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Synergizing multi-criteria diagnosis for safeguarding cultural heritage and the restoration of vanished legacy: A historical exploration in science, technology, and archaeology

Abstract. *The urgent need to preserve cultural heritage is starkly evident in contemporary society, particularly poignant in Morocco where its rich cultural legacy faces unprecedented threats. The rapid forces of urbanization and relentless economic development have converged, resulting in the alarming devaluation and irreversible degradation of a substantial portion of this invaluable heritage. Within this disconcerting backdrop, certain remarkable vestiges have managed to endure the ravages of time. One such exemplar is the Marinid Madrasa, an architectural marvel from the 4th century, nestled within the Chellah archaeological site in Rabat, Morocco. Beyond its physical grandeur, the Madrasa plays a pivotal role as a conduit between the past and the future, facilitating the transmission of cultural heritage to generations yet unborn. This paper embarks on a multidisciplinary journey, employing advanced techniques such as terrestrial photogrammetry, numerical modeling, and specialized archaeological characterization, to undertake comprehensive diagnostic study processes. The convergence of these diverse methodologies lays a robust foundation for a holistic diagnostic study. This endeavor serves not only academic curiosity but becomes the cornerstone upon which strategies for compatible conservation and restoration interventions are erected. In the intricate interplay between historical* *preservation and the imperatives of progress, these methodologies form a bridge. This bridge links the architectural magnificence of the Madrasa with the imperatives of safeguarding it in a rapidly changing world. The ultimate aspiration of this multidisciplinary approach is twofold: to ensure the enduring protection of the Marinid Madrasa and other archaeological remnants against the erosive forces of time and urban development, and to forge a narrative that sensitively navigates the challenges posed by preserving cultural heritage in the face of modernity. In this endeavor, advanced technologies are interwoven with a profound recognition of the historical, social, and cultural significance of these sites, ultimately charting a course that not only conserves architectural brilliance but also honors the profound stories they encapsulate across the epochs.*

Keywords: *cultural assets; material analysis; restoration; antiquities; archaeology; 3D technology*

Introduction.

The preservation of archaeological and destroyed heritage holds significant importance in safeguarding tangible cultural artifacts, while also carrying long-term implications by fostering the implementation of sustainable development policies that effectively conserve the past for the benefit of future generations (Mekonnen, Bires, & Berhanu, 2022). Additionally, it is conserved and managed with the aim of benefiting tourists and actively contributing to the utilization of cultural heritage and tourism as powerful tools in fostering a more respectful, inclusive society, and promoting a sustainable future (Almasri & Ababneh, 2021; Jeong, Karimov, Sobirov, Saidmamatov, & Marty, 2023). These considerations are particularly valuable if integrated into the ongoing debates on the future of tourism after Covid-19, specifically regarding how archaeological heritage is managed and the value of cultural tourism to society (Haq, Yasin, & Nair, 2023). The preservation of inherited tangible and intangible assets necessitates the collaboration of various professions, presenting additional challenges in effectively organizing collective conservation efforts in a holistic approach (Nilson & Thorell, 2018). Significant requirements for the choice of materials for the conservation of heritage remains have been gathered from the literature and through consultation with experts working on the preservation of cultural heritage (Choriyev, Shaydullaeva, & Raxmonkulova, 2023).

The protection and valorization of archaeological heritage are mainly promoted through multidisciplinary approaches and the development of new technologies (Di Benedetto et al., 2020). These technologies are available to produce and visualize high-quality 3D models in real-time, considering geometric resolution, textural detail, and large dimensions (Shanoer & Abed, 2018). Several authors have proposed the use of terrestrial and aerial photogrammetry as potential tools for surveying archaeological heritage (Adamopoulos & Rinaudo, 2021; Salagean-Mohora, Anghel, & Frigura-Iliasa, 2023). These techniques have made a significant contribution to the digital conservation and dissemination of these artifacts (Chen, Wu, Sun, Ali, & Zhou, 2023; Simou, Baba, & Nounah, 2022). In this study, the application of 3D laser scanning technology is used for data collection, data processing, and model construction. Surveys have gained significant favor within the scientific community, particularly in the documentation of cultural heritage, as they play a crucial role in capturing and documenting the diverse range of building materials utilized in these contexts (Lu, Wang, Q., Wang, S., & Zhang, 2015; Maté-González, Di Pietra, & Piras, 2022). Survey methods are developed and integrated, providing a textured 3D model (Tsilimantou, Delegou, Nikitakos, Ioannidis, & Moropoulou, 2020). On the other hand, the characterization of building materials is important for the protection of monuments. Many materials such as rammed earth, clay, and stone are used as major building materials in the construction of historical and archaeological buildings in Morocco and worldwide (Sanchez-Calvillo et al., 2021). The purpose of this study is to investigate a multidisciplinary approach by studying architectural, historical, geometric, and documentation data on building materials and their interaction for archaeological building structures. This contributes to the assessment of the current condition of the structure using 3D technology, particularly terrestrial photogrammetry and laser scanning, to provide numerical data for various conservatory analyses and thematic maps, incorporating both qualitative and quantitative information. Furthermore, this approach facilitates the planning and implementation of compatible conservation interventions (Tsilimantou et al., 2020). The selected historical site for the implementation of this procedure is the preserved remnants of the Marinid Madrasa of Abu Al-Hassan, which dates back to the 14th century. This significant historical structure is situated within the Chellah archaeological site in Rabat, Morocco. Originally, it served as a Quranic school designed to fulfill the dual purpose of a college and a student residence, commissioned by the Marinid dynasty.

