervening in earthen heritage, there is a lack of specific criteria for the adaptation of EASs (Correia and Walliman, 2014, p.582). Without dedicated frameworks, there is a lack of guidance and direction for integrating adaptation measures into preservation efforts. This leads to fragmented approaches and inadequate resource allocation. Firstly, the absence of dedicated frameworks for EASs means that there is no clear roadmap or set of guidelines for integrating climate change adaptation into preservation efforts. Without a well-defined framework, decision-makers may struggle to prioritize and allocate resources effectively, resulting in adaption measures that are inconsistent, insufficient, or inappropriate.

Additionally, the lack of criteria or legal instruments specifically addressing the adaptation of EASs to climate change can lead to a regulatory gap. Without clear legal provisions and

obligations, there may be limited accountability and enforcement mechanisms for ensuring the protection and conservation of these sites in the face of climate change impacts.

Furthermore, the absence of legal reforms can hinder the establishment of collaborative partnerships and governance structures necessary for effective climate change adaptation in EASs (Landorf, 2009, p.496). Clear legal frameworks can provide the basis for engaging multiple stakeholders, including local communities, heritage experts, policymakers, and developers, in decision-making processes. Legal reforms can facilitate the creation of participatory mechanisms, enabling the inclusion of diverse perspectives and local knowledge in adaptation strategies.

5.5. Overcoming the barriers

Overcoming the barriers to climate change adaptation in EASs requires a multi-faceted approach. To overcome the barriers various potential solutions and approaches can be considered (Fig 5.3). It is crucial to establish a strong connection between scientific knowledge and traditional knowledge, while actively engaging local communities in climate change discussions (Nakhaei, 2020, p.72). Collaborative efforts involving researchers, cultural heritage experts, and community members can facilitate the exchange of knowledge, integrating traditional practices and experiences into adaptation strategies. Additionally, educational and awareness-raising initiatives should be developed to inform local communities about the impacts of climate change. These initiatives should emphasize the importance of preserving traditional knowledge and implementing proactive adaptation measures (Cuaton and Su., 2020, p.2).

Fig 5.3: Some methods for overcoming barriers

Another crucial aspect is advocating for increased budget allocation specifically for the protection and adaptation of earthen sites. Exploring alternative funding mechanisms and establishing partnerships with government agencies, private sectors, and international funding

bodies can help secure additional financial resources for climate change adaptation in earthen sites (Bouwer and Aerts, 2006, p.50). Efforts should also focus on capacity-building programs and training initiatives to enhance the technical expertise of professionals involved in earthen heritage conservation. By investing in education and skill development, heritage management organizations can strengthen their internal capacity and reduce reliance on external experts, thereby reducing costs associated with technical expertise. Furthermore, research and innovation should be encouraged to identify alternative, cost-effective materials and technologies suitable for preserving and adapting earthen sites. Exploring sustainable and locally available materials, as well as developing efficient preservation techniques, can help overcome resource limitations and reduce the overall financial burden.

Additionally, comprehensive risk management plans need to be developed to address the specific vulnerabilities of EASs. These plans should encompass strategies for risk assessment, early warning systems, emergency preparedness, and post-disaster recovery. It is crucial to integrate traditional knowledge and community participation in these plans to ensure that local communities are actively involved in decision-making processes and the implementation of adaptation measures.

The establishment of comprehensive institutional frameworks is also important to address the unique challenges of earthen heritage conservation in the context of climate change. These frameworks should integrate climate change considerations into heritage management practices, provide clear guidelines for adaptation strategies, and facilitate collaboration between different sectors and stakeholders.

Raising awareness about the value of earthen heritage is essential. It is crucial to educate stakeholders, including conservators, archaeologist, policymakers, developers, and the public, about the cultural significance and resilience of these structures in the face of climate change (Fatorić and Biesbroek, 2020, p.313). It is also important to prioritize and promote specialized training and education programs focused on earthen heritage conservation and adaptation. This includes providing opportunities for restoration specialists, conservators, architects, and other relevant professionals to acquire in-depth knowledge and practical skills specific to working with earthen materials.

Comprehensive research and data collection initiatives focused specifically on EASs and their vulnerability to climate change are needed. This includes conducting detailed surveys and assessments of the physical condition of these sites, monitoring their response to climate-related stressors, and documenting their socio-cultural significance.

To address the uncertainty associated with future climate change, it is essential to invest in climate research and modeling at local scales (Slavich et al., 2014, p.958). This can help generate more accurate projections specific to earthen sites, enabling decision-makers to better anticipate and plan for the future climate conditions that will affect these sites.

The development of dedicated frameworks, criteria, and legal reforms is also crucial. These instruments should address the unique vulnerabilities and adaptation needs of EASs, providing clear guidelines for integrating climate change considerations into preservation efforts. They should establish legal provisions that mandate the protection and conservation of these sites in the face of climate change impacts and promote the inclusion of stakeholders in decision-making processes.

5.6. Summary of Key Issues

This article highlights the barriers to climate adaptation of EASs. These barriers encompass a range of factors that hinder the implementation of concrete actions to reduce vulnerability and increase adaptive capacity. The identification and understanding of these barriers are crucial for bridging the gap between climate change science and adaptation planning for earthen heritage. It is essential to recognize that barriers can arise at various stages of the adaptation process and are often interconnected, reinforcing one another. Overcoming these barriers requires concerted efforts from policymakers, site managers, conservation practitioners, and local communities. To effectively address the barriers, it is necessary to enhance knowledge and understanding of climate change impacts on EASs, invest in capacity building and technical expertise, promote community engagement and sense of ownership, and establish comprehensive institutional frameworks for risk management and adaptation planning. Bridging the gap between scientific knowledge and traditional knowledge can integrate valuable insights and practices into adaptation strategies. Additionally, financial constraints should be addressed by exploring alternative funding mechanisms and partnerships. Adapting earthen archaeological sites in response to climate change is of utmost importance in mitigating the current and future effects of climate change. By addressing the barriers discussed in this article, stakeholders can work together to develop and implement effective adaptation measures, ensuring the long-term preservation and resilience of these invaluable sites.

Understanding these barriers underscores the need for practical, material-level interventions that enhance resilience while maintaining authenticity. The next chapter therefore turns to the experimental dimension of the study, presenting laboratory-based research on material adaptation for earthen conservation under climatic stress.

References

Andrachuk, M., and Smit, B. (2012). Community-based vulnerability assessment of Tuktoyaktuk, NWT, Canada to environmental and socio-economic changes. *Regional Environmental Change*, *12*(4), 867–885. https://doi.org/10.1007/s10113-012-0299-0

Bouwer, L. M., & Aerts, J. C. J. H. (2006). Financing climate change adaptation. *Disasters*, *30*(1), 49–63. https://doi.org/10.1111/j.1467-9523.2006.00306.x

Correia, M. (2016). *Conservation in Earthen Heritage: Assessment and Significance of Failure, Criteria, Conservation Theory, and Strategies*. Cambridge: Cambridge Scholars Publishing.

Daly, C., Fatorić, S., Carmichael, B., Pittungnapoo, W., Adetunji, O., Hollesen, J., Nakhaei, M., & Diaz, A. H. (2022). Climate change adaptation policy and planning for cultural heritage in low- and middle-income countries. *Antiquity*, *96*(390), 1427–1442. https://doi.org/10.15184/aqy.2022.114

Eisenack, K., Moser, S. C., Hoffmann, E., Klein, R. J. T., Oberlack, C., Pechan, A., Rotter, M., & Termeer, C. J. A. M. (2014). Explaining and overcoming barriers to climate change adaptation. *Nature Climate Change*, *4*(10), Article 10. https://doi.org/10.1038/nclimate2350

Fatorić, S., & Biesbroek, R. (2020). Adapting cultural heritage to climate change impacts in the Netherlands: Barriers, interdependencies, and strategies for overcoming them. *Climatic Change*, *162*(2), 301–320. https://doi.org/10.1007/s10584-020-02831-1

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), Article 11. https://doi.org/10.3390/su9112143

Khatibi, F. S., Dedekorkut-Howes, A., Howes, M., & Torabi, E. (2021). Can public awareness, knowledge and engagement improve climate change adaptation policies? *Discover Sustainability*, *2*(1), 18. https://doi.org/10.1007/s43621-021-00024-z

Landorf, C. (2009). A Framework for Sustainable Heritage Management: A Study of UK Industrial Heritage Sites. *International Journal of Heritage Studies*, *15*(6), 494–510. https://doi.org/10.1080/13527250903210795

Lee, T. M., Markowitz, E. M., Howe, P. D., Ko, C.-Y., & Leiserowitz, A. A. (2015). Predictors of public climate change awareness and risk perception around the world. *Nature Climate Change*, *5*(11), Article 11. https://doi.org/10.1038/nclimate2728

Mubaideen, S., & Al Kurdi, N. (2017). Heritage conservation and urban development: A supporting management model for the effective incorporation of archaeological sites in the planning process. *Journal of Cultural Heritage*, *28*, 117–128. https://doi.org/10.1016/j.culher.2017.05.007

Nakhaei , M., & Correia, M. (2021). Assessment of vulnerability and site adaptive capacity to the risk of climate change: The case of Tchogha Zanbil World Heritage earthen site in Iran. *Journal of Cultural Heritage Management and Sustainable Development*, *12*(2), 107–125. https://doi.org/10.1108/JCHMSD-06-2021-0108

Nakhaei, M. (2020). Facing climate change: the importance of protecting earthen heritage traditional knowledge. In *2020 ICOMOS 6 ISCs Joint Meeting Proceedings* (Vol. 68).

Nakhaei, M. (2022a). Community Engagement as a Tool for Managing Climate Change Risks: Challenges and Problems. *Climate, Culture and Peace conference, case studies,* 24 - 28 January 2022.

Nakhaei, M. (2022b). Disaster Risk Management of Persepolis World Heritage Site (Multi-hazard and place approach). *Institute of Disaster Mitigation for Urban Cultural Heritage.* Ritsumeikan University. ITC 2022, 16th year.

Nakhaei, M., & Correia, M. (2020). Water-risk management in Tchogha Zanbil World Heritage Site in Iran, with a focus on the Ancient Management System. *International Society for Photogrammetry and Remote Sensing.* https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-683-2020

Nguyen, K. N., & Baker, S. (2023). Climate Change and UNESCO World Heritage-Listed Cultural Properties: A Systematic Review, 2008–2021. *Heritage*, *6*(3), Article 3. https://doi.org/10.3390/heritage6030126

Rama, H.-O., Roberts, D., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B., & Ayanlade, S. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability*, Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009325844

Richards, J., Bailey, R., Mayaud, J., Viles, H., Guo, Q., & Wang, X. (2020). Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty. *Scientific Reports*, *10*(1), 16419. https://doi.org/10.1038/s41598-020-73456-8

Richards, J., Zhao, G., Zhang, H., & Viles, H. (2019). A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain. *Heritage Science*, *7*(1), 51. https://doi.org/10.1186/s40494-019-0293-7

Rosado Correia, M. R. A., & Walliman, N. S. R. (2014). Defining Criteria for Intervention in Earthen-Built Heritage Conservation. *International Journal of Architectural Heritage*, *8*(4), 581–601. https://doi.org/10.1080/15583058.2012.704478

Sesana, E., Gagnon, A. S., Bonazza, A., & Hughes, J. J. (2020). An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *Journal of Cultural Heritage*, *41*, 211–224. https://doi.org/10.1016/j.culher.2019.06.013

Sesana, E., Gagnon, A. S., Ciantelli, C., Cassar, J., & Hughes, J. J. (2021). Climate change impacts on cultural heritage: A literature review. *WIREs Climate Change*, *12*(4), e710. https://doi.org/10.1002/wcc.710

Slavich, E., Warton, D. I., Ashcroft, M. B., Gollan, J. R., & Ramp, D. (2014). Topoclimate versus macroclimate: How does climate mapping methodology affect species distribution models and climate change projections? *Diversity and Distributions*, *20*(8), 952–963. https://doi.org/10.1111/ddi.12216

Traoré, L. B., Rojat, F., Fabbri, A., & McGregor, F. (2023). Experimental study of strain-temperature behavior of earthen materials under freezing-thawing cycles. *Cold Regions Science and Technology*, *205*, 103685. https://doi.org/10.1016/j.coldregions.2022.103685

6. Chapter 6 - Climate-resilient earthen heritage conservation: magnesium-based additives for improved adobe erosion resistance

This chapter introduces the experimental phase of the research, focusing on the material aspects of climate adaptation. It investigates how innovative stabilization methods can improve the physical resistance of earthen materials while remaining consistent with conservation ethics. The chapter describes the design and testing of magnesium-based additives to strengthen adobe under moisture and erosion pressures.

Earthen materials like adobe are commonly found in vernacular architecture and archaeological sites but remain highly susceptible to moisture-related deterioration, an issue increasingly critical under climate change scenarios marked by intensified rainfall and humidity. This study explores the use of two magnesium-based additives, magnesium oxide (MgO) and Sorel cement (SC), to improve the durability and water resistance of adobes. A comprehensive set of laboratory tests, including artificial rainfall simulation, capillary absorption, immersion testing, X-ray diffraction (XRD), and SEM-EDS, were conducted to evaluate both the overall performance and microstructural changes. MgO-stabilized samples, particularly at 10–15 wt%, demonstrated superior performance across all tests, with significantly reduced erosion, water uptake, and physical disintegration. Mineralogical analyses confirmed the transformation of montmorillonite to chlorite, a non-swelling mineral that enhances long-term stability in wet conditions. In contrast, SC-treated samples showed less mineralogical change and were prone to degradation at higher concentrations due to the formation of brittle magnesium oxychloride phases. Given that MgO is cheaper and more environmentally friendly than SC, particularly in moisture-prone environments, this study offers valuable insights for the conservation of earthen structures facing climate-related challenges.

6.1. Introduction

Earthen construction is carried outby using clay, silt, sand, and gravel, including organic and non-organic components to enhance its performance. This building tradition has shaped ancient human settlements and architectural traditions and is part of today's historical heritage. Adobe, commonly used in earthen architecture, is prized for its availability, eco-friendliness, and excellent thermal properties (Al Zohbi et al., 2024).

Studies have identified significant threats to earthen heritage, such as surface erosion and structural collapse, especially when exposed to rain and harsh environmental factors (Richards

et al., 2019). Shifts in climate, including more frequent and intense rainfall, worsen these challenges, speeding up the deterioration of earthen structures (Nakhaei & Correia, 2021, Nakhaei et al., 2025). In recent decades, there has been growing interest in stabilizing earthen materials for both new construction and the preservation of archaeological sites (Oliver, 2008; Medvey & Dobszay, 2020). This is largely due to their natural susceptibility to weathering, especially water erosion, which poses a significant challenge (Rainer, 2008; Morel et al., 2012) due to climate change. Water contributes to erosion, cracking, and structural deterioration by breaking down binding agents, seeping into porous surfaces, and causing materials to expand or contract (Illampas et al., 2013). Research in material science has addressed various stabilization methods to enhance adobe's durability, making it more resistant to moisture and mechanical stress (Degirmenci, 2008; Eires et al., 2015; Stazi et al., 2016; Medvey & Dobszay, 2020; Savary et al., 2020; Rao, 2023; Bailly et al., 2024; Gutierrez et al., 2024).

Despite the progress made on these issues, there is still a need for comprehensive research methodologies and lifecycle analyses to refine these techniques and develop effective conservation strategies (Bailly et al., 2024; Medvey & Dobszay, 2020). Studies emphasize that innovative stabilization approaches offer effective protection against erosion and weathering (Hart et al., 2023; Reynolds & Muramoto, 2024). In particular, the review of Medvey & Dobszay (2020) emphasizes the need for unified durability assessment methods for stabilized adobe, either through new test methods or refined standards, and calls for further investigation into alternative low-impact stabilizers. While many alternative stabilization methods are emerging, the challenge lies in finding solutions that are not only effective but also compatible with the cultural and historical significance of adobe structures, particularly in archaeological contexts. Within this spectrum of evolving methods, magnesium-based additives have garnered attention due to their inorganic nature, compatibility with heritage materials, and favourable performance characteristics. Magnesium oxide (MgO), in particular, has demonstrated promise as a stabilizer due to its low solubility and water resistance (Bahobail, 2012; Walling & Provis, 2016). Likewise, Sorel Cement (SC), a magnesium oxychloride compound, is valued for its high early strength and bonding capacity, offering a potential solution for reinforcing deteriorating adobe without the drawbacks of Portland-type cements, which, despite its widespread use, poses well-documented compatibility issues with traditional earthen structures, including excessive stiffness, low permeability, and salt-related degradation (Temiz & Tandirci, 2023; Ahmad et al., 2024).

Despite their potential, few studies have directly compared the performance of MgO and SC under realistic hydromechanical stress scenarios. This work addresses this gap by experimentally evaluating the behaviour of adobe bricks treated with MgO and SC under simulated rainfall conditions. Among all testing methods, artificial rainfall simulation has emerged as particularly valuable (Reynolds & Muramoto, 2024). Unlike other test method, artificial rainfall replicates the active, impact-driven forces of natural precipitation. It enables researchers to observe how adobe bricks respond to surface erosion, mass loss, and structural stress in conditions that closely resemble real-world rainfall.

6.1.1. Research aim

This research aims at evaluating the effectiveness of MgO and SC in enhancing the performance of adobes through a series of controlled yet climatically relevant durability tests, including quantitative rainfall simulation, capillary absorption and immersion tests. The overarching goal is to advance scientific understanding of inorganic stabilization mechanisms and to provide evidence that can contribute to the conservation of earthen heritage structures and the development of sustainable, climate-resilient building strategies using adobe in contemporary contexts. The outcomes contribute to the growing effort to integrate environmental resilience and cultural compatibility into the science of earthen material stabilization.

6.2. Materials and methods

Adobe samples were produced from a silty clay loam soil with ~2 wt% straw and MgO or SC as additives at 5, 10 and 15 wt%. Adobe samples (5 × 5 × 5 cm) were air- and oven-dried and subjected to artificial rainfall, capillary and immersion tests to simulate high-moisture scenarios. Microstructural and mineralogical analysis were examined using XRD and BSEM-EDS methods to link the adobes' test performances with additives. Full details of the used starting materials and analytical procedures are provided in Supplementary Materials #1.

6.3. Results

This section presents the visual condition and quantitative measurement of the experimental evolution of both treated and untreated adobes, as documented through surface scans. These observations are followed by the results of the immersion and capillary absorption tests, providing a comparative assessment of moisture-related performance.

6.3.1. Rainfall simulation tests

An example of the simulated rainfall is shown in Fig. 6.1, whereas Fig. 6.2 illustrates the cumulative surface erosion maps for SC–treated adobe samples and for the untreated reference adobes under progressive rainfall durations. Erosion rate values (E.R., in mm/h) are extracted from high-resolution topographic scans, highlighting both surface deformation and material loss patterns over time.

In the reference sample (Fig. 6.2a), erosion developed rapidly. Within 3 minutes, the surface exhibited significant deepening (18.6 mm/h), and by the 4-minute mark, the erosion rate spiked to 39.3 mm/h, indicating structural breakdown.

In contrast, the SC-5% sample (Fig. 6.2b) exhibited initially moderate erosion rate with respect to the reference sample and intensified with time. At 1 minute, erosion rate was minimal (0.1 mm/h), but by 8 minutes it increased to 17.9 mm/h and exceeded 46 mm/h at 32 minutes. Surface patterns reveal patchy erosion zones that eventually coalesce, forming unstable pockets that penetrate deeper with continued exposure. The SC-10% sample (Fig. 6.2c) showed relatively consistent and moderate resistance across all time intervals. Although erosion gradually progressed, the magnitude remained subdued even after 32 minutes (2.6 mm/h). The erosion remained evenly distributed with minimal localized fragmentation. However, the SC-15% sample (Fig. 6.2d) relatively, performed poorly despite higher stabilizer concentration. Erosion began at a substantial rate (18.2 mm/h at 1 minute), followed by dramatic surface collapse over time, culminating in 43.3 mm/h at 32 minutes. Specifically, the erosion maps reveal marginal retreat, edge rounding, and core fragmentation, indicating early disintegration and poor cohesion under hydraulic stress.

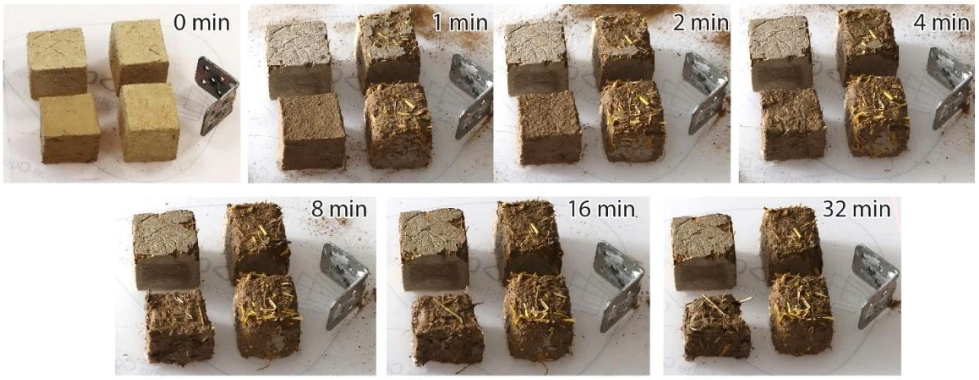


Fig. 6.1: Examples of surface erosion condition for samples MgO-10% and SC-10% exposed to simulated rain.

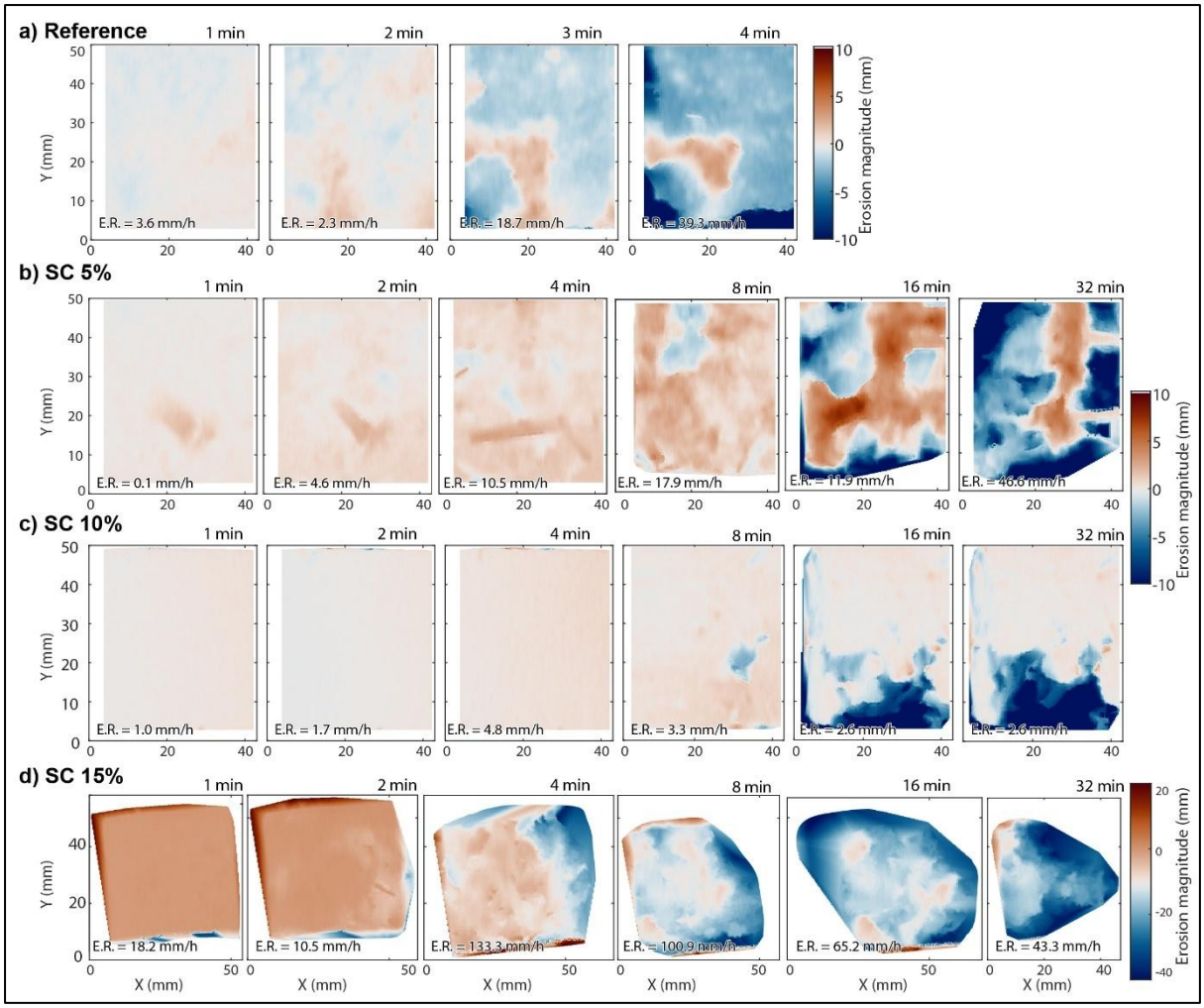


Fig. 6.2: Progressive surface degradation of SC-treated and untreated adobe under simulated rainfall

Fig. 6.3 presents the cumulative erosion behaviour of adobes treated with MgO at 5%, 10%, and 15% by weight, over increasing durations of simulated rainfall. The MgO-5% sample initially resisted surface degradation, showing negligible erosion at 1 minute (1.5 mm/h). However, erosion became more pronounced over time, reaching 6.5 mm/h at 4 minutes and 10 mm/h by 32 minutes. The surface maps reveal expanding localized erosion zones and progressive deepening, particularly along surface irregularities (Fig. 6.3b). In contrast, the MgO-10% sample displayed remarkable stability throughout the test. From 1 to 32 minutes, erosion rates remained consistently low, peaking only at 5.4 mm/h. The corresponding maps show minimal surface change with no sharp gradients or deep craters (Fig. 6.3c). The MgO-15% sample exhibited the best performance: despite slightly elevated erosion at early intervals (2 mm/h at 1 minute), the rate rapidly declined and remained below 4 mm/h through the full 32-minute rainfall simulation. The topography remained essentially intact, with only

superficial surface softening visible (Fig. 6.3d). The maps confirm that this sample experienced neither structural fragmentation nor perimeter retreat.

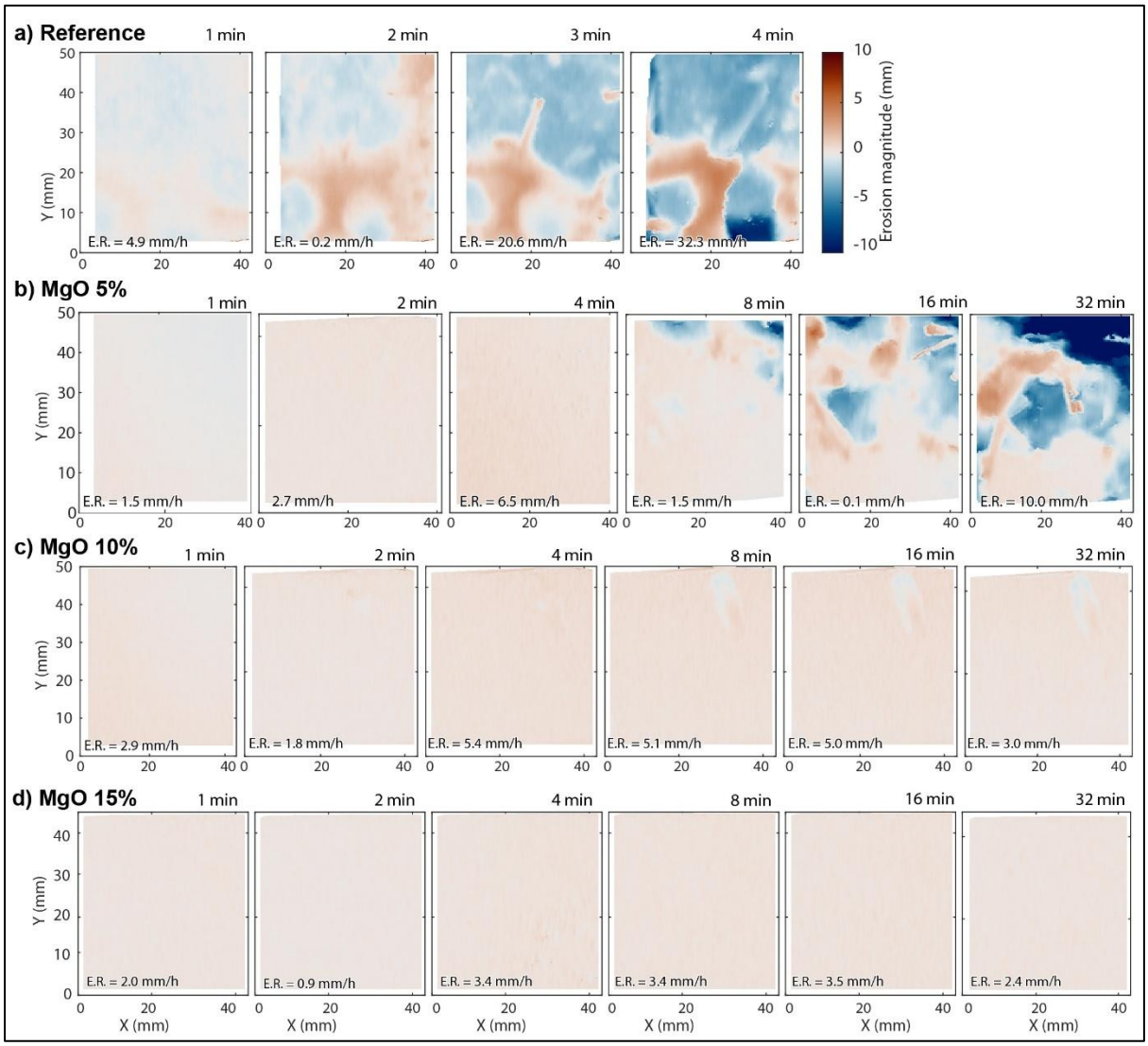


Fig. 6.3: Progressive surface degradation of MgO-treated and untreated adobe under simulated rainfall

To quantify the erosion behaviour of treated and untreated adobes under simulated rainfall, area-normalized erosion (ANE) volumes (in mm^3) were calculated for each sample at cumulative rainfall durations (Table S2 and Fig. 6.4). To avoid boundary effects induced by the laser scanner at the extremes of the samples (e.g., water reflectivity on the table floor), the boundary sections of the point clouds representing the samples were removed. Due to the samples' slightly different dimensions (induced by preparation, drying, etc.), the eroded volumes were normalised using a reference area that considers an average value of all the samples' dimensions (35 mm side). This allows for direct comparison of eroded volume values, eliminating the need to adjust for varying sample dimensions. The data demonstrates

substantial differences in erosion behaviour between the control sample and the MgO and SC-admixed adobes, with stark contrasts in erosion resistance between different stabilizer types and concentrations. The reference sample exhibited severe erosion from the outset, with recorded volumes of 391.8 mm³ at 1 minute and escalating to 5095.1 mm³ by the 4-minute mark, after which the sample disintegrated and was withdrawn from further testing. In contrast, while both SC and MgO treatments enhanced adobe erosion resistance (excluding SC 15%), MgO proved to be significantly more effective. The MgO-10% and MgO-15% sample consistently demonstrated the lowest erosion volumes across all time intervals, for which the erosion remained at 1 and 1.5 mm³ after 1 minute, and reached at low amounts, as low as 0.6 and 12.9 mm³, even at 32 minutes respectively. MgO-10% SC samples exhibited more variable erosion profiles. While SC-5% and SC-10% maintained moderate resistance during early rainfall stages, their erosion volumes significantly increased beyond 8 minutes, particularly for SC-10%, which surged to 5453 mm³ at 32 minutes. SC-15% performed worst, showing extreme erosion even at 1 minute (3437 mm³) and peaking at over 97,540 mm³ by 32 minutes.

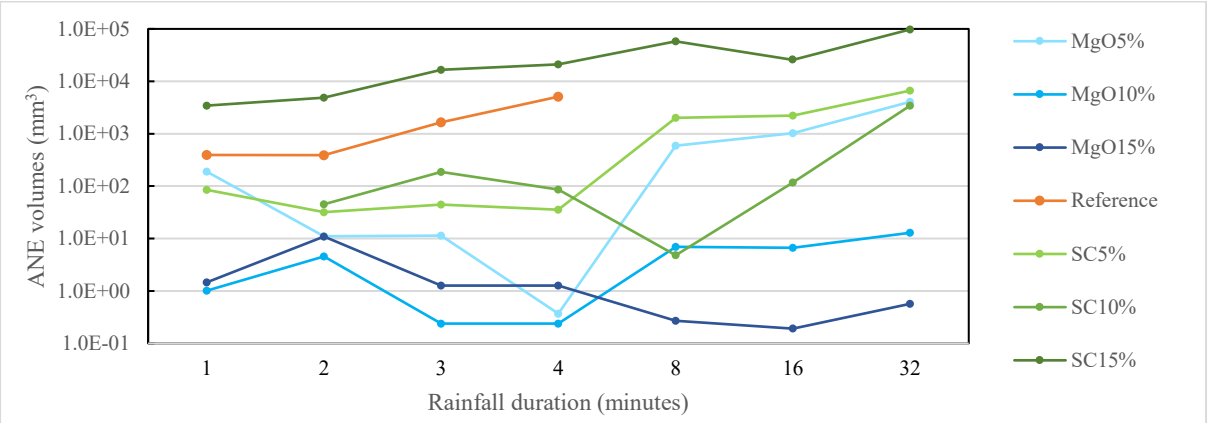


Fig. 6.4. Area-normalized erosion (ANE) volumes of adobe samples under simulated rainfall (Normalized to the reference sample).

6.3.2. Capillary water absorption

The same set of materials was used in the capillary absorption test. The reference sample exhibited the most rapid capillary behaviour, with moisture visibly ascending to a height of 48 mm by the end of the test (Table S3 and Fig. 6.5). In contrast, the samples treated with MgO revealed a significant reduce of water uptake, with the extent of capillary rise inversely proportional to the stabilizer concentration. The MgO-10% and 15% sample demonstrated the lowest water ascent, reaching only 29 and 32 mm after 30 minutes, respectively, MgO-10% suggesting that MgO significantly reduces pore connectivity and surface suction. In contrast,

Sorel cement–treated samples absorbed water more rapidly, almost following the pattern observed for the reference sample. Both SC-15% and SC-10% reached the maximum test height of 50 mm within the 30-minute period. Notably, SC-15% displayed higher early-stage uptake, with 17 mm absorbed in just 3 minutes, compared to 9 mm for MgO 10%. Lower additive concentrations (5%), for both MgO and SC, also reached the 50 mm limit, performing only marginally better than the reference in early stages.

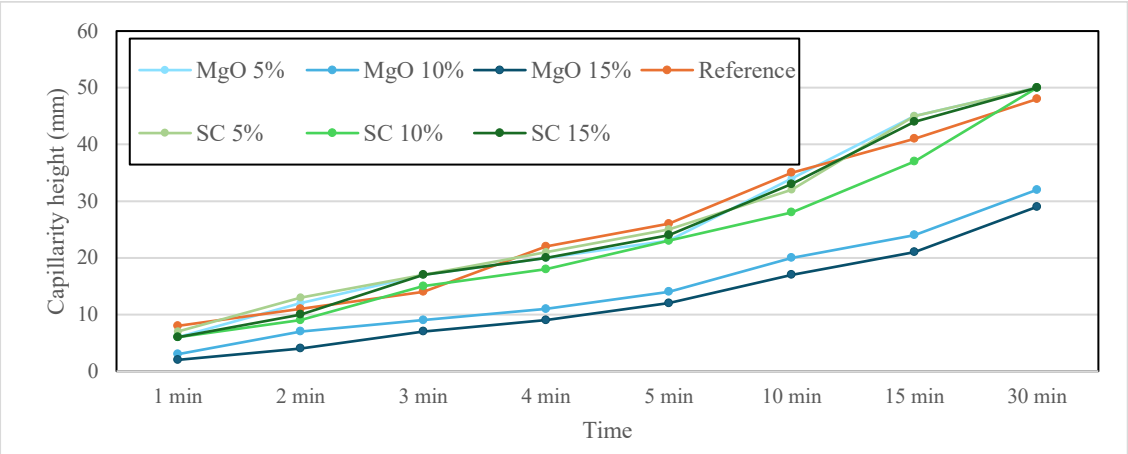


Fig. 6.5: Comparative capillary water absorption (height) of treated and untreated adobe samples.

6.3.3. Immersion test

To assess the resistance of the adobes to prolonged water exposure, all samples were fully submerged in distilled water for a duration of 72 hours. The evaluation focused on key indicators of deterioration, including physical disintegration, crack development, swelling, and edge erosion. Each sample was assigned a degradation rating on a scale from 1 to 5, where a score of 5 denoted complete disintegration and a score of 1 indicated no observable damage (Table S4 and Fig. 6.6).

The reference adobe exhibited the most significant degradation during the 72-hour water immersion test. It underwent extensive cracking (rated 5), complete structural disintegration (rated 5), and demonstrated maximum irresistibility to water exposure (rated 1). These results underscore its inherent vulnerability to saturated conditions and its lack of cohesive integrity. In contrast, the sample MgO-15% demonstrated superior durability. It maintained its structural integrity with no observable disintegration (rated 1), exhibited only minor cracking (rated 2), and achieved a high-water resistance score (rated 4.5). The sample preserved its geometry and cohesion throughout the test, emerging as the most water-resilient formulation assessed. Both samples MgO-5% and MgO-10% also showed improved water resistance compared to the

reference. MgO-5% exhibited slightly greater cracking (4.5) but maintained moderate resistance (3.5), while MgO-10% scored 3.5 for crack formation, 2 for disintegration, and 3.5 for water resistance, MgO-5%. In the other hand, SC-stabilized samples showed mixed results. SC-5% exhibited substantial cracking (4) but limited disintegration (1), with only 2.5 for water resistance, highlighting the limited effectiveness of lower concentrations. SC-10% performed moderately, scoring 3.5, 2, and 3 across the three categories, respectively. However, SC-15%, despite its higher concentration, performed poorly in long-term immersion, scoring 3, 4 and 2, respectively.

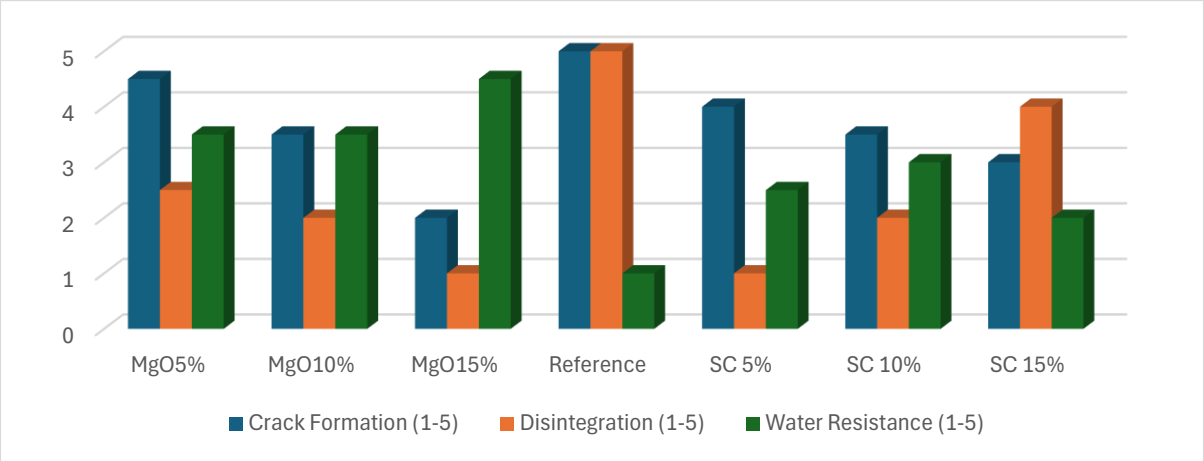


Fig. 6.6: Physical degradation of adobe samples after 72 hours of water exposure.

6.3.4. Mineralogy and Microstructural examination of adobes

The XRD results of sample MgO-15% (Fig. 6.7a) reveals the formation of $Mg(OH)_2$ (magnesium hydroxide), indicated by the appearance of new peaks, while some unreacted MgO is still present. A significant disappearance of the montmorillonite peak is observed, which correlates with the appearance of a new chlorite peak. The analysis of sample SC-15% (Fig. 6.7b) shows numerous new peaks corresponding to the formation of magnesium oxychloride cement, (phase 5: $5Mg(OH)_2 \cdot MgCl2 \cdot 8H2O$; Jiříčková et al., 2020.). Similar to the 15% MgO sample, the montmorillonite peak has disappeared, and a new chlorite peak is detected.