Materials and Methods.

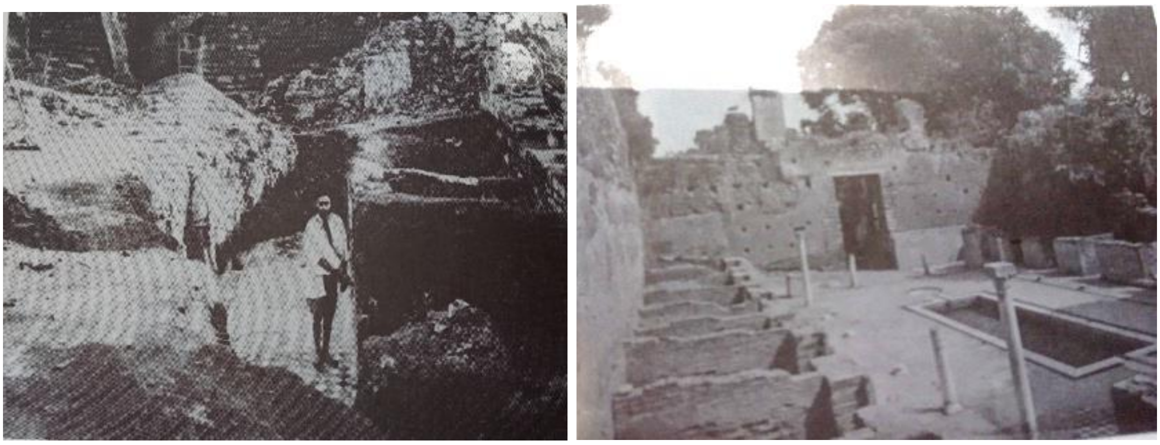
When it comes to archaeological buildings, ensuring structural safety and durability are paramount considerations, with a primary focus on respecting their cultural, historical, and architectural values, thus safeguarding their distinctive characteristics during preservation efforts (Spennemann, 2023). In this paper, we describe the multi-criteria approach aimed at assessing the remains of the Marinid Madrasa (Figure 1), using geometric data from a 3D model generated by terrestrial photogrammetry, which provides important information for physical characterization and numerical analysis.

Presentation of case study.

The presented research was conducted as collaboration between High School of Technology-Salé, Mohammed V University, LAMEREN laboratory, and Region of Rabat-Salé-Kénitra. Through a series of activities, workshops, and conferences, an endeavor was undertaken to promote and disseminate knowledge about the Chellah archaeological site by employing innovative techniques for documenting and conserving its rich cultural heritage.

Figure 1. Location of study area, (a): the map of Rabat city (Google Earth Pro), (b): Chellah archeological site (Google maps), (c): Marinid Madrasa site (UAV- DJI Phantom 4 Pro, taken by Authors).

The site encompasses remnants left by diverse civilizations, including the Phoenicians, Carthaginians, Romans, and Islamic peoples. Specifically, the focus was on the Marinid Madrasa (Figure 2), a remarkable architectural gem constructed by the Marinid dynasty, which held dominion over Morocco and the entire Maghreb region for nearly two centuries, spanning from the mid-13th century to the mid-15th century (Terrisse, 2011).



a b

Figure 2. Documentation of excavations at the Medersa site in 1912 (a), Photographic documentation of the Medersa in 1920 (b) (source: Archive of the Ministry of Culture (Rabat, Morocco)).

In-situ investigations.

Typology of construction.

Many archaeological building monuments have suffered severe damage due to natural weathering processes, pollution influences, insufficient maintenance, utilization, and use of sensitive materials or inappropriate conservation (Theodoridou & Török, 2019). The current archaeological site (Marinid Madrasa) (Figure 3) has suffered these damages, and also the impact of groundwater due to rising aquifers. In (Table 1), the material type is presented as the entry, while the corresponding damage type/state is reported.

Table 1. The material building of Madrasa and the damage type.

Material type	Damage/state
Wood	Mold and fungi growth, gilding degradation, polychrome deterioration, cracks, displacement, deformation, delamination, water stains, and moisture marks.
Stone	Damage caused by water and moisture, moss and lichen growth, cracks, alterations in polychromy, erosion, attrition, and delamination (for limestone).
Rammed earthen	Erosion, stain loss, cracking
Marble	Alteration of gilding, adhesive repairs, staining, chipped paint, changes to polychromy, watermarks, missing fragments, and faded inscriptions.
Zellige	Gaps, tears, soiling, cracks, chips, mold, holes, changes in the pictorial layer, color fading, alterations