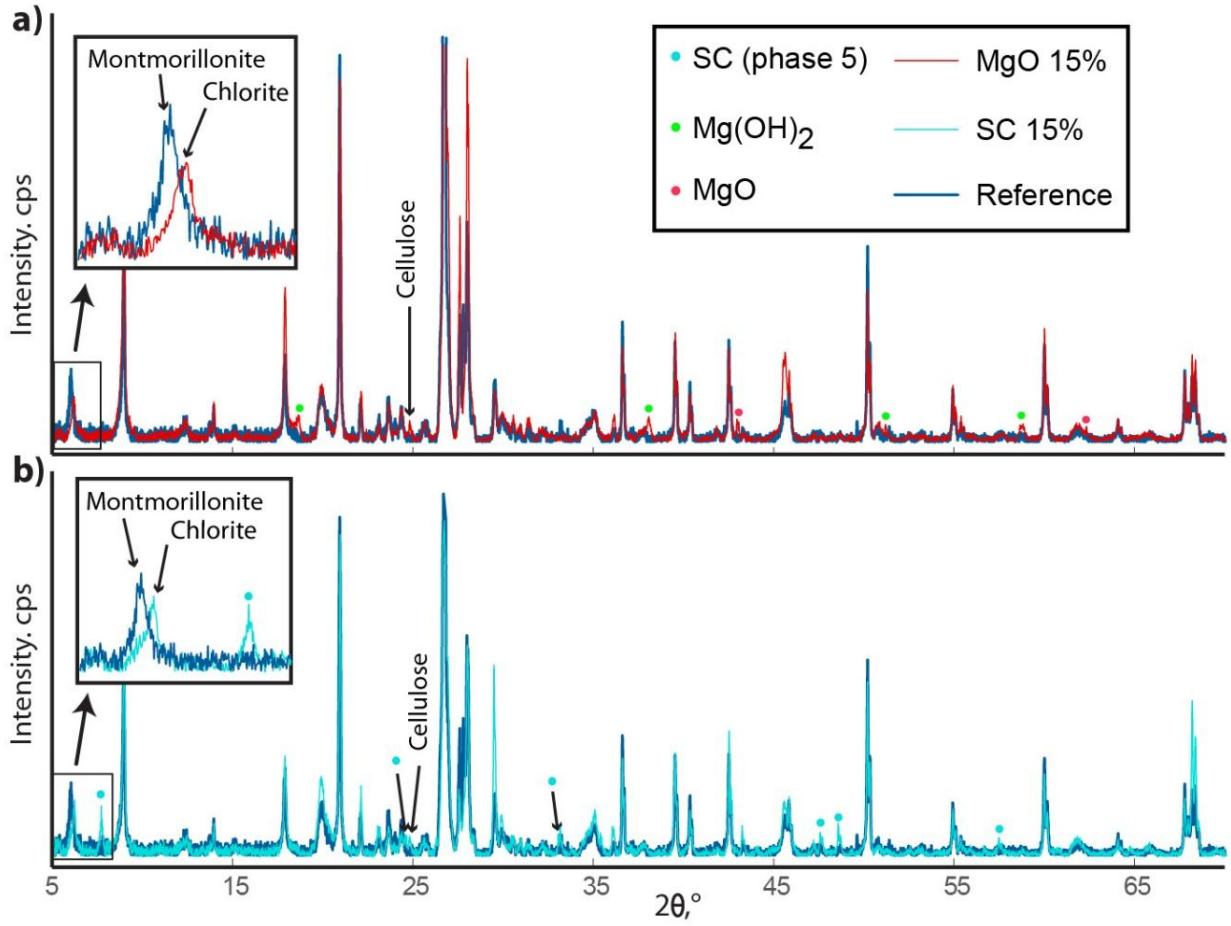


Fig. 6.7: X-ray diffraction (XRD) results of samples MgO-15% (a) and SC-15% (b).

A mineralogical and chemical analysis of the clay fraction of samples MgO-15% and SC-15% was performed by FE-SEM, combining BSE imaging and EDS elemental mapping (Fig. 6.8). The analysis of sample MgO-15% revealed an extremely diffused distribution of Mg. EDS spectroscopy (Figs 6.8a,b) revealed that while minor amounts of magnesium could be assigned to MgO and/or $Mg(OH)_2$, most Mg was associated with Si, an information that coupled with XRD results indicated the presence of very fine chlorite crystals, with a size of less than 1 μm. In contrast, while sample SC-15% showed a similar distribution of chlorite, it was entirely lacking MgO and/or $Mg(OH)_2$ (Fig. 6.8b). As anticipated, the analysis also identified patches of SC (phase 5) as a reaction product between MgO and $MgCl_2$, which constituted 5-10% of the sample and had sizes up to approximately 5 μm, embedded within the grains.

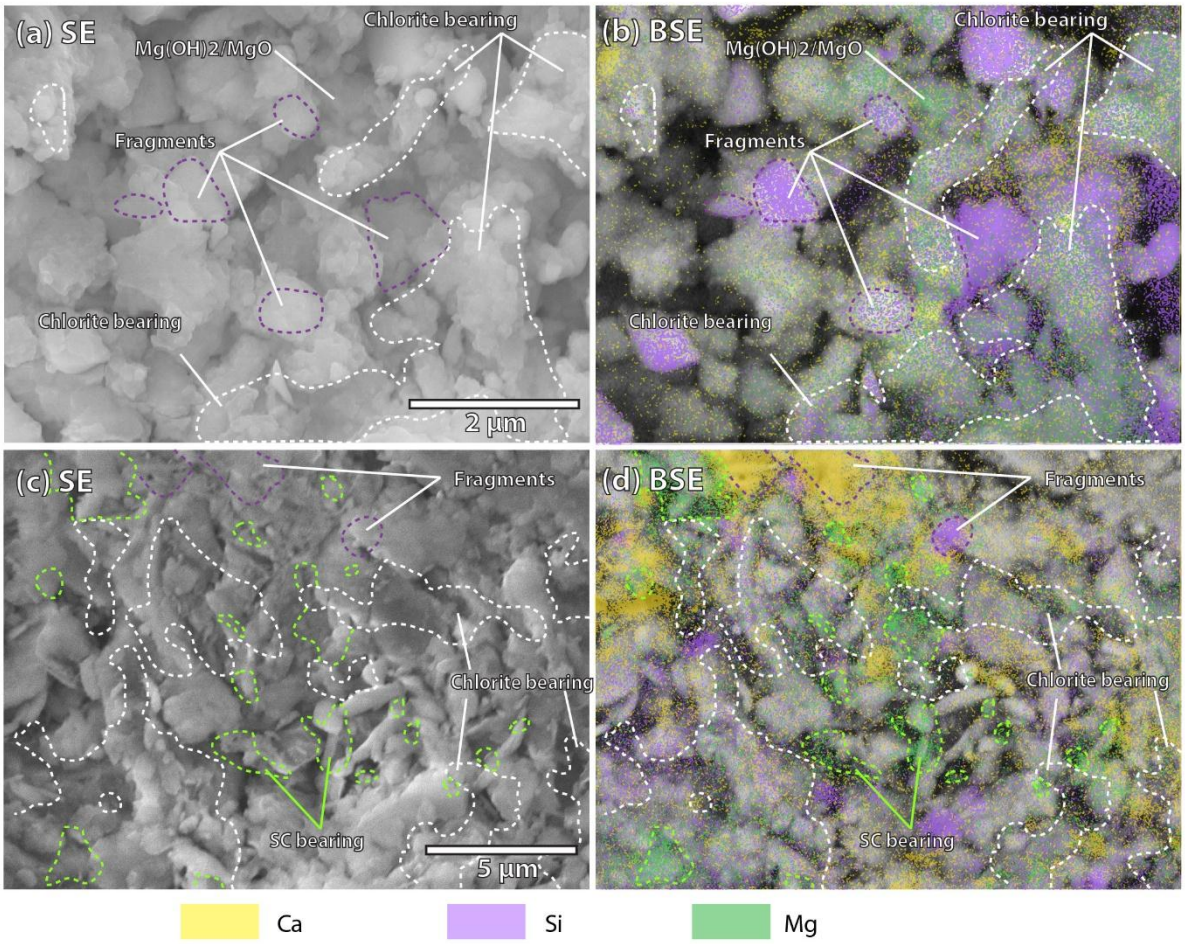


Fig. 6.8: FESEM-BSE images and EDS results from samples MgO-15% (a and b, respectively) and SC-15% (c and d, respectively). (a) and (c) are SEM images for samples MgO-15% and SC-15%, respectively. (b) and (d) are EDS elemental maps of Mg, Si and Ca, superimposed on the BSEM images for samples MgO-15% and SC-15%, respectively. The areas containing chlorite (see text) and $Mg(OH)_2$/MgO are shown.

The FESEM-EDS analyses provided detailed information on the distribution of magnesium in the adobe samples treated with MgO and SC. Magnesium was consistently observed in the interparticle regions of both sample types. However, distinct patterns in distribution and compound formation were noted between the two stabilizers.

In the MgO-15% sample, magnesium appeared primarily dispersed between soil particles, with only rare indications of unreacted MgO or distinct $Mg(OH)_2$ zones. The overall elemental mapping suggested that magnesium was well integrated into the matrix, with no visible clustering or accumulation, indicating a uniform distribution within the clay framework.

In contrast, the SC-treated samples, particularly at 15%, displayed a higher number of magnesium-rich zones concentrated in interstitial spaces. These zones were primarily

associated with crystalline magnesium oxychloride phases. The EDS spectra revealed localized accumulations of magnesium and chlorine, consistent with Sorel cement formation.

6.4. Discussion

This study aimed at evaluating the effectiveness of MgO and SC as stabilizing additives for adobes, through a comprehensive series of laboratory tests, including artificial rainfall simulation and quantitative assessments of the erosion, capillary absorption, immersion, durability, XRD and FESEM analyses, clear patterns emerged regarding the suitability of each additive in different concentrations, for moisture-prone environments.

6.4.1. Erosion resistance and stabilizer performance

The reference sample, disintegrating completely after 4 minutes of rainfall exposure, highlights the inherent vulnerability of untreated silty clay loam adobe and underscores the need to stabilize earthen cultural heritage sites in climates exposed to even moderate rainfall.

The erosion results under the simulated rainfall from Fig. 6.4 demonstrate a strong correlation between stabilizer type, concentration, and erosion resistance. Among all formulations tested, MgO at 15 wt% concentration exhibited outstanding performance, maintaining erosion volumes below 1.5 mm^3 across all rainfall durations. The low erosion volume rate over time further suggests excellent structural integrity under prolonged hydric stress, making this formulation particularly well-suited for environments with frequent or intense precipitation. Whereas, sample MgO-10% maintained slightly higher erosion values throughout the test, suggesting it still would be considered effective for budget-sensitive conservation contexts, where reduced additive content is desirable (Hart et al., 2023). By contrast, the performance of SC was notably more variable and samples SC-5% and SC-10% provided moderate protection in the initial phases of rainfall exposure but exhibited a sharp increase in erosion beyond 8–16 minutes. Most strikingly, SC-15% showed extremely high erosion volumes, with degradation beginning almost immediately and escalating to over $97 \cdot 10^3$ mm^3 at 32 minutes (Table S2, Fig. 6.4). Although SC products have been proven water-resistant (Ma et al., 2023), this is not the case in our adobes' samples, possibly due to used soil characteristics, the adobe's preparation procedure and the influence of drying time on SC curing. These results align with previous studies, noting the limited durability of SC under saturated or cyclic wetting conditions (Li & Chau, 2007; An et al., 2024).

In the other hand, the results of the capillary absorption and immersion tests also revealed a clear relationship between stabilizer concentration and the ability of adobe to resist moisture

ingress (Table S3, Fig. 6.5). These enhancements contribute to sustained resistance even when submerged, an essential trait for materials exposed to fluctuating water tables or environments prone to rising damp. In contrast, samples containing SC did not provide comparable moisture resistance to those containing MgO. For MgO, even moderate incorporation contributes to improved durability, though its effectiveness becomes markedly pronounced beyond a certain concentration. In contrast, low-dose SC may produce localized consolidation but lacks the network strength to prevent moisture-driven deterioration at the macro level.

6.4.2. Soil characteristics and mineralogical insights

Based on granulometric analysis, the soil used in this study was classified as silty clay loam, thus characterized by a high proportion of silt and clay and relatively low sand content (Fig. S1). This composition results in poor natural cohesion, and a heightened tendency for capillary water rise and moisture retention (Reddy et al., 2022). Consequently, the material is particularly prone to structural degradation when exposed to rainfall or prolonged water saturation (Fig. 6.2, 6.3, 6.4, and 6.6). The XRD results show that the main component of the clay minerals fraction is montmorillonite which is a swelling mineral in the presence of water. This results in quenching and cracking of the adobe during drying and losing water from the mineral structure.

In both MgO and SC-based adobes, magnesium was detected predominantly at interparticle regions, but its spatial behaviour suggests distinct mechanisms of integration with the clay matrix (Figs. 6.8a, b). In the sample MgO-15% only limited evidence of unreacted MgO or discrete zones of magnesium hydroxide $Mg(OH)_2$ formation were observed. This distribution pattern supports the hypothesis that magnesium ions might have effectively incorporated into the crystal structure of the clay minerals, particularly into montmorillonite, which likely facilitated its transformation into chlorite (see for example Slaughter and Milne, 1958), as also confirmed by the XRD results (Figs. 6.7a, b). This mineralogical transformation is crucial in reducing swelling behaviour and enhancing moisture resistance, as chlorite's rigid structure offers superior dimensional stability under hydric stress.

By contrast, the SC-treated samples exhibited a higher frequency of magnesium-rich zones, particularly in the form of crystalline magnesium oxychloride (MOC) phases, distributed primarily in the interstitial spaces between particles. This suggests that a significant portion of the available magnesium in these samples contributed to the formation of SC compounds, rather than inducing mineralogical transformation of the montmorillonite. As a result, the extent of montmorillonite-to-chlorite conversion was likely lower in SC samples compared to

those treated with MgO alone. The transformation of montmorillonite as a swelling smectite clay into chlorite, a more structurally stable, non-expansive mineral (Chesworth, 2007; Liu et al., 2016; Slaughter and Milne, 1958) plays a critical role in improving the moisture resistance of the treated adobe units. Montmorillonite is well-known for its high-water absorption capacity and its tendency to expand and contract depending on moisture levels. Due to its 2:1 layer structure, water molecules can easily enter its interlayer spaces, causing the material to swell when wet and shrink upon drying. These repeated hydration-dehydration cycles lead to visible cracking, surface flaking, and gradual deterioration, especially in humid environments or during heavy rainfall (Murray, 2007; Al-Rawas & Goosen, 2006). In contrast, the formation of chlorite, identified by a diagnostic peak near $2\theta \approx 38°$ in the XRD patterns, indicates a more stable mineral phase. Chlorite has a 2:1:1 layer structure that includes a (Mg, Fe, Al)-hydroxide sheet, which acts as a barrier to water absorption. This structural difference reduces swelling, enhances dimensional stability, and lowers water uptake through capillary action, as also were observed in our experiments. This mineral-level improvement explains the reduced cracking, minimal erosion, and improved immersion resistance observed in the MgO- and SC-treated adobe units. The chemical environment created by MgO not only promotes this mineralogical stabilization but also supports the formation of SC phases. However, our findings show that by increasing the level of MOC formation, the stability of the adobe decreases, as pronounced in the sample SC-15% with respect to sample SC-10% in rainfall and immersion tests (Tables S2-4 and Figs 6.4-6). MOC phases are known to exhibit poor long-term durability in saturated environments due to instability under water exposure and potential phase decomposition (Chang et al., 2023). Likely, the localized accumulation of MOC may lead to micro-fracturing and a lack of cohesive integration within the matrix, contributing to accelerated surface erosion and structural failure.

6.5. Implications for heritage conservation

The findings of this study hold critical implications for the conservation of earthen heritage, particularly in regions increasingly affected by climatic instability, including intensified rainfall, prolonged wet seasons, and rising groundwater levels, where even episodic rainfall can result in irreversible loss of material fabric (Nakhaei & Correia, 2021; Richards et al., 2019).

The current research provides evidence supporting the use of environment-friendly stabilization, specifically MgO, as viable conservation treatment. MgO's ability to reduce capillarity, limit surface erosion, and maintain structural integrity under saturation conditions

is particularly important for heritage applications, where passive resilience to water exposure is often the most effective preservation strategy. Equally important is MgO's material compatibility with traditional adobe, offering chemical and physical cohesion without drastically altering the visual or tactile properties of the earthen fabric. Unlike Portland cement, which is often discouraged in heritage interventions due to its high alkalinity, low breathability, and irreversible interactions with clay particles (Rainer, 2008; Medvey & Dobszay, 2020), MgO offers a reversible, breathable, and low-impact alternative. These characteristics, coupled with its accessibility and economic feasibility, make MgO a strong candidate for use in conservation contexts that prioritize minimal intervention and material authenticity, in alignment with international charters such as the Venice Charter (ICOMOS, 1964). Unlike MgO, the long-term performance of SC under water exposure, as well as its dissolution in water and formation of corrosive salts (Jiříčková et al., 2020) requires further investigation before it can be recommended for broader use at sensitive heritage sites. Additionally, the methods used in this study, such as rainfall simulation, and standardized water exposure tests, can be adopted as part of a diagnostic toolkit for earthen heritage assessment.

Findings of this study also suggest that an SC dosage of approximately 10% represents an optimal balance between mechanical enhancement and moisture tolerance. Higher concentrations may not only reduce durability but also raise conservation concerns, including magnesium salt leaching, which can negatively impact adjacent structures. Additionally, the higher cost, complex processing, and curing sensitivity of SC, when compared to MgO, present significant limitations for its large-scale or long-term application in heritage conservation.

The mineral transformation realized in XRD analysis, has important implications for the conservation of earthen heritage, in regions where moisture variability poses ongoing risks. Since the instability of clay-rich soils often stems from their swelling behaviour, the shift to chlorite presents a pathway for extending the life and resilience of adobe structures. Especially in archaeological or historic contexts, where material compatibility and environmental adaptability are essential, such mineralogical improvements offer an important tool for sustainable and climate-responsive conservation.

Drawing from the results of this study, the following guidelines are proposed for the practical use of stabilizing additives in earthen site conservation:

- MgO at 15% concentration is recommended for high-moisture-risk areas, such as the base of walls, foundation levels, and other exposed exterior surfaces. MgO at 10%

concentration may be appropriate for interior walls or semi-sheltered environments. While it offers a moderate level of moisture protection, it provides a cost-effective solution where full exposure to water is limited.

- SC is not recommended for moisture-sensitive applications in adobe construction. Its reduced stability under prolonged water exposure, slower drying rate, and the presence of chloride salts, which may contribute to long-term degradation, make it a less reliable choice for humid or rain-exposed environments.

6.6. Summary of Key Issues

This study provided a comprehensive evaluation of adobes stabilized with MgO and SC, using quantitative rainfall simulation, capillary absorption and immersion tests and microstructural analysis designed to replicate real-world moisture exposure. The findings highlight clear differences in performance between the two stabilizers, with outcomes varying notably by concentration. The MgO-stabilized adobe samples consistently outperformed all others in terms of resistance to surface erosion, water absorption, and structural disintegration across the various moisture exposure tests. A key finding from the XRD analysis revealed a notable mineralogical transformation in these samples: montmorillonite, an expansive clay known for its poor dimensional stability, was partially converted into chlorite, a non-swelling and more structurally stable mineral. This transformation likely played a central role in enhancing the material's durability. Supporting this, FESEM-EDS results showed a uniform distribution of magnesium within the clay matrix, indicating effective integration that contributed to matrix densification and the reduction of pore connectivity, ultimately limiting water uptake.

In contrast, SC-treated adobe showed more mixed results. While samples treated with 10% SC exhibited moderate improvements in short-term moisture resistance, higher concentrations (15%) led to early-stage degradation under prolonged rainfall simulation. This decline in performance is attributed to the localized formation of brittle magnesium oxychloride phases, which lacked the cohesive bonding and long-term water stability observed in MgO-treated bricks. Additionally, the SC-treated samples revealed limited mineralogical transformation, reducing their ability to effectively stabilize weak, clay-rich soils over time.

Importantly, the study also demonstrated that even low-strength silty clay loam soil, typically unsuitable for long-lasting adobe construction, can be significantly improved through targeted stabilization. The artificial rainfall test proved especially valuable in capturing real-time erosion behaviour and identifying the most resilient formulations for moisture-prone

environments. These findings offer a cost-effective and environment-friendly solution with minimal interventions, for preservation earthen structures exposed to increasing moisture risks under changing climate conditions.

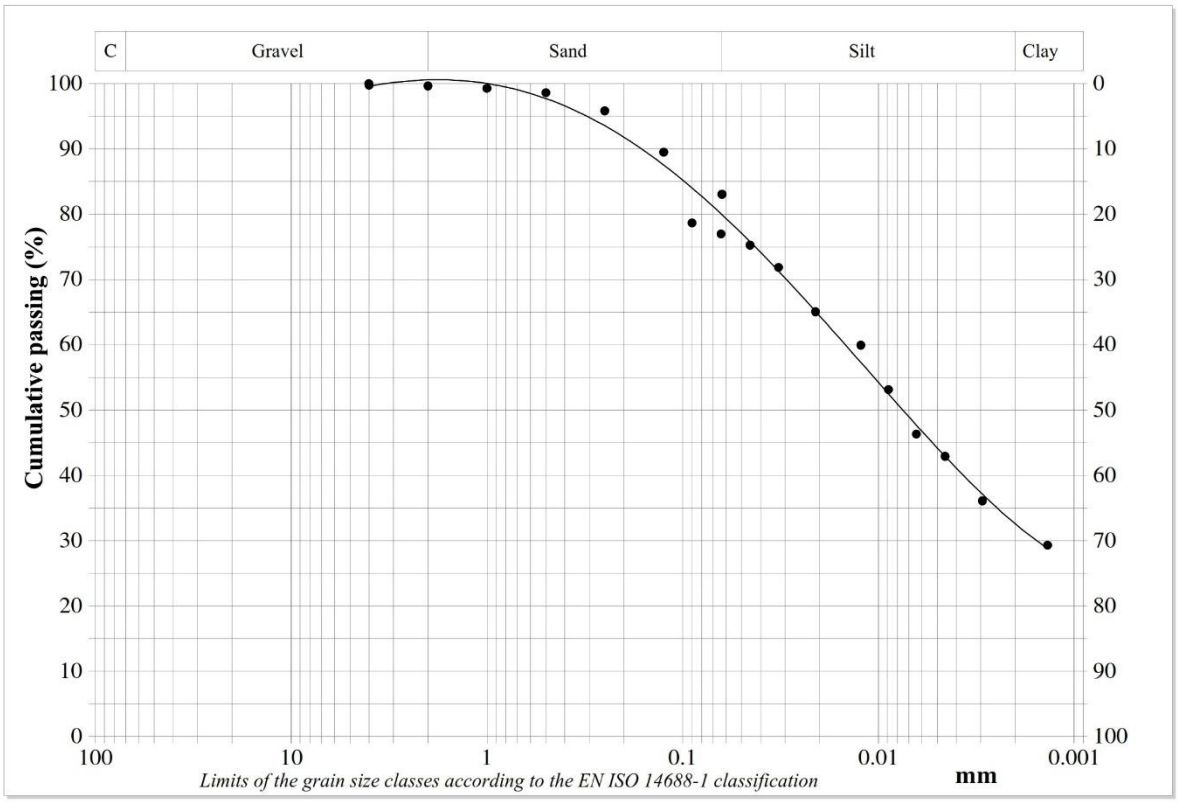
The findings demonstrate the potential of scientific innovation to complement traditional practices in enhancing resilience. Building on these results, the final chapter integrates all preceding stages, conceptual, empirical, and experimental, into a holistic framework for climate-resilient earthen heritage conservation.

6.7. Supplementary material

6.7.1. Soil characteristics

The primary material utilized for adobe brick production in this study was natural soil collected from the archaeological site of Campo del Pozzo (Nazzano, Rome) in central Italy. The soil was first air-dried and sieved through a 2 mm mesh to remove coarse particles, then subjected to granulometric and chemical characterization. Granulometric distribution was determined through particle size analysis (Fig S1). The data indicated that the soil comprised 50.6% silt, 32.8% clay, and 16.6% sand and can be classified as silty clay loam (USDA, 1951; Fig. S2). Additionally, X-ray diffraction (XRD) analysis showed quartz, plagioclase, orthoclase and montmorillonite as major components of the soil minerals (Fig S3).

Gravel	0.4 %	Norm ASTM D 422		D_{10}	--- mm
Sand	16.5 %	Sieve mesh 10 (2 mm)	99.6 %	D_{30}	0.00148 mm
Silt	50.4 %	Sieve mesh 40 (0.42 mm)	97.9 %	D_{50}	0.00764 mm
Clay	32.7 %	Sieve mesh 200 (0.075 mm)	84.7 %	D_{60}	0.01236 mm
		---	---	D_{90}	0.13180 mm



Diameter mm	Passed %	Diameter mm	Passed %	Diameter mm	Passed %	Diameter mm	Passed %	Diameter mm	Passed %
4.0100	100.00	0.0895	78.68	0.0089	53.13				
4.0000	99.76	0.0637	76.98	0.0064	46.32				
2.0000	99.64	0.0630	83.05	0.0046	42.92				
1.0000	99.27	0.0453	75.27	0.0029	36.10				
0.5000	98.60	0.0324	71.87	0.0014	29.29				
0.2500	95.83	0.0210	65.06						
0.1250	89.52	0.0123	59.95						

Fig S1: Granulometric (particle size distribution) curve for a soil sample from Nazzano

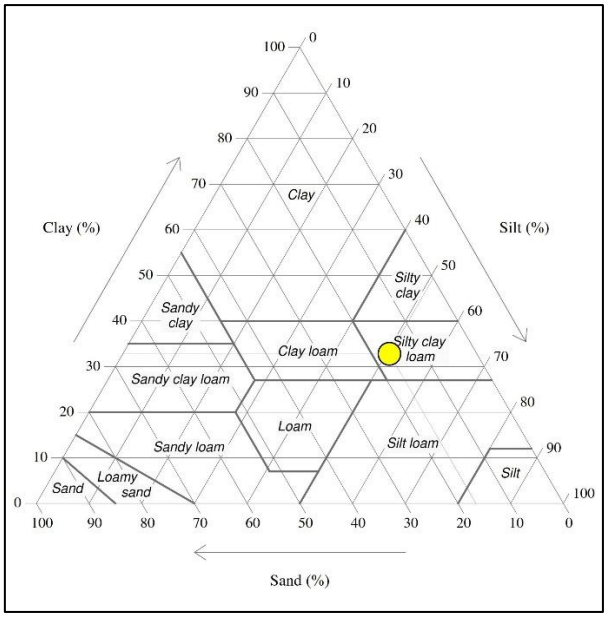


Fig. S2: Soil texture classification based on particle size distribution

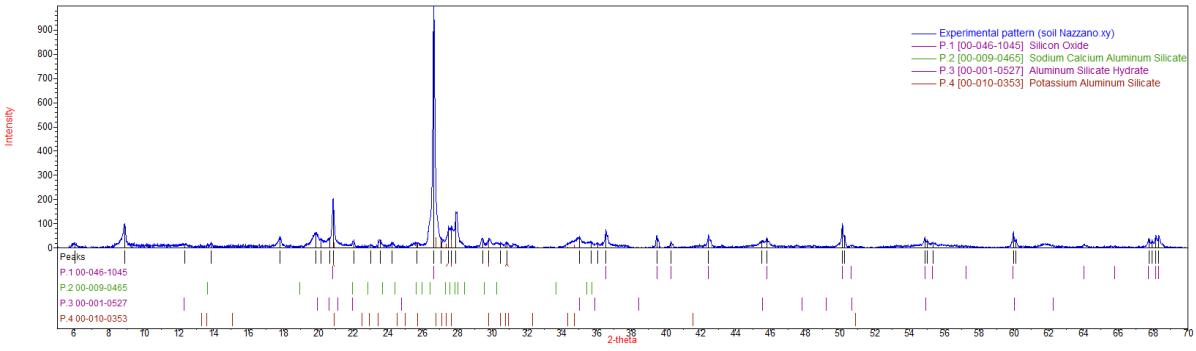


Fig S3: XRD analysis of the soils sample from Nazzano (Rome), Italy

6.7.2. Additive selection and properties

Two magnesium-based additives, MgO and SC, were selected for this study due to their known potential to improve the performance of masonry materials (Espuelas et al., 2017; Kotwa & Kłak., 2024). MgO was selected because its hydration precipitates platelet or tabular $Mg(OH)_2$ crystals, which are hypothesized to reduce water permeability in the adobe structure (Maryska et al., 1997; Henrist et al., 2003; WU et al., 2014). A reactive, light-burned grade of MgO of 90-92 wt% was obtained from Persia Paya Madan Co. (www.persiapaya.com) (Table S1), supplied in fine powdered form to ensure homogeneous mixing. SC was included for its ability to form a crystalline magnesium oxychloride within the matrix with high early strength and strong adhesion to soil particles, making it suitable for structural enhancement (Li & Chau, 2007; Guo, 2020). The magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$) was purchased as a 99% pure powder from Sigma-Aldrich (www.sigmaaldrich.com). The SC was prepared in the

laboratory by combining MgO and magnesium chloride hexahydrate in a molar ratio of 5:1, following the procedure outlined by Temiz and Tandirci (2023), to ensure reproducibility and optimal binding phase formation. Both additives were tested at varying concentrations (5, 10 and 15 wt %) to evaluate their influence on the durability and microstructural performance of adobe bricks under controlled environmental conditions. Moreover, a constant amount of straw (~2 wt%), similar to that found in most traditional adobes (e.g., Costi de Castrillo et al. 2017), was added to all treated adobe units, including the reference samples.

Table S1: The chemical analysis of major oxides from the used MgO

ID	SiO2 (wt%)	MgO (wt%)	CaO (wt%)	Fe2O3 (wt%)	Al2O3 (wt%)	LOI (wt%)
PPM-5	7±1	91 ± 1	2 ± 1	< 1	< 1	< 3

6.7.3. Adobe preparation

All adobes were fabricated following a standardized production procedure (Reddy et al., 2022) that integrated both laboratory protocols and traditional construction practices to ensure consistency and relevance to real-world applications. The adobes were prepared adding the MgO and SC (MgO + $MgCl_2$) to the dry soil mixture, at different concentrations. Water was gradually added to the soil to achieve a workable consistency suitable for forming adobe units. All mixtures were thoroughly hand-kneaded to promote uniform distribution of the modifying agents throughout the soil matrix. Moreover, a certain number of adobes was prepared without any additives, to be considered as control samples for experimental tests.

The prepared mixtures were cast into 5 cm cubic molds. Each mold was filled in successive layers and compacted to minimize internal voids and ensure consistent sample density. Following demoulding, the adobes underwent a two-stage drying process. Initially, the samples were air-dried under ambient laboratory conditions (approximately 25°C and 45% relative humidity) for 72 hours to simulate natural environmental drying. Subsequently, the adobes were placed in a laboratory oven and dried at 50°C for 48 hours, to ensure complete removal of residual moisture.

6.7.4. Laboratory studies

To assess the performance of the adobes with MgO and SC, a series of controlled laboratory experiments were conducted. These include artificial rainfall simulation, capillary water

absorption and full immersion test. Moreover, the textures of the samples and the distribution of the additives were investigated through Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray Spectroscopy (EDS).

6.7.4.1. Artificial rain simulation

For the artificial rainfall simulation, a custom-designed environmental chamber was developed specifically for this study (Fig. S4). Given that preliminary tests demonstrated the adobes' high resistance to water erosion, the rainfall intensity was set at a near-maximum value of approximately 80,000 mm/h, a rate equivalent to roughly 100 years of precipitation for a region with an annual rainfall of 500 mm. Both the treated and untreated adobe samples were subjected to artificial rainfall for up to 32 minutes. Following each rainfall exposure cycle, the surface topography of the samples was recorded using a high-resolution laser scanner at predetermined time intervals of 1, 2, 3, 4, 8, 16, and 32 minutes, allowing accurate quantitative assessment of surface erosion and morphological changes over time. The laser scanner had horizontal and vertical resolutions of 50 μm and 70 μm, respectively. In addition, photographic documentation was carried out at each time interval to visually record changes in the samples throughout the experiment.

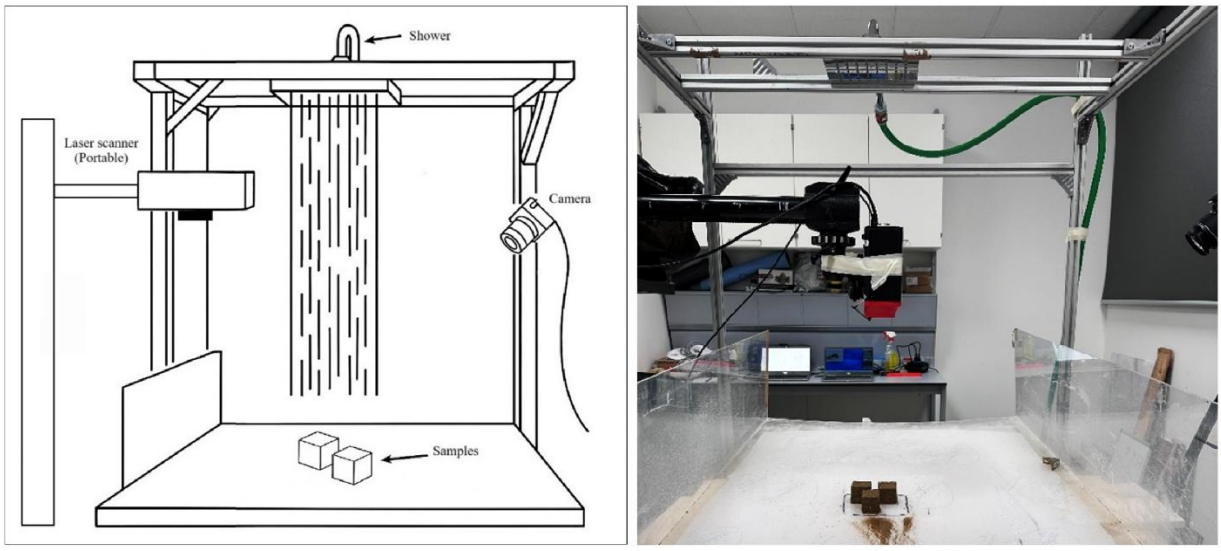


Fig. S4: Experimental setup for simulated rainfall and surface scanning of the samples

Time (min)/ Sample	1	2	3	4	8	16	32
Reference 1	391.8	389.9	1,656.5	5,095.1	-	-	-
Reference 2	449.9	510.9	1,687.4	2,766.1	-	-	-
SC5%	85.5	31.9	44.5	35.7	2,016.7	2,228.5	6,648.4
SC10%	45.1	187.5	86.1	4.8	117.9	3,435.3	5,453.4
SC15%	3,437.1	4,899.1	16,653.4	20,903.0	57,827.5	25,629.0	97,540.5
MgO5%	188.5	11.1	11.4	0.4	590.3	1,017.1	4,059.7
MgO10%	1.0	4.6	0.2	0.2	7.0	6.7	12.9
MgO15%	1.5	10.9	1.3	1.3	0.3	0.2	0.6

Table S2: Area-normalized erosion volumes (mm^3) recorded during the artificial rainfall simulation time

6.7.4.2. Capillarity test

The capillarity test was designed to simulate the capillary rise of moisture into earthen structures. The adobe samples were placed in a shallow container partially filled with water, with a sponge positioned beneath the samples to ensure uniform contact and consistent moisture distribution at the base (Fig. S5). The capillary water uptake was monitored by recording the height of moisture penetration along the vertical surfaces of the adobes at fixed time intervals: 1, 2, 3, 4, 5, 10, 15, and 30 minutes (Table S3). These measurements enabled a comparative evaluation of the capillary absorption behaviour between treated and untreated samples, thereby assessing the effectiveness of each stabilizing treatment in mitigating water uptake through capillary action.

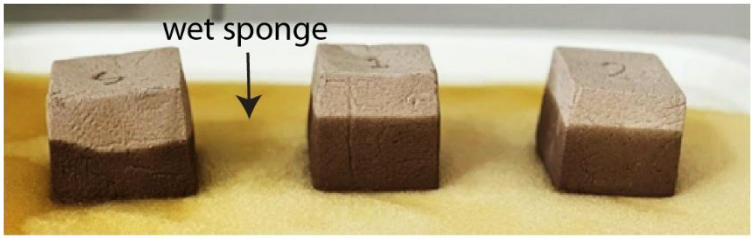


Fig. S5: Example of experimental setup of the capillarity test.

Adobe Mixture	1 min	2 min	3 min	4 min	5 min	10 min	15 min	30 min
MgO 5%	6	12	17	20	23	34	45	50
MgO 10%	3	7	9	11	14	20	24	32
MgO 15%	2	4	7	9	12	17	21	29
Reference	8	11	14	22	26	35	41	48
SC 5%	7	13	17	21	25	32	45	50
SC 10%	6	9	15	18	23	28	37	50
SC 15%	6	10	17	20	24	33	44	50

Table S3: Effect of treatment on capillary water absorption in adobe samples (Hight of moisture penetration (mm))

6.7.4.3. Immersion tests

For the immersion test, adobes were fully submerged in individual beakers filled with distilled water and monitored over 72 hours (Fig. S6). During this time, the physical integrity of each sample was assessed through regular visual inspections (see text for the explanation). Key parameters included the onset and progression of cracking, the extent of surface and structural disintegration, and the overall resistance to prolonged water exposure (Table S4). Comprehensive documentation was maintained for each specimen, facilitating a comparative evaluation of the durability and effectiveness of the various stabilizers under saturated conditions.

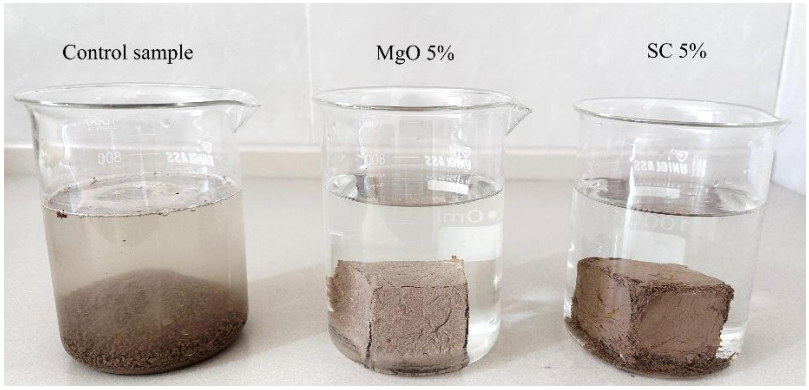


Fig. S6: Setup of the immersion test showing adobe samples submerged in distilled water for durability evaluation over 72 hours

Adobe Mixture	Crack Formation (1-5)	Disintegration (1-5)	Water erodibility (1-5)
MgO5%	4.5	2.5	3.5
MgO10%	3.5	2	3.5
MgO15%	2	1	4.5
Reference	5	5	1
SC 5%	4	1	2.5
SC 10%	3.5	2	3
SC 15%	3	4	2

Table S4: Deterioration of adobe samples following 72 hours of water immersion

6.7.4.4. FESEM-EDS analysis

To investigate the microstructural characteristics of the treated adobes, FESEM backscattered electron images and EDS microanalyses were collected on thin sections prepared from representative samples of each experimental group. The primary objective of this analysis was to assess the distribution of the additives in the samples and any new crystalline phase formed from the additives. These sections were dry polished with SiC abrasive paper up to 1 μm, to achieve smooth surfaces suitable for high-resolution imaging. BSE images and EDS-WDS spectra were collected using a 10 kV electron beam acceleration at 8.5 mm working distance. Images of phases and their textures were first identified and collected by back-scattered electrons using a FE-SEM WD/ED probe (model ZEISS Merlin II. EDS model: OXFORD X-MAX 50). This kind of instrument has the capacity of focalize and maintain stable the beam current up to the high-resolution condition. the crystal phases were characterized; their chemical compositions were then accurately determined by EDS microanalyzer at the CERTEMA multidisciplinary laboratory of Grosseto (Italy). The operative conditions were opportunely selected in order to minimize the charging up of the sample. Infact, the high porosity of the sample did not allow for adequate electron conduction on the surface. The Analytical conditions were 10 kV accelerating voltage and 2 nA beam current.

References

Aguilar, R., Nakamatsu, J., Ramírez, E., Elgegren, M., Ayarza, J., Kim, S., Pando, M.A. & Ortega-San-Martin, L. (2016). The potential use of chitosan as a biopolymer additive for

enhanced mechanical properties and water resistance of earthen construction. *Construction and Building Materials*, *114*, 625-637.

Ahmad, F., Rawat, S., & Zhang, Y. (2024). Magnesium Oxychloride Cement: Development, Opportunities and Challenges. *Applied Sciences*, *14*(7), Article 7. https://doi.org/10.3390/app14073074

Al Zohbi, G., Askar, S. A., Kumar, A., Kumar, P., Dahiya, M., & Rani, S. (2024). Sustainable building materials for Eco-friendly construction. *AIP Conference Proceedings*, *3217*(1), 040005. https://doi.org/10.1063/5.0234594

An, L., Wang, Z., Meng, L., Chang, C., Zhou, Z., & Yan, F. (2024). Research on Deterioration Behavior of Magnesium Oxychloride Cement Under High Humidity and High Temperature. *Materials*, *17*(21), 5226.

Ashour, T., & Wu, W. (2010). An experimental study on shrinkage of earth plaster with natural fibres for straw bale buildings. *International Journal of Sustainable Engineering*, *3*(4), 299-304.

Bahobail, M. A. (2012). The mud additives and their effect on thermal conductivity of adobe bricks. *JES. Journal of Engineering Sciences*. https://doi.org/10.21608/jesaun.2012.112711

Bailly, G. C., El Mendili, Y., Konin, A., & Khoury, E. (2024). Advancing Earth-Based Construction: A Comprehensive Review of Stabilization and Reinforcement Techniques for Adobe and Compressed Earth Blocks. *Eng*, *5*(2), Article 2. https://doi.org/10.3390/eng5020041

Bayat-Afshary, N., & Danesh-Yazdi, M. (2023). Analysis of Long-Term Changes in Precipitation Pattern in the Khuzestan Province: Lessons Learned from April 2019 Floods. *Iran-Water Resources Research*, *18*(4), 19-36.

Capitelli, F., Dida, B., Ventura, G. D., Baldassarre, F., Capelli, D., Senesi, G. S., Mele, A., & Siliqi, D. (2021, January). Functional nano-hydroxyapatite for applications in conservation of stony monuments of cultural heritage. In *Proceedings* (Vol. 62, No. 1, p. 11). MDPI.

Chesworth, W. (Ed.). (2007). Encyclopedia of soil science. Springer Science & Business Media. Canada.

Chang, C., An, L., Dong, J., Zheng, W., Wen, J., Yan, F., & Xiao, X. (2023). Study on deterioration process of magnesium oxychloride cement under the environment of dry–wet cycles. *Materials*, *16*(5), 1817.

Costi de Castrillo, M., Philokyprous, M. and Joannou, J. (2017) Comparison of adobe from pre-hystory to-date. Journal of archeological Science: Reports, 12, 437-448.

Degirmenci, N. (2008). The using of waste phosphogypsum and natural gypsum in adobe stabilization. *Construction and Building Materials*, *22*(6), 1220–1224. https://doi.org/10.1016/j.conbuildmat.2007.01.027

Eires, R., Camões, A., & Jalali, S. (2015). Ancient Materials and Techniques to Improve the Earthen Building Durability. *Key Engineering Materials*, *634*, 357–366. https://doi.org/10.4028/www.scientific.net/KEM.634.357

Elert, K., Biçer-Simşir, B., Correa, E., Rodriguez-Navarro, C., & Gulotta, D. (2024). Surface characterization of consolidated earthen substrates using an innovative multi-analytical strategy. *Construction and Building Materials*, *438*, 137154.

Espuelas, S., Omer, J., Marcelino, S., Echeverría, A. M., & Seco, A. (2017). Magnesium oxide as alternative binder for unfired clay bricks manufacturing. *Applied Clay Science*, *146*, 23-26.

García-Vera, V. E., Tenza-Abril, A. J., Solak, A. M., & Lanzón, M. (2020). Calcium hydroxide nanoparticles coatings applied on cultural heritage materials: Their influence on physical characteristics of earthen plasters. *Applied Surface Science*, *504*, 144195.

Guo, Y. (2020). *Development of water-resistant magnesium oxychloride cement* (Doctoral dissertation, UNSW Sydney).

Gutierrez, L. F., Casas, J. R., & Delgadillo, R. M. (2024). Experimental Evaluation of Adobe Bricks Reinforced with Rice Husk, Lime and Neem Fibers for the Construction of Sustainable Housing in Andean Areas. *Key Engineering Materials*, *986*, 11–16. https://doi.org/10.4028/p-jwEW7R

Hart, S., Raymond, K., Williams, C. J., Rutherford, W. A., & DeGayner, J. (2023). Modeling Earthen Treatments for Climate Change Effects. *Heritage*, *6*(5), Article 5. https://doi.org/10.3390/heritage6050222

Henrist, C., Mathieu, J.-P., Vogels, C., Rulmont, A. & Cloots, R., 2003. Morphological study of magnesium hydroxide nanoparticles precipitated in dilute aqueous solution. Journal of crystal growth, 249(1-2): 321-330.

Illampas, R., Ioannou, I., & Charmpis, D. C. (2013). Overview of the Pathology, Repair and Strengthening of Adobe Structures. *International Journal of Architectural Heritage*. https://www.tandfonline.com/doi/abs/10.1080/15583058.2011.624254

International Council on Monuments and Sites. (1964). International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter). ICOMOS. Available at: https://admin.icomos.org/wp-content/uploads/2025/03/Venice_Charter_EN.pdf

Jiříčková, A., Lojka, M., Lauermannová, A. M., Antončík, F., Sedmidubský, D., Pavlíková, M., Záleská, M., Pavlík, Z & Jankovský, O. (2020). Synthesis, structure, and thermal stability of magnesium oxychloride 5Mg (OH) 2· MgCl2· 8H2O. Applied Sciences, 10(5), 1683.

Kotwa, A., & Kłak, A. (2024). Assessment of the properties of mortars made of sorel cement. *Archives of Civil Engineering*, *70*(2).

Li, Z., & Chau, C. K. (2007). Influence of molar ratios on properties of magnesium oxychloride cement. *Cement and Concrete Research*, *37*(6), 866-870.

Lin, H., Liu, F. Y., Lourenço, S. D. N., Schwantes, G., Trumpf, S., Holohan, D., & Beckett, C. T. S. (2021). Stabilization of an earthen material with Tung oil: compaction, strength and hydrophobic enhancement. *Construction and Building Materials*, *290*, 123213.

Liu, Y., Li, Q., Zhou, R., & Yusufu, R. (2024). Research Progress of Superhydrophobic Coatings in the Protection of Earthen Sites. *Coatings*, 14, 710.https://doi.org/ 10.3390/coatings14060710.

Liu, Y. P., Zhang, S. Y., & Zhang, H. F. (2016). Advances on mineral genesis of chlorite: a review. Advances in Geosciences, 6(3), 264-282.

Ma, H., Liang, J., Wang, L., He, H., Wang, W., Han, T., ... & Han, J. (2023). Mechanical properties and water resistance of magnesium oxychloride cement–solidified residual sludge. Processes, 11(2), 413.

Maryska, M., Blaha, J. & Nemecek, K., 1997. Kinetics of hydration of magnesium oxide in aqueous suspension Part 2-The effect of conditions of firing basic magnesium carbonate on the specific surface area of magnesium oxide. CERAMICS SILIKATY, 41: 21-28.

Medvey, B., & Dobszay, G. (2020). Durability of stabilized earthen constructions: a review. *Geotechnical and Geological Engineering*, *38*(3), 2403-2425.

Morel, J.-C., Bui, Q.-B., & Hamard, E. (2012). 11—Weathering and durability of earthen material and structures. In M. R. Hall, R. Lindsay, & M. Krayenhoff (Eds.), *Modern Earth Buildings* (pp. 282–303). Woodhead Publishing. https://doi.org/10.1533/9780857096166.2.282

Nakhaei Ashtari, M., & Correia, M. (2021). Assessment of vulnerability and site adaptive capacity to the risk of climate change: The case of Tchogha Zanbil World Heritage earthen site in Iran. *Journal of Cultural Heritage Management and Sustainable Development*, *12*(2), 107–125. https://doi.org/10.1108/JCHMSD-06-2021-0108

Nakhaei Ashtari, M., Della Ventura, G., & Correia, M. (2025). From drought to deluge: the complex impacts of climate change on earthen heritage. *Journal of Cultural Heritage Management and Sustainable Development*.

Oliver, A. (2008). Modified earthen materials. *Terra Literature Review*, *97*.

Pan, C., Chen, K., Chen, D., Xi, S., Geng, J., & Zhu, D. (2020). Research progress on in-situ protection status and technology of earthen sites in moisty environment. *Construction and Building Materials*, *253*, 119219.

Rainer, L. (2008). Deterioration and pathology of earthen architecture. *Terra Literature Review*, 45.

Rao, S. M. (2023). Stabilization of Adobes by Cow Dung Particles. In S. M. Rao (Ed.), *Stabilization of Earthen Building Materials by Select Native Binders* (pp. 185–209). Springer International Publishing. https://doi.org/10.1007/978-3-031-48987-7_6

Reddy, B. V., Morel, J. C., Faria, P., Fontana, P., Oliveira, D. V., Serclerat, I., Walker, P & Maillard, P. (2022). Codes and standards on earth construction. *Testing and Characterisation of Earth-based Building Materials and Elements: State-of-the-Art Report of the RILEM TC 274-TCE*, 243-259.

Reynolds, E. K., & Muramoto, M. (2024). Durability of Japanese-earth cob walls subjected to accelerated rain simulation. *Heritage Science*, *12*(1), 154. https://doi.org/10.1186/s40494-024-01251-z

Richards, J., Zhao, G., Zhang, H., & Viles, H. (2019). A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain. *Heritage Science*, *7*(1), 51. https://doi.org/10.1186/s40494-019-0293-7

Savary, M., Mehdizadeh Saradj, F., Shayganmanesh, M., Tahmasebiboldaji, N., & Kazemi, A. S. (2020). Improving the adobe material properties by laser material processing. *Construction and Building Materials*, *249*, 118591. https://doi.org/10.1016/j.conbuildmat.2020.118591

Slaughter, M. and Milne, I.H. (1958) The formation of chlorite-like structures from montmorillonite. Clays Clay Miner. 7, 114–124 (1958). https://doi.org/10.1346/CCMN.1958.0070105

Sreenivasan, H., Bernard, E., Santos, H. S., Nguyen, H., Moukannaa, S., Adediran, A., Provis, J.L. & Kinnunen, P. (2024). A critical review of magnesium silicate hydrate (MSH) phases for binder applications. Cement and Concrete Research, 178, 107462.

Stazi, F., Nacci, A., Tittarelli, F., Pasqualini, E., & Munafò, P. (2016). An experimental study on earth plasters for earthen building protection: The effects of different admixtures and surface treatments. *Journal of Cultural Heritage*, *17*, 27–41. https://doi.org/10.1016/j.culher.2015.07.009

Temiz, H., & Tandirci, E. (2023). Investigation of mechanical and insulation properties of Sorel cement binding light concrete. *Construction and Building Materials*, *379*, 131270. https://doi.org/10.1016/j.conbuildmat.2023.131270

United States. Department of Agriculture. Agricultural Research Administration, United States. Bureau of Plant Industry, Soils, & Agricultural Engineering. (1951). *Soil survey manual* (No. 18). Agricultural Research Administration, US Department of Agriculture.

WU, J., Du, J. & Gao, Y.-M., 2014. Crystal growth morphology of magnesium hydroxide. Turkish Journal of Chemistry, 38(3): 402-412.

Walling, S. A., & Provis, J. L. (2016). Magnesia-based cements: a journey of 150 years, and cements for the future? *Chemical reviews*, *116*(7), 4170-4204.

Zhang, Q., Chen, W., Han, N., Cai, T., & Du, Y. (2023). Feasibility of polyvinyl alcohol-treated soil in a mud state as the anti-weathering material for earthen sites. *International Journal of Architectural Heritage*, *17*(3), 486-499.

Zhang, T., Zou, J., Wang, B., Wu, Z., Jia, Y., & Cheeseman, C. R. (2018). Characterization of magnesium silicate hydrate (MSH) gel formed by reacting MgO and silica fume. Materials, 11(6), 909.

7. Chapter 7 - Improving the resilience of earthen materials to heavy precipitation through hydrated lime and magnesium oxide stabilization

Building upon the conceptual and empirical foundations established in the preceding chapters, this chapter advances the research toward the experimental phase. Previous analyses demonstrated that earthen heritage sites are increasingly vulnerable to climate-related hazards, particularly heavy rainfall and flooding, which accelerate erosion, moisture infiltration, and structural degradation. While earlier chapters identified adaptation needs and management challenges, this chapter addresses the material dimension of resilience, developing and testing stabilization methods capable of mitigating hydraulic decay while preserving the authenticity of archaeological earthen materials.

The increasing frequency of intense rainfall events poses a major threat to the structural stability of earthen heritage sites. This study investigates the potential of magnesium oxide and hydrated lime stabilization to enhance the hydraulic properties of earthen materials derived from the Campo del Pozzo (Nazzano, Rome, Italy) archaeological site. Adobe samples were prepared with hydrated lime (HL; at 5, 10, and 15 wt%) and magnesium oxide-hydrated lime (MgO-HL;at 5 + 5 wt% and 10 + 10 wt%) blends and subjected to artificial rainfall, capillary absorption, and immersion tests. Surface morphology was examined after simulating rainfall using high-resolution laser scanning, while XRD and scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS) characterized the mineralogical and microstructural transformations. Results showed that lime stabilization resulted in conversion of montmorillonite to Ca-montmorillonite through consumption of promoted the formation of calcium silicate hydrate, significantly reducing erosion and water uptake. The addition of MgO further improved durability through the formation of brucite ($Mg(OH)_2$), hydrotalcite-like layered double hydroxides (LDHs), and mixed Mg-Ca carbonates, which filled micropores and produced a denser matrix. The MgO-HL mixture with 10% of each additive (LM2) exhibited the lowest normalized erosion rate and complete resistance to disintegration during immersion. Microstructural analysis confirmed a compact, multiphase matrix with co-localized Ca, Mg, and Si, consistent with the observed water stability. MgO-lime stabilization provides a compatible, sustainable, and effective strategy for enhancing the resilience of earthen heritage materials against extreme precipitation, offering a conservation approach that integrates environmental durability with material authenticity.

7.1. Introduction

Earthen heritage, encompassing a wide range of archaeological sites and historic structures, represents a significant portion of the world's tangible cultural heritage (Correia, 2016). Despite its global importance, earthen architecture is inherently vulnerable to environmental stressors, particularly those related to moisture (Nakhaei et al., 2025; Trizio et al., 2022) Climate change has intensified the frequency and severity of heavy precipitation events in many regions, amplifying the risks of erosion, loss of surface integrity, and structural instability in earthen archaeological sites (Richards et al., 2020; Reynolds & Muramoto, 2024). These challenges necessitate the development of scientifically grounded conservation strategies aimed at enhancing the resilience of earthen materials under changing climatic conditions (Sesana et al., 2021; Nakhaei et al., 2025).

Stabilization of earthen materials has long been practiced mitigating the effects of water ingress, yet traditional methods often fall short in withstanding prolonged or extreme rainfall (Gomes et al., 2016; Medvey & Dobszay, 2020). In recent years, mineral-based stabilizers have garnered attention for their potential to improve the mechanical and hydrological properties of earthen materials while maintaining compatibility with historic fabric. Among these, magnesium oxide-hydrated lime (MgO-HL) and hydrated lime (HL) present important options due to their pozzolanic reactions, low environmental impact, and long history of use in conservation (Yue et al., 2022; Omid & Mojtaba, 2022). However, empirical data on their performance under simulated heavy precipitation conditions remain limited, while there are studies on strength, PH, slaking time and humidity effects (Zeng & Schwantes, 2024; Gomes et al., 2016), tests involving accelerated or simulated intense rainfall exposure for MgO-HL stabilized earthen heritage are rare.

This study investigates the efficacy of MgO-HL and HL stabilization in enhancing the durability of earthen materials subjected to simulated rainfall. By replicating intense precipitation events in a controlled environment, the research provides insights into the mechanisms by which these stabilizers reduce material loss and improve cohesion. The findings aim to contribute to climate change adaptation strategies for earthen archaeological sites, offering practical recommendations for earthen heritage professionals seeking sustainable solutions to water-related deterioration.

7.2. Materials and Methods

For this study soil was collected from the Campo del Pozzo archaeological site (Nazzano, Rome), air-dried, and sieved to 2 mm before characterization (See section 6.7, Supplementary material). Particle-size distribution (50.6% silt, 32.8% clay, 16.6% sand) classified the material as silty clay loam, while XRD identified quartz, plagioclase, orthoclase, and montmorillonite as dominant minerals. Two stabilizers were selected: a reactive light-burned MgO (91 ± 1 wt%; www.persiapaya.com) and a commercial hydrated lime composed of 54% $Ca(OH)_2$ and 46% $CaCO_3$, with $Ca(OH)_2$ content verified by thermogravimetric loss at 600 °C, the temperature in which H2O release from the molecular structure. Adobe mixtures were prepared as untreated soil, HL-stabilized soil (5–15 wt%), and MgO-HL blends (5%+5% and 10%+10%). Stabilizers were dry-mixed into the soil before adding water, and 5 × 5 × 5 cm cubes were cast, compacted in layers, air-dried for 72 h, and oven-dried at 60 °C for 48 h. Rainfall resistance was assessed using a custom environmental chamber applying extreme precipitation (≈80,000 mm/h) for up to 32 min, with surface changes measured by a high-resolution laser scanner (50 μm horizontal, 70 μm vertical resolution) at fixed intervals. Capillary rise was recorded over 1–30 min, and immersion durability was evaluated during 72 h of full submersion. Mineralogical and microstructural changes were examined using powder X-ray diffraction (Rigaku SmartLab SE, Cu $K\alpha_1$ radiation, 5–70° 2θ, 1°/min step) and FESEM–EDS on polished thin sections (ZEISS Merlin II with OXFORD X-MAX 50 detector; 10 kV, 2 nA), enabling phase identification, additive distribution, and microtextural analysis. Full experimental procedures and calibration details are reported in the Supplementary Materials.

7.3. Results

The following results compare the moisture-related performance of treated and untreated adobe units, integrating surface scans, immersion and capillary tests, and XRD and SEM–EDS analyses.

7.3.1. Rainfall simulation tests

Rainfall simulation experiments were conducted to assess the erosion resistance of untreated and stabilized adobe samples under extreme precipitation. The high-intensity rainfall (≈80,000 mm/h) induced rapid runoff and particle detachment, allowing quantification of material loss and surface deformation over a 32-minute exposure period. Figure 7.1 shows the spatiotemporal evolution of erosion for the reference soil (a), lime-stabilized samples (L1-L3),

and MgO-lime mixtures (LM1-LM2), while Table 7.1 summarizes the normalized erosion area values derived from 3D laser scanning analyses.

The untreated reference sample exhibited severe and progressive degradation, with visible riling and surface pitting forming within the first four minutes. Erosion magnitude reached values exceeding 20 mm in localized zones, corresponding to an area normalized erosion (ANE) of 2867.20 at 4 min (Figure 7.2). To quantify surface loss across all mixtures, ANE volumes (mm^3) were calculated at cumulative rainfall durations. To avoid boundary effects induced by the laser scanner at the extremes of the samples (e.g., water reflectivity on the table floor), the boundary sections of the point clouds representing the samples were removed. Due to the samples' slightly different dimensions (induced by preparation, drying, etc.), the eroded volumes were normalized using a reference area that considers an average value of all the samples' dimensions (35 mm side). This allows for direct comparison of eroded volume values, eliminating the need to adjust for varying sample dimensions. The erosion rate subsequently stabilized as the surface compacted under runoff, yet significant mass loss was evident.

In contrast, all lime-stabilized samples (L1-L3) showed markedly improved resistance to erosion. Sample L1 (5% HL) displayed a gradual reduction in erosion rate over time, with normalized erosion increasing from 3513.07 at 1 min to 8568.51 at 32 min, corresponding to shallow but spatially extensive detachment zones. Samples L2 and L3 (10% and 15% HL, respectively) exhibited significantly lower erosion intensity, particularly L3, which maintained almost uniform surface integrity with limited material loss after 32 min (150.41 normalized units).

The MgO-lime blends (LM1 and LM2) demonstrated the most efficient protection against rainfall-induced surface degradation. The LM1 mixture (5% MgO + 5% HL) showed moderate early-stage erosion (1656.68 at 1 min), which increased gradually to 7387.37 at 32 min but without forming deep erosion channels. LM2 (10% MgO + 10% HL) displayed the lowest erosion across all samples, maintaining nearly constant normalized values below 900 throughout the entire test duration. The surface remained largely intact even after 32 minutes of rainfall exposure, confirming the high resilience of the MgO-lime composite.

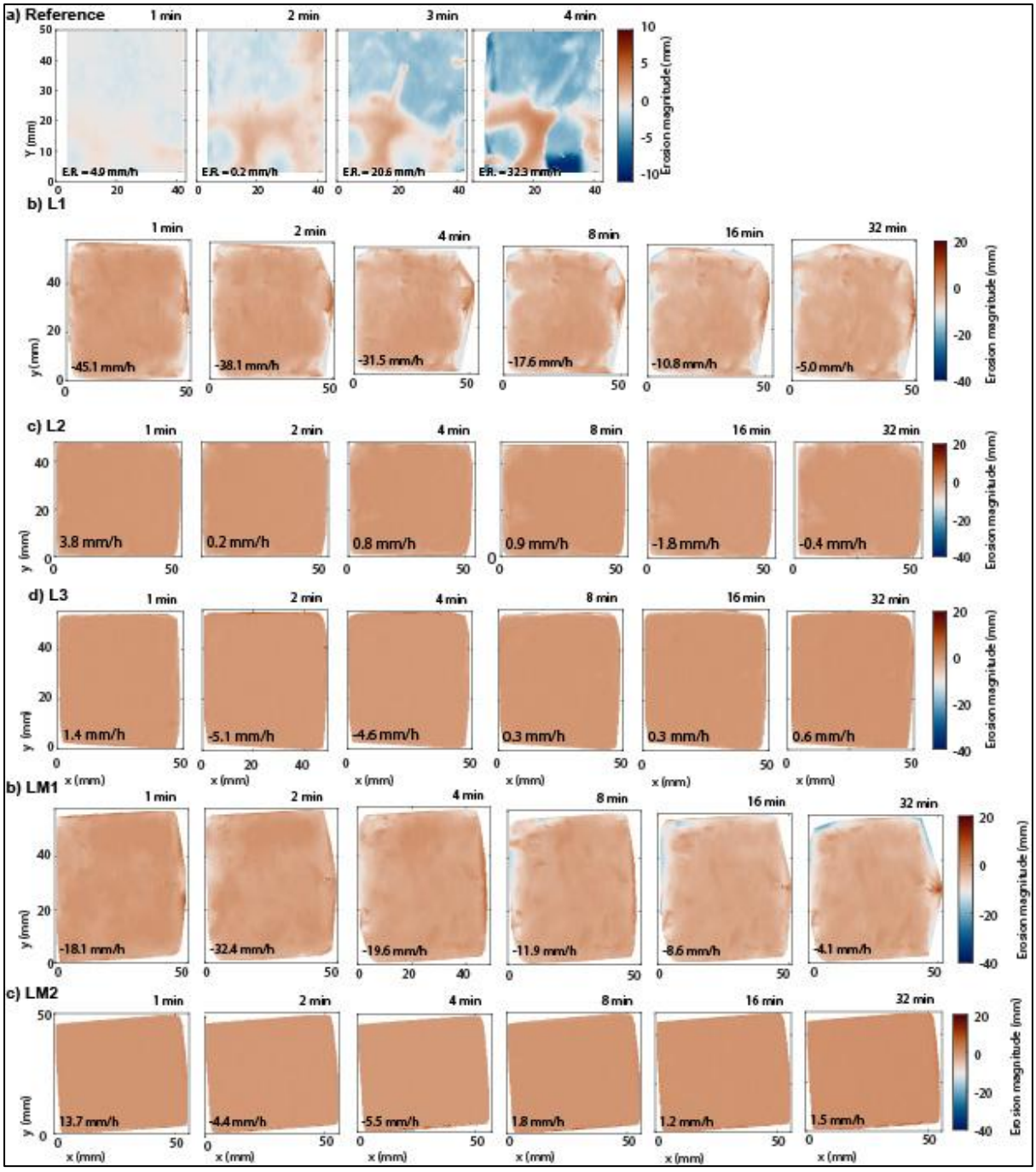


Fig. 7.1: Progressive surface degradation of HL and MgO + HL and untreated adobe under simulated rainfall

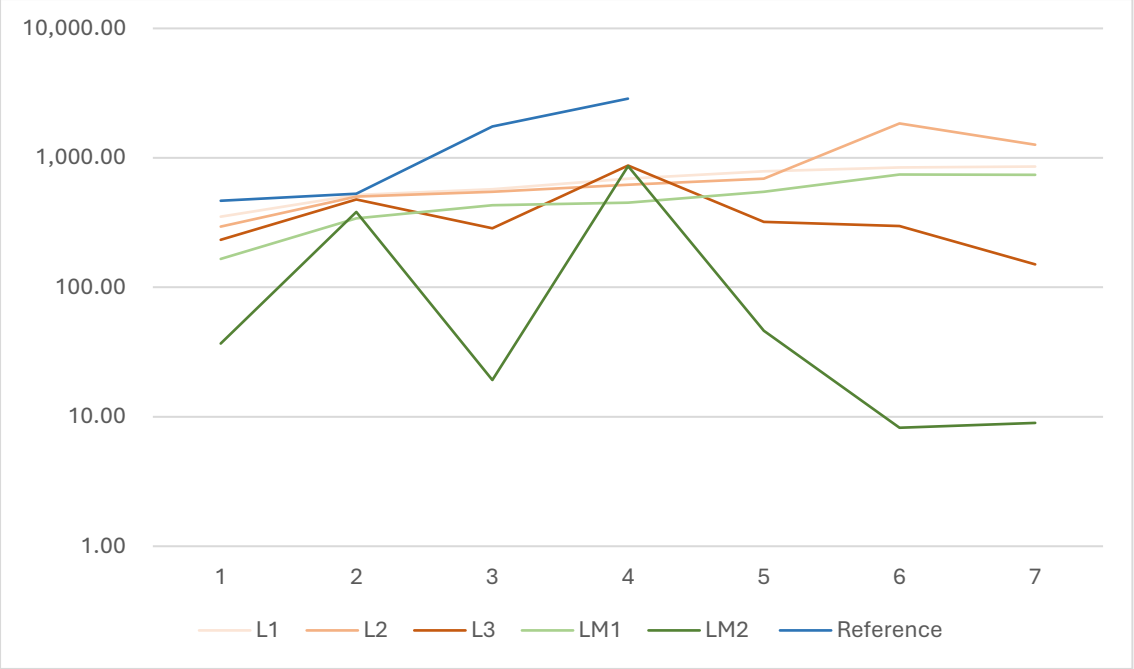


Fig 7.2: Area-normalized erosion volumes of adobe samples under simulated rainfall

Table 7.1: Area-normalized erosion volumes (mm^3) (ANE) recorded during the artificial rainfall simulation time

Time	1	2	3	4	8	16	32
L1	3513.074	5162.578	5730.018	6889.39	7863.048	8419.78	8568.508
L2	294.5212	501.1094	546.8009	618.9561	690.9328	1845.124	1260.314
L3	232.2641	476.2775	285.2359	872.7445	320.7266	297.4836	150.4091
LM1	1656.679	3403.635	4298.581	4501.773	5467.98	7435.172	7387.373
LM2	36.69785	382.3172	19.23002	863.436	46.1649	8.228833	8.964946
Reference	466.3168	529.5389	1748.952	2867.199			

7.3.2. Effect of treatment on capillary water absorption

Capillary water absorption tests were performed to evaluate the influence of lime (L-series) and MgO-lime (LM-series) on the moisture uptake behavior of adobe samples (Fig 7.3). Table 7.2 presents the cumulative water absorption at time intervals from 1 min to 30 min for untreated and treated mixtures. The untreated reference exhibited the highest absorption rate, increasing rapidly from 7 at 1 min to 50 at 30 min, indicating high surface porosity and continuous capillary pathways. All stabilized specimens showed reduced water uptake relative to the reference, with variations according to additive type and concentration. Among lime-only mixtures, water absorption decreased progressively with increasing lime content. Sample

L1 (5 % HL) displayed a similar trend to the reference, reaching 50 at 30 min, while L2 (10 % HL) and L3 (15 % HL) exhibited notably lower final absorption values of 42 and 40, respectively. The slower absorption rate observed after 10 min in L2 and L3 suggests a partial densification effect from lime addition. The MgO-lime blends showed the lowest capillary absorption across all time intervals. LM1 (5 % MgO + 5 % HL) reached 30 at 30 min, representing a 40 % reduction compared to the reference, while LM2 (10 % MgO + 10 % HL) demonstrated the most significant improvement, increasing only from 4 at 1 min to 22 at 30 min.

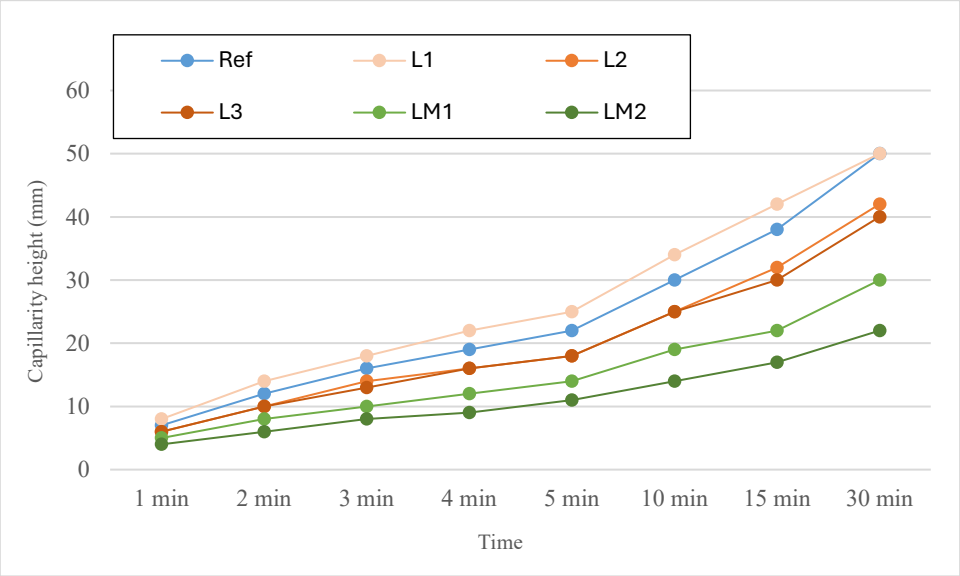


Fig. 7.3: Comparative capillary water absorption (height) of treated and untreated adobe samples

Table 7.2: Effect of treatment on capillary water absorption in adobe samples

Adobe Mixture	1 min	2 min	3 min	4 min	5 min	10 min	15 min	30 min
Ref	7	12	16	19	22	30	38	50
L1	8	14	18	22	25	34	42	50
L2	6	10	14	16	18	25	32	42
L3	6	10	13	16	18	25	30	40
LM1	5	8	10	12	14	19	22	30
LM2	4	6	8	9	11	14	17	22

7.3.3. Immersion test

Immersion tests were conducted to assess the behaviour of untreated and stabilized adobe samples under direct and prolonged contact with water (Fig 7.4). The results are summarized in Table 7.3, where lower values of crack formation and disintegration indicate improved performance, while higher water-resistance scores represent enhanced durability. The untreated reference sample showed severe cracking and complete disintegration immediately after immersion, with maximum scores of 5 for both parameters and the lowest possible water-resistance value of 1. Among the lime-treated samples, progressive improvement was observed with increasing lime content. Sample L1 (5 % HL) exhibited moderate cracking (score 4) and partial disintegration (score 3), corresponding to a water-resistance rating of 3. L2 (10 % HL) displayed reduced cracking and disintegration (both 3) but a slightly lower water-resistance score (2.5), likely due to early softening upon immersion. L3 (15 % HL) showed minimal cracking and disintegration (both 1) and achieved the highest water-resistance score of 5, maintaining its structural integrity throughout the test. The MgO-lime mixtures also demonstrated a substantial improvement over the untreated sample. LM1 (5 % MgO + 5 % HL) exhibited minor disintegration (score 2) and moderate cracking (score 4), corresponding to a water-resistance rating of 3.5. LM2 (10 % MgO + 10 % HL) performed comparably to L3, showing no visible cracking or disintegration (scores 1) and a maximum water-resistance value of 5 (Fig 7.5).

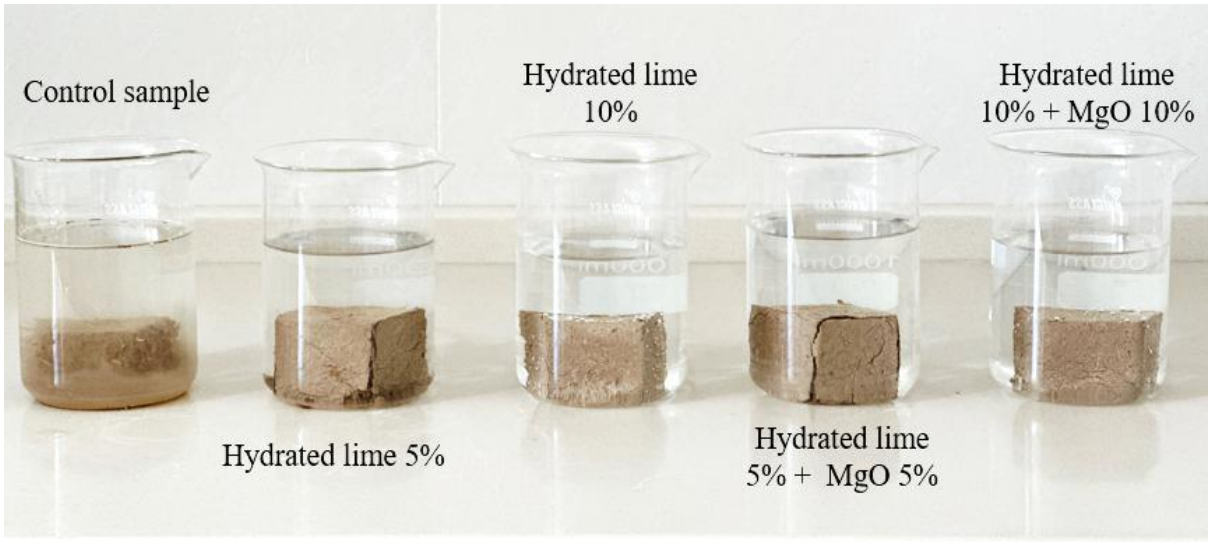


Fig. 7.4. Immersion test setup with adobe samples submerged in distilled water for 72-hour durability assessment

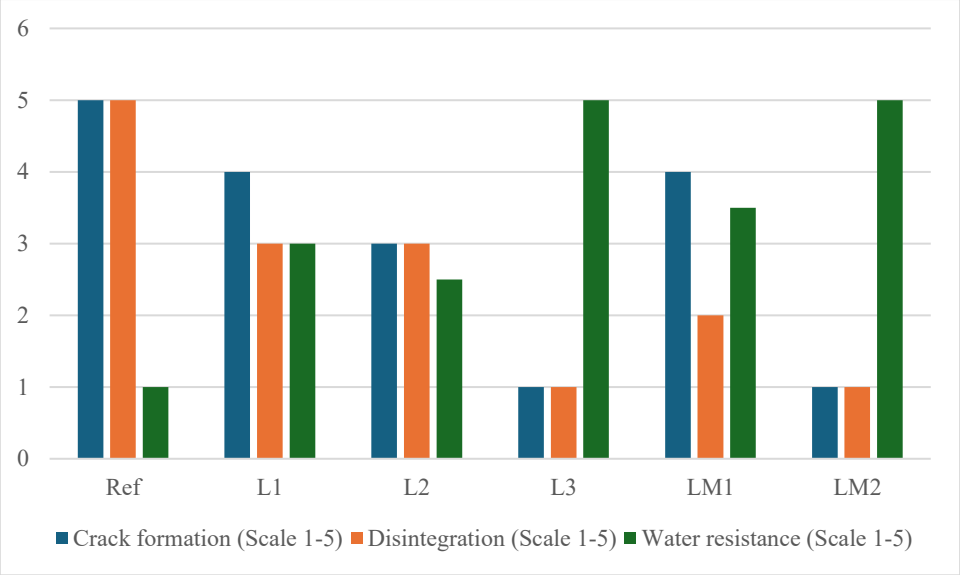


Fig. 7.5: Physical degradation of adobe samples after 72 hours of water exposure

Table 7.3: Deterioration of adobe samples following 72 hours of water immersion

Adobe mixture	Crack formation (Scale 1-5)	Disintegration (Scale 1-5)	Water resistance (Scale 1-5)
Ref	5	5	1
L1	4	3	3
L2	3	3	2.5
L3	1	1	5
LM1	4	2	3.5
LM2	1	1	5

7.3.4. Mineralogy and microstructural examination of adobes

XRD analysis was conducted to identify the mineralogical changes induced by the addition of hydrated lime and the combined hydrated lime-MgO stabilizers in adobe samples. The diffraction patterns of the treated samples were compared with those of the untreated reference soil (Figure 7.6).

7.3.4.1. Hydrated lime treatment

The XRD pattern of the lime-stabilized sample (Figure 7.6a) revealed distinct modifications in mineral composition relative to the reference soil. The principal clay phase montmorillonite,

dominant in the untreated material, was largely removed after lime addition, indicating structural alteration or consumption during pozzolanic reaction. Minor chlorite peaks persisted, reflecting residual clay minerals. Several diffraction peaks present in the reference soil disappeared upon lime stabilization, including those at 6°, 21.6°, 24°, 27.5°, 27.8°, 28.3°, 33.1°, and 51.4° 2θ, suggesting the consumption of silicate phases, during the formation of new hydration products.

Correspondingly, new diffraction peaks appeared at 39° and 66.4° 2θ, attributed to poor crystalline C-S-H and calcium hydroxide-derived compounds. Peaks associated with calcite ($CaCO_3$) emerged at 29.5°, 32.8°, 36.1°, and 43° 2θ, confirming carbonation of the lime. The absence of the original $Ca(OH)_2$ peaks indicates that all hydrated lime was consumed during reaction. The relatively weak intensity of the 39° 2θ peak suggests limited crystal growth, consistent with predominantly amorphous C-S-H formation.

7.3.4.2. Hydrated lime + MgO treatment

The XRD pattern of the sample stabilized with the combined hydrated lime + MgO additive (Figure 7.6b) exhibited a greater degree of mineralogical transformation compared with lime-only treatment. Like the lime sample, the characteristic montmorillonite peaks were reduced, indicating clay layer alteration. A new small reflection at 8.5° 2θ was observed, likely associated with clay mineral transformation under the influence of Mg^{2+} ions.

Several peaks corresponding to the original soil were removed or weakened, notably those at 6°, 12.25°, 13.75°, 21.75°, 24°, 27.5°, 27.8°, 28.3°, 33.1°, and 51.4° 2θ, confirming extensive consumption of primary silicate phases. In parallel, new or intensified peaks appeared at 18.6°, 37.8°, 51.2°, 68.2°, and 68.4° 2θ, which correspond to magnesium hydroxide (brucite) and additional C-S-H reflections.

Calcite-related peaks were more pronounced in the MgO-lime mixture, appearing at 29.5°, 32.8°, 36.1°, 43°, 47.5°, 48.5°, and 62.3° 2θ, reflecting enhanced carbonation. Additional diffraction maxima attributed to magnesium hydroxide were detected at 18.6°, 37.8°, and 62.3° 2θ, confirming the presence of brucite as a new hydration product. The persistence of minor montmorillonite and chlorite peaks (25.6°, 12°, and 13.75° 2θ) suggests partial retention of clay minerals within the stabilized matrix.

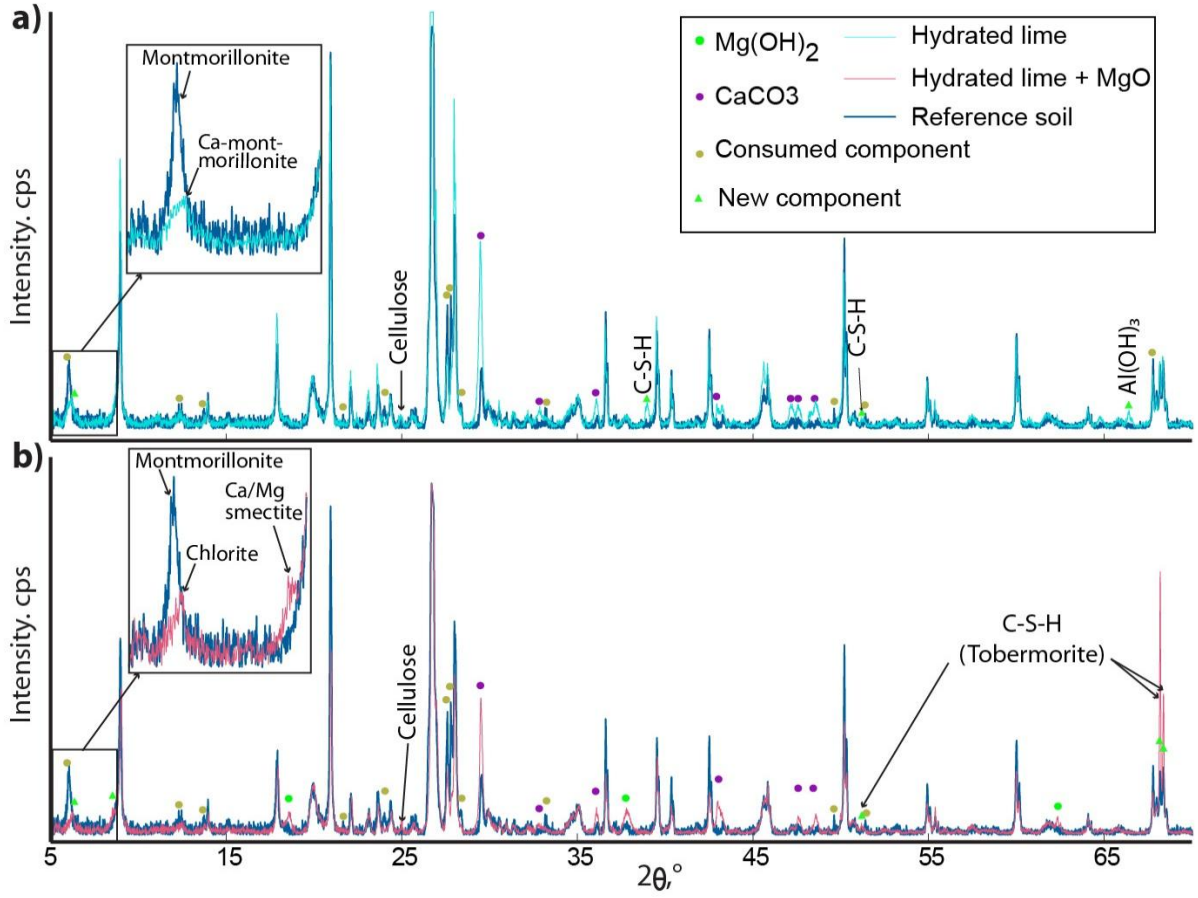


Fig. 7.6:X-ray diffraction patterns of (a) hydrated lime–treated adobe and (b) hydrated lime + MgO–treated adobe compared with reference soil.

7.3.5. Scanning Electron Microscopy (SEM–EDS) Analysis

The microstructural characteristics of the lime-stabilized adobe were examined using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) elemental mapping (Figure 7.7). The SE image (Figure 7.7a) reveals a dense and compact matrix composed of fine, interlocking particles with limited visible porosity. The structure shows an intimate association of calcite, clay minerals, and calcium silicate hydrate phases, forming a cohesive microfabric. Elemental mapping confirms the distribution of key components within the matrix. The magnesium map (Figure 7.7b) shows a diffuse distribution throughout the matrix, indicating partial incorporation of Mg into secondary hydration or carbonation products, likely derived from residual dolomitic or minor Mg-bearing impurities in the lime. The silicon map (Figure 7.7c) highlights a uniform dispersion of silica associated with C–S–H and unreacted clay particles, consistent with the pozzolanic activity between lime and silicate phases. The calcium map (Figure 7.7d) displays a dense, homogeneous signal corresponding to the predominant presence of calcite and C–S–H phases.

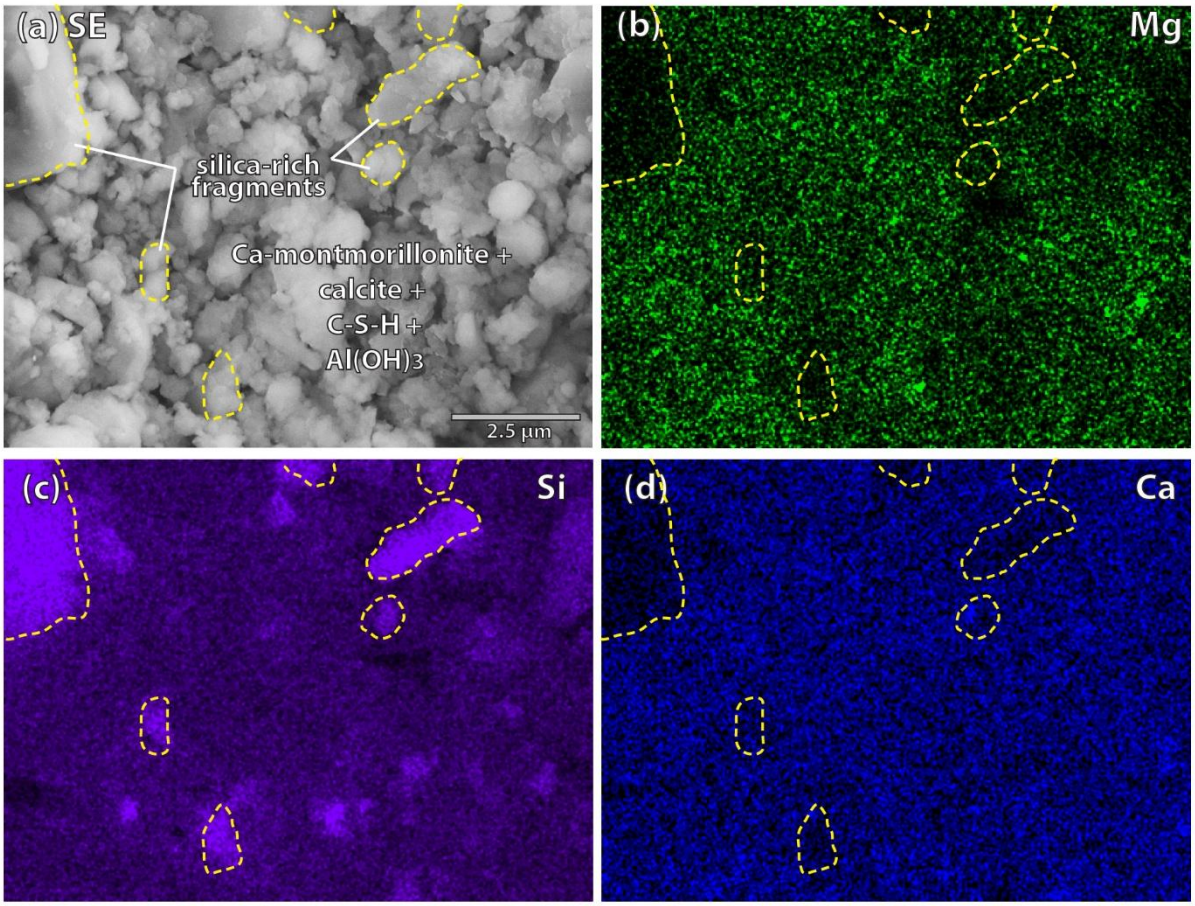


Fig. 7.7. (a) SEM micrograph of lime-stabilized adobe showing compacted matrix of calcite + clay + C–S–H; (b) elemental map of Mg; (c) elemental map of Si; (d) elemental map of Ca.

The microstructure of the MgO–lime–stabilized adobe (LM2) sample exhibits a highly compact and homogenous morphology, as shown in Figure 7.8. The secondary electron (SE) image (Figure 7.8a) displays a dense matrix consisting of finely interlocked particles with embedded angular fragments (outlined in yellow), suggesting advanced reaction between the stabilizers and soil minerals. Elemental mapping confirms the homogeneous distribution of the principal elements. The magnesium map (Figure 7.8b) shows an extensive and even dispersion of Mg across the matrix, consistent with the formation of magnesium hydroxide (brucite) phases. The presence of these Mg-bearing compounds contributes to the filling of micropores and densification of the matrix. The silicon (Si) map (Figure 7.8c) indicates a uniform distribution of silicate phases, reflecting both unreacted soil minerals and silicate components of calcium silicate hydrate (C–S–H) gels. The calcium (Ca) map (Figure 7.8d) shows an even spread throughout the structure, suggesting strong chemical interaction between Ca- and Si-bearing phases and confirming the coexistence of C–S–H and carbonate compounds. The co-

localization of Mg, Ca, and Si regions demonstrates a multiphase network of C–S–H, brucite, and carbonate compounds that form a continuous, cohesive matrix.

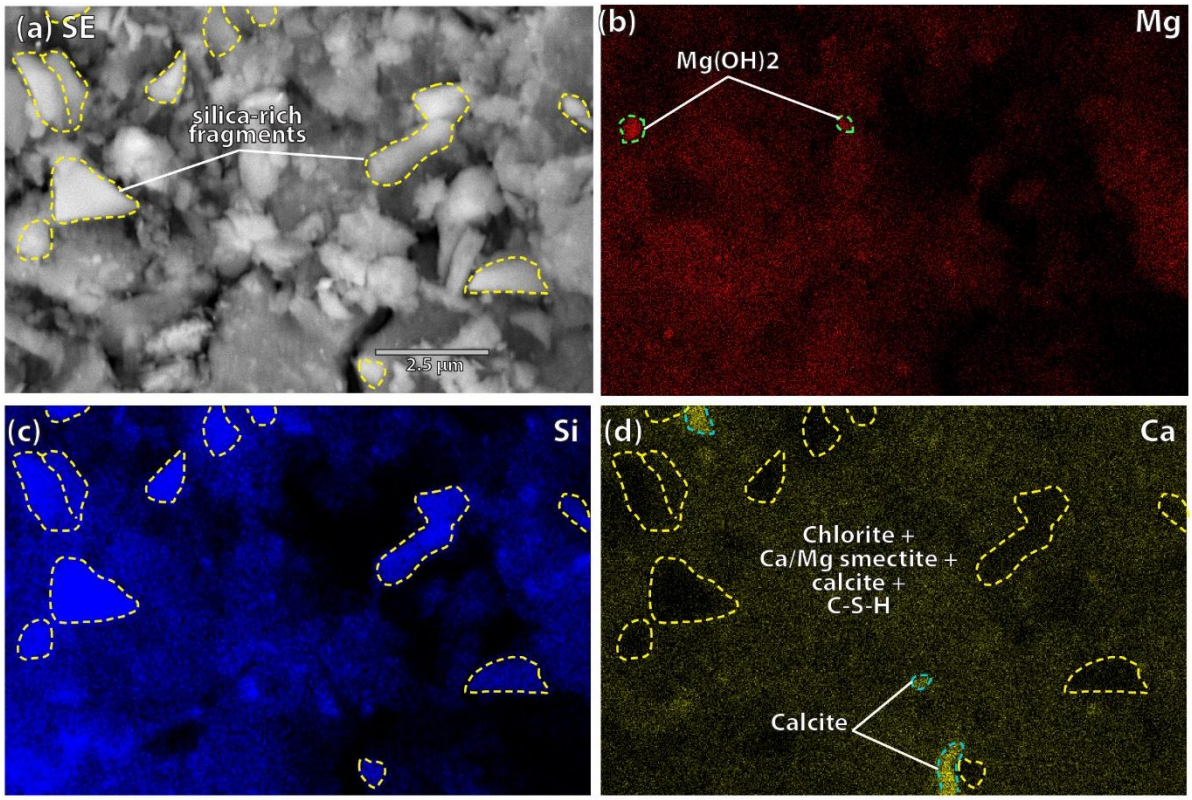


Figure 7.8. (a) SEM micrograph of MgO–lime–stabilized adobe showing dense, compact matrix with reacted fragments; (b) elemental Mg map; (c) Si map; (d) Ca map.

7.4. Discussion

The rainfall simulation tests demonstrated that MgO-lime stabilization significantly enhanced the erosion resistance of earthen materials under high-intensity precipitation, confirming the synergistic effect of combined magnesia-lime treatment. The substantial difference in surface degradation between untreated and treated adobes indicates that stabilization not only improves mechanical integrity but also modifies the wetting dynamics and hydraulic behaviour of the material.

The untreated reference samples exhibited rapid disaggregation and riling within the first minutes of rainfall exposure. Such behaviour is typical of fine-grained, clay-rich soils where high silt and clay fractions promote capillary rise and surface crusting (U.S. NRCS, 2011; Baldovino et al., 2021). Once the surface crust fractures, the underlying fine-grained structure becomes exposed and aggregate disintegration accelerates, as rapid wetting and swelling forces

break down clay aggregates and mobilize particles (Moragoda et al., 2022; Le Bissonnais, 2016). Indeed, management sheets note that raindrop-impact crusts in high shrink-swell soils tend to break down into a granular condition that greatly increases erodibility (USDA NRCS, 2011). In contrast, the addition of hydrated lime (L-series samples) induced the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels, improving inter-particle bonding and reducing pore continuity (Ahmadullah & Chrysochoou., 2025). These effects explain the reduced erosion observed in L2 and L3, as denser microstructures minimize both infiltration and particle detachment. However, the progressive surface smoothing observed in L1 suggests that low lime content may be insufficient to stabilize expansive montmorillonite clays against hydraulic stress (Pedarla, et all., 2010). The most significant improvement was observed in MgO–lime mixtures (LM-series). The superior erosion resistance of LM2 (10% MgO + 10% HL) can be attributed to the formation of brucite ($Mg(OH)_2$) and hydrotalcite-like (Mg–Al layered double hydroxide) phases, which fill capillary pores and create a protective surface film (Bernard et al., 2022; Lauermannová et al., 2020). The hydration of reactive MgO proceeds gradually, allowing controlled expansion that compensates for shrinkage and microcracking typically associated with lime-only stabilization (Iqra et al., 2025). This micro-expansive behavior leads to improved pore sealing and surface densification, effectively reducing permeability and enhancing resistance to splash erosion.

Additionally, the dual carbonation of MgO and $Ca(OH)_2$ produces a combination of magnesite ($MgCO_3$) and calcite ($CaCO_3$), both of which contribute to long-term matrix strengthening (Zhang et al., 2023). These carbonates act as binders, forming a cohesive crust that dissipates raindrop energy and limits particle ejection. The persistence of LM2's low normalized erosion even after 32 minutes indicates that the hydration–carbonation products maintain integrity under continuous hydraulic impact. Such mineralogical stabilization also enhances compatibility with heritage earthen materials due to their similar pH and mineral assemblages, avoiding issues of chemical incompatibility commonly found in cementitious interventions (Ansar Shourijeh et al., 2023). The evolution of erosion across treatment types highlights the balance required between reactivity and durability. Excessive MgO content can cause delayed hydration and reduce early mechanical performance, as partially observed in LM1's moderate erosion. Conversely, low MgO concentrations may not generate sufficient brucite to fill micropores. Therefore, an intermediate MgO–lime ratio (1:1 by weight) appears optimal for balancing microstructural densification, volumetric stability, and long-term resilience against precipitation.

The capillary water absorption results demonstrate that stabilization through hydrated lime and especially the combined MgO–lime treatments significantly reduce moisture uptake in adobe samples. These differences can be explained through a sequence of inter-related microstructural and physico-chemical mechanisms. The lime-only treatments (L1, L2, L3) reduced capillary water absorption compared with the untreated reference, with higher lime contents (L2, L3) showing more effectiveness. This is consistent with the known mechanisms of lime treatment of fine-grained soils: the addition of $Ca(OH)_2$ elevates pH, promotes cation exchange and flocculation of clay particles, and over time leads to pozzolanic reactions forming cementitious phases (e.g., Ca-silicate hydrates, C-S-H; Ca-aluminate hydrates, C-A-H) that contribute to pore refinement and reduced permeability (Bhattacharja et al., 2003). Hence, the progressively lower absorption in L2 and L3 (versus L1) likely reflects a greater degree of secondary mineral development and pore sealing.

The MgO-lime blends (LM1 and LM2) show still greater reductions in capillary uptake, with LM2 (10% MgO + 10% HL) giving the lowest absorption values at all time intervals. Several mechanisms may contribute to this enhanced performance: reactive MgO hydrates slowly to $Mg(OH)_2$ (brucite) and may further carbonate, whereas the lime component contributes to the earlier pozzolanic reactions. The combined system thus provides both early pore filling (from lime) and a more gradual development of additional mineral phases (from MgO), which further refine the pore structure. For instance, Wang et al. (1966) observed that MgO + $Ca(OH)_2$ systems produced long-term strength gains in soil stabilization, indicating delayed but sustained reaction processes.

The slower hydration and expansion associated with MgO may help compensating for shrinkage and micro-cracking that can accompany lime-only stabilization (which tends to densify rapidly and may lead to micro-fracturing under drying). This densification and crack control reduce capillary connectivity and thus water uptake. The combined system may produce mineral phases (e.g., hydrotalcite-like layered double hydroxides, basic magnesium carbonates) that further block fine pores and disrupt capillary suction. This phenomenon is observed in MgO-based stabilizations in other soil/earth systems (Gardeh et al., 2022). Together, these mechanisms explain why LM2 shows a markedly lower capillary absorption curve (from 4 at 1 min to 22 at 30 min) compared to the reference (7 → 50) or even the higher-lime only sample (L3: 6 → 40). The result indicates almost a ~55% reduction in absorption by 30 min relative to L3, and more than a ~100% improvement relative to the untreated material.

The immersion test results confirm the significant enhancement of water resistance in adobe samples stabilized with hydrated lime and MgO–lime blends compared with the untreated reference. The observed improvements can be explained through the chemical, mineralogical, and physical mechanisms induced by these stabilizers. The untreated reference underwent rapid cracking, swelling, and disintegration upon immersion, typical of fine-grained, clay-rich soils with high water affinity and weak particle bonding (Ciancio & Beckett, 2013). Upon full saturation, capillary cohesion is lost, resulting in particle dispersion and collapse of the soil structure. In contrast, lime treatment (L1-L3) markedly improved water stability, with performance increasing alongside lime content. The reaction of lime with siliceous and aluminous components of the clay matrix leads to the formation of calcium silicate hydrate and calcium aluminate hydrate gels, which fill pores and create cementitious bridges between particles (Bhattacharja et al., 2003). These pozzolanic reactions reduce permeability and improve matrix cohesion by generating a denser microstructure. At higher lime dosage (L3, 15 %), the stabilization reached near-complete water resistance (score = 5). This can be attributed to sufficient $Ca(OH)_2$ availability to drive complete pozzolanic reactions, leading to the development of a continuous C-S-H/C-A-H network. Such networks are known to enhance resistance against prolonged water exposure and prevent the propagation of cracks under hydraulic stress (Akula et al., 2020; Ahmadullah & Chrysochoou, 2025).

The MgO–lime composites (LM1 and LM2) further improved immersion resistance, with LM2 (10 % MgO + 10 % HL) showing equivalent performance to L3. The enhanced behaviour can be explained by the dual hydration-carbonation mechanism characteristic of MgO systems. Reactive MgO gradually hydrates to form brucite ($Mg(OH)_2$), a slightly expansive phase that fills microvoids and counteracts shrinkage or cracking associated with lime-only stabilization (Mahmood et al., 2021; Wang et al., 1966). Simultaneously, $Mg(OH)_2$ and $Ca(OH)_2$ undergo carbonation, precipitating magnesite ($MgCO_3$) and calcite ($CaCO_3$), both of which reinforce the microstructure and enhance water resistance through pore sealing (Zhang et al., 2023).

The XRD analysis revealed that the addition of hydrated lime and hydrated lime + MgO stabilizers resulted in significant mineralogical transformations within the adobe matrix. In the lime-stabilized sample, the disappearance or shortening of quartz-related peaks (27.5-27.8° 2θ) and the complete removal of $Ca(OH)_2$ reflections indicate that these phases were consumed in pozzolanic reactions, leading to the formation of calcium silicate hydrate and calcium aluminate hydrate gels. These poorly crystalline hydration products, often detected as broad low-intensity peaks around 29-39° 2θ, are well documented to act as primary binding agents

that bridge clay particles, reduce porosity, and increase cohesion (Bhattacharja et al., 2003; Akula et al., 2020).

The emergence of calcite peaks at 29.5°, 32.8°, 36.1°, and 43° 2θ demonstrates the carbonation of $Ca(OH)_2$. This process contributes to microstructural densification and reduced permeability, as confirmed in previous lime-treated earthen and masonry systems (Barbero-Barrera et al., 2020). The combined formation of C-S-H and calcite phases explains the lower capillary water absorption and complete water resistance observed in the high-lime sample (L3).

The incorporation of MgO alongside lime produced additional mineral phases, evidenced by new peaks at 18.6°, 37.8°, and 62.3° 2θ corresponding to magnesium hydroxide (brucite). The slow hydration of reactive MgO to $Mg(OH)_2$ generates controlled expansion, which compensates for drying-shrinkage microcracks that often form in lime-only matrices. This mechanism has been demonstrated in MgO-modified cementitious and soil systems (Mahmood et al., 2021; Wang et al., 1966). Simultaneously, the dual carbonation of $Ca(OH)_2$ and $Mg(OH)_2$ produced both calcite ($CaCO_3$) and magnesite ($MgCO_3$), as evidenced by intensified carbonate peaks at 29.5°, 32.8°, 36.1°, 43°, 47.5°, and 62.3° 2θ. The coexistence of these carbonates enhances long-term stability through pore filling and matrix reinforcement (Zhang et al., 2023).

In addition, minor new reflections at 8.5° 2θ indicate partial transformation of clay minerals and the possible formation of hydrotalcite-like Mg-Al layered double hydroxides (LDHs). Such LDH phases are known to nucleate on brucite layers in MgO-bearing systems and contribute to pore sealing and resistance to leaching, thus improving durability under wet conditions (Lauermannová et al., 2020; Bernard et al., 2022).

The combined XRD evidence indicates that both lime- and MgO-based stabilization triggered a transition from a clay-dominated structure to a cemented composite matrix rich in C–S–H, brucite, and carbonate phases. The consumption of quartz and $Ca(OH)_2$, coupled with the formation of low-crystallinity hydrates, correlates directly with the enhanced erosion resistance, lower water absorption, and improved immersion durability observed experimentally. Similar relationships between mineral phase evolution and hydraulic behaviour have been reported in stabilized earthen materials (Barbero-Barrera et al., 2020; Bhattacharja et al., 2003).

The SEM–EDS analysis provides microstructural validation of the mineralogical findings from XRD, confirming the formation of a compact, calcium-silicate-hydrate-rich matrix intergrown

with calcite and residual clay minerals. The co-localization of Ca, Si, and Mg demonstrates that the lime stabilizer effectively transformed the clay-rich matrix into a dense, cohesive structure responsible for the enhanced water stability of the treated adobe.

The SEM–EDS results of the LM2 sample confirm the formation of a dense, multiphase matrix composed of C–S–H, brucite ($Mg(OH)_2$), and calcite. The widespread distribution of Mg, Ca, and Si indicates simultaneous hydration and carbonation reactions, producing a cohesive microstructure with limited porosity. The presence of Mg-bearing phases suggests the development of hydrotalcite-like (Mg–Al LDH) compounds, which contribute to long-term durability by refining pores and stabilizing C–S–H under wet conditions (Lauermannová et al., 2020; Bernard et al., 2022). The compact texture and interlocked particles observed correspond to LM2's exceptional resistance to erosion and water-induced disintegration, confirming that MgO enhances lime stabilization through brucite formation and dual carbonation (Zhang et al., 2023; Mahmood et al., 2021).

7.5. Compatibility with heritage earthen materials

The findings of this study demonstrate that MgO-lime stabilization offers a highly effective and materially compatible strategy for protecting earthen heritage structures against increasingly intense rainfall events and moisture-driven decay. The formation of C-S-H, calcite, brucite, and hydrotalcite-like phases significantly enhances cohesion, reduces permeability, and strengthens the adobe matrix without introducing the chemical incompatibilities, salt formation, or excessive stiffness often associated with Portland cement interventions. Because both MgO and lime share mineralogical and pH affinities with traditional earthen and lime-based construction materials, their use supports conservation principles of reversibility, compatibility, and minimal intervention, enabling structural reinforcement while preserving authenticity (Groot et al., 2022; Gomes et al., 2016). The improved resistance to erosion, capillary rise, and immersion observed in stabilized samples suggests that MgO-lime treatments could serve as sustainable, low-impact consolidation methods for vulnerable archaeological sites and historic earthen buildings.

7.6. Summary of Key Issues

This study demonstrates that the stabilization of earthen heritage materials using hydrated lime and magnesium oxide significantly enhances their resistance to hydraulic erosion, water absorption, and disintegration. Experimental results from rainfall simulation, capillary absorption, and immersion tests revealed that both lime and MgO-lime treatments effectively

improved the physical durability of adobe samples derived from the Campo del Pozzo archaeological site. Lime addition (L-series) promoted the formation of calcium silicate hydrate (C-S-H) and calcium carbonate ($CaCO_3$), which reduced porosity and improved matrix cohesion. The 15% HL sample (L3) achieved near-complete resistance to erosion and immersion, confirming the stabilizing effect of pozzolanic reactions between lime and clay minerals. The combination of MgO and HL (LM-series) provided an even more effective stabilization mechanism. In particular, the 10% MgO + 10% HL blend (LM2) exhibited the lowest erosion rate, minimal capillary uptake, and full structural integrity under immersion. XRD and SEM–EDS analyses confirmed that MgO hydration produced brucite ($Mg(OH)_2$) and hydrotalcite-like Mg–Al layered double hydroxides (LDHs), while carbonation of both $Ca(OH)_2$ and $Mg(OH)_2$ generated calcite and magnesite, resulting in a dense, multiphase matrix. The co-localization of Ca, Mg, and Si in the microstructure reflects strong interparticle bonding and extensive pore filling, accounting for the superior hydraulic and mechanical performance of LM2. From a conservation perspective, the MgO–lime system offers a sustainable, reversible, and mineralogically compatible approach for strengthening earthen heritage materials without introducing cementitious incompatibilities. The combined hydration-carbonation pathway not only improves resilience to extreme rainfall events but also maintains the authenticity and chemical harmony essential for long-term preservation of archaeological earthen architecture.

References

Ahmadullah, T., & Chrysochoou, M. (2025). Development of a kinetic-thermodynamic model for lime-stabilization of Na-bentonite. *Geochemical Transactions*, *26*(1), 6.

Akula, P., & Little, D. N. (2020). Analytical tests to evaluate pozzolanic reaction in lime stabilized soils. *MethodsX*, *7*, 100928.

Ansar Shourijeh, A., Raeesi Estabragh, A., & Amini, M. (2023). Effect of Magnesium Oxide and Lime on the Improvement a Clay Soil Contaminated with MTBE. *Civil Infrastructure Researches*, *9*(1), 29-45.

Baldovino, J. A., Izzo, R., & Millan-Paramo, C. (2021). The capillary rise in fine and coarse-grained soils considering the matric suction.

Barbero-Barrera, M. M., Jové-Sandoval, F., & Iglesias, S. G. (2020). Assessment of the effect of natural hydraulic lime on the stabilisation of compressed earth blocks. *Construction and Building Materials*, *260*, 119877.

Bernard, E., Zucha, W. J., Lothenbach, B., & Mäder, U. (2022). Stability of hydrotalcite (Mg-Al layered double hydroxide) in presence of different anions. *Cement and Concrete Research*, *152*, 106674.

Bhattacharja, S. A. N. K. A. R., Bhatty, J. I., & Todres, H. A. (2003). Stabilization of clay soils by Portland cement or lime–a critical review of literature. *PCA R&D Serial*, *60*(1), 124-133.

Ciancio, D., & Beckett, C. (2013, January). Rammed earth: An overview of a sustainable construction material. In *3rd International Conference on Sustainable Construction Materials and Technologies, SCMT 2013* (pp. 1-9).

Eires, R., Camões, A., & Jalali, S. (2017). Enhancing water resistance of earthen buildings with quicklime and oil. *Journal of Cleaner Production, 142*, 3281-3292.

Fabbri, A., Morel, J. C., & Gallipoli, D. (2018). Assessing the performance of earth building materials: A review of recent developments. *RILEM Technical Letters, 3*, 46-58.

Gardeh, M. G., Kistanov, A. A., Nguyen, H., Manzano, H., Cao, W., & Kinnunen, P. (2022). Exploring mechanisms of hydration and carbonation of MgO and Mg (OH) 2 in reactive magnesium oxide-based cements. *The Journal of Physical Chemistry C*, *126*(14), 6196-6206.

Gomes, M. I., Gonçalves, T. D., & Faria, P. (2016). Hydric behavior of earth materials and the effects of their stabilization with cement or lime: study on repair mortars for historical rammed earth structures. *Journal of Materials in Civil Engineering*, *28*(7), 04016041.

Groot, C., Veiga, R., Papayianni, I., Van Hees, R., Secco, M., Alvarez, J. I., Faria, P., & Stefanidou, M. (2022). RILEM TC 277-LHS report: Lime-based mortars for restoration–a review on long-term durability aspects and experience from practice. *Materials and Structures, 55(10)*, 245.

Houben, H., & Guillaud, H. (1994). *Earth construction: A comprehensive guide*. Intermediate Technology Publications, London.

Iqra, Soe, K., Yang, R., & Zhang, Y. X. (2025). A Review of Recent Advances in MgO-Based Cementitious Composites for Green Construction: Mechanical and Durability Aspects. *Buildings*, *15*(19), 3513.

Lauermannová, A. M., Paterová, I., Patera, J., Skrbek, K., Jankovský, O., & Bartůněk, V. (2020). Hydrotalcites in construction materials. *Applied Sciences*, *10*(22), 7989.

Le Bissonnais, Y. (2016). Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science*, *67*(1), 11-21.

Mahmood, A., Kaish, A. A., Gulam, N. F. B. A., Raman, S. N., Jamil, M., & Hamid, R. (2021). Effects of MgO-based expansive agent on the characteristics of expansive concrete. *Engineering Proceedings*, *11*(1), 14.

Moragoda, N., Kumar, M., & Cohen, S. (2022). Representing the role of soil moisture on erosion resistance in sediment models: Challenges and opportunities. *Earth-Science Reviews*, *229*, 104032.

Morel, J. C., Bui, Q. B., & Hamard, E. (2012). Weathering and durability of earthen material and structures. In *Modern earth buildings* (pp. 282-303). Woodhead Publishing.

Omid, A., & Mojtaba, G. (2022). Geotechnical properties of lime-magnesium slag stabilized clayey sand: experimental study. *Arabian Journal for Science and Engineering*, *47*(10), 13673-13685.

Panagiotou, R., Kyriakides, M. A., Illampas, R., & Ioannou, I. (2022). An experimental approach for the investigation of the performance of non-stabilized Compressed Earth Blocks (CEBs) against water-mediated weathering. *Journal of Cultural Heritage, 57*, 184-193.

Pedarla, A., Chittoori, S., Puppala, A. J., Hoyos, L. R., & Saride, S. (2010). Influence of lime dosage on stabilization effectiveness of montmorillonite dominant clays. In *GeoFlorida 2010: Advances in Analysis, Modeling & Design* (pp. 767-776).

Reynolds, E. K., & Muramoto, M. (2024). Durability of Japanese-earth cob walls subjected to accelerated rain simulation. *Heritage Science*, *12*(1), 154.

Richards, J., Bailey, R., Mayaud, J., Viles, H., Guo, Q., & Wang, X. (2020). Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty. *Scientific Reports*, *10*(1), 16419.

Sesana, E., Gagnon, A. S., Ciantelli, C., Cassar, J., & Hughes, J. J. (2021). Climate change impacts on cultural heritage: A literature review. *Wiley Interdisciplinary Reviews: Climate Change*, *12*(4), e710.

Trizio, F., Garzón-Roca, J., Eguibar, M. Á., Bracchi, P., & Torrijo, F. J. (2022). Above the ravines: flood vulnerability assessment of earthen architectural heritage in Quito (Ecuador). *Applied Sciences*, *12*(23), 11932.

U.S. Natural Resources Conservation Service (NRCS). (2011). *Soil Quality Indicators: Soil Crusts – Information Sheet.*

Wang, J. W., & Handy, R. L. (1966). Role of MgO in soil-lime stabilization. *HRB Special Report*, *90*, 475-492.

Yue, J., Li, W., Zhu, X., Kong, Q., Huang, X., Yang, X., & Han, Z. (2022). Experimental Study on Restoration Materials of Newly Earthen Ruins under Different Slaking Times. *Materials*, *15*(12), 4356.

Zeng, R., & Schwantes, G. (2024). Investigation of the effect of relative humidity on micro lime consolidation of degraded earthen structures. *Heritage Science*, *12*(1), 267.

Zhang, Z., Liu, Z., Wang, F., & Hu, S. (2023). Elucidating the interaction mechanism of Mg (OH) 2 and Ca (OH) 2 under enforced carbonation. *ACS Sustainable Chemistry & Engineering*, *11*(25), 9442-9454.

8. Chapter 8 – Conclusion

This final chapter synthesizes the outcomes of the experimental work and situates them within the broader framework of climate change adaptation for earthen heritage. It connects laboratory findings to site-level management practices and discusses how material innovation, when guided by cultural and environmental sensitivity, can contribute to long-term conservation strategies.

8.1. Key findings

This research confirms that climate change poses multifaceted threats to cultural heritage, particularly to earthen archaeological sites, which are among the most climate-sensitive types of heritage. The study's integrated approach, combining literature review, site-based vulnerability assessment, and laboratory experimentation.

First, the literature review demonstrated that while awareness of climate change impacts on heritage has expanded, responses remain fragmented across regions and disciplines. Studies tend to concentrate on European and North American contexts (Sesana et al., 2021; Fatorić & Biesbroek, 2020), with limited empirical data from Asia, Africa, and South America, where earthen heritage predominates. Moreover, most heritage adaptation research emphasizes risk identification rather than practical implementation. Frameworks such as the Climate Vulnerability Index (Day et al., 2019) and UNESCO's adaptation directives (UNESCO, 2018) provide valuable guidance, yet their application to earthen sites remains inconsistent.

Second, vulnerability assessments conducted on Iranian earthen heritage sites revealed that climatic factors, particularly precipitation variability, humidity fluctuations, and wind erosion, are accelerating deterioration processes. Erosion, salt crystallization, and thermal cracking emerged as primary mechanisms of decay. The modified IPCC-based framework developed in this study successfully contextualized these findings by linking hazard exposure with material sensitivity and adaptive capacity, allowing for an understanding of site-specific risks.

Third, the experimental phase demonstrated that MgO can significantly enhance the resilience of adobe under simulated rainfall and moisture conditions. At concentrations between 10 and 15 wt%, MgO stabilized the clay matrix by facilitating the transformation of swelling montmorillonite to non-swelling chlorite minerals, thus reducing erosion and moisture absorption. In contrast, SC showed higher brittleness and limited compatibility with traditional

adobe compositions. These results indicate that low-cost, environmentally compatible additives can serve as effective material-level adaptation strategies.

8.2. Contribution to climate change risk management of earthen heritage

This research advances the field of climate change risk management for earthen heritage through several original contributions:

Building upon the IPCC risk model, the study proposed a multi-dimensional framework that integrates hazard exposure, material sensitivity, and adaptive capacity, tailored specifically to earthen architecture. This framework bridges the gap between theoretical climate risk models and the physical realities of heritage conservation, allowing for more accurate site-based assessments. The experimental results on magnesium-based stabilizers provide evidence of how material-level interventions can mitigate climate-induced deterioration. This empirical data contributes to a growing body of evidence supporting the integration of climate adaptation principles into conservation science. The research emphasizes the compatibility of traditional practices with modern conservation science, promoting hybrid methodologies that align cultural values with technical adaptation. This approach strengthens not only material resilience but also social and cultural continuity, which are central to long-term sustainability. By linking laboratory research with international policy frameworks, such as the World Heritage Convention, ICOMOS Climate Change and Heritage Working Group, and UNESCO adaptation guidance, the study provides a translational model that connects scientific findings to management strategies and global heritage governance.

8.3. Conclusions

Climate change has emerged as one of the most profound and complex challenges facing the preservation of cultural heritage, demanding an urgent, multidisciplinary response. This thesis has explored the relationship between climate change and earthen heritage from theoretical, analytical, and practical perspectives, highlighting the gaps, challenges, and opportunities in adapting conservation practices to an evolving climate reality. Through the synthesis of global literature, case studies, and laboratory experimentation, it demonstrates that while the impacts of climate change on cultural heritage are increasingly well-documented, effective and systematic adaptation, particularly for earthen sites, remains limited and unevenly distributed across regions.

The theoretical exploration confirmed that cultural heritage, both tangible and intangible, is deeply embedded in environmental systems and social resilience. The literature review emphasized that while the interlinkages between climate change and heritage are widely recognized, adaptation strategies are still fragmented. Existing scholarship is often geographically biased toward Europe, China, and North America, with limited focus on arid and semi-arid regions where earthen heritage predominates. Despite policy frameworks such as those established by UNESCO, ICOMOS, and the World Heritage Convention, implementation gaps persist, particularly regarding site-specific adaptation tools and cross-sectoral coordination. This phase of the research underlined the necessity of integrating both scientific innovation and traditional knowledge to strengthen the resilience of heritage systems under changing climatic conditions.

The second analytical phase, focusing on the impacts of climate change on earthen heritage, demonstrated the heightened vulnerability of these sites due to their material composition and environmental exposure. The four case studies, Tchogha Zanbil, Persepolis, Yazd, and Sistan, served as key references for understanding how earthen sites respond to climatic stressors such as temperature extremes, precipitation variability, and wind erosion. Findings revealed that the major impacts include surface erosion, cracking, and collapse of structural elements, alongside broader degradation of cultural landscapes and intangible values. The modified IPCC-based framework developed in this study integrated hazard exposure, material sensitivity, and adaptive capacity, providing a structured approach to understanding risk at both site and regional levels. This framework contributes a model for climate risk assessment of earthen heritage that can be adapted to other regions.

The review of adaptation barriers identified several critical challenges to implementing climate-resilient practices in earthen archaeological sites. These include financial limitations, insufficient technical expertise, lack of coordination among heritage and climate institutions, and socio-cultural barriers that constrain the integration of traditional practices into modern conservation planning. Moreover, conflicting priorities between heritage preservation and development often exacerbate these challenges. Overcoming these barriers requires coordinated action across multiple levels, local, national, and international, and the creation of funding and capacity-building mechanisms to support adaptive heritage management.

The final experimental phase translated theoretical insights into practical adaptation strategies at the material level, addressing one of the most fundamental dimensions of earthen heritage

vulnerability: material instability under moisture stress. Laboratory testing of magnesium-based stabilizers, MgO and SC, demonstrated that MgO, particularly at 10–15 wt%, provides significant improvements in erosion resistance, moisture control, and long-term durability. The transformation of montmorillonite to chlorite, a non-swelling mineral, was found to be a critical factor in enhancing resilience against wetting-drying cycles. These findings not only offer a promising conservation material for earthen heritage under changing climatic conditions but also align with sustainable conservation principles, as MgO is cost-effective, environmentally benign, and compatible with traditional earthen technologies. This practical experimentation bridges a key research gap by providing an example of "material adaptation," whereby stabilization serves as both a technical and cultural adaptation strategy to climate change.

Future research should aim to refine predictive models of deterioration under specific climate scenarios, expand experimental stabilization studies across diverse soil types, and establish standardized protocols for assessing adaptation effectiveness. Collaboration among heritage scientists, climate researchers, policymakers, and local communities will be essential to translating these insights into practice.

Concluding the thesis, this chapter integrates insights from all research stages to propose a comprehensive model for climate change risk management of earthen archaeological sites. It emphasizes the importance of interdisciplinary collaboration, traditional knowledge integration, and adaptive conservation planning as pathways toward sustainable heritage resilience in the face of accelerating climate change.

8.4. Limitations of the Research

Despite the comprehensive scope of this study, several limitations must be acknowledged when interpreting the findings and their wider applicability. The research was conducted within a limited timeframe, which constrained the number of sites, datasets, and experimental cycles that could be analysed. The case studies, though representative of diverse climatic conditions, cannot encompass the full variability of earthen heritage worldwide. In addition, the availability and resolution of climate and environmental data varied across sites, requiring reliance on secondary sources and introducing uncertainties into exposure and vulnerability assessments. The experimental stabilization tests, while rigorously designed, were performed under controlled laboratory conditions that do not fully replicate long-term weathering, soil-structure interactions, or environmental complexity encountered in situ. The performance of

MgO, SC, HL and MgO-HL stabilization over extended timescales, therefore, remains a topic for future field-based validation.

References

Day, J. C., Heron, S. F., Markham, A., Downes, J., Gibson, J., Hyslop, E., Jones, R and Lyall, A. (2019). Climate Risk Assessment for the Heart of Neolithic Orkney World Heritage Site.

Fatorić, S., & Biesbroek, R. (2020). Adapting cultural heritage to climate change impacts in the Netherlands: Barriers, interdependencies, and strategies for overcoming them. *Climatic Change*, *162*(2), 301–320. https://doi.org/10.1007/s10584-020-02831-1

Sesana, E., Gagnon, A. S., Ciantelli, C., Cassar, J., & Hughes, J. J. (2021). Climate change impacts on cultural heritage: A literature review. *WIREs Climate Change*, *12*(4), e710. https://doi.org/10.1002/wcc.710

UNESCO. W. H. C. (2018). *41 COM 7—Decision*. UNESCO World Heritage Centre. Retrieved 29 March 2023, from https://whc.unesco.org/en/decisions/6940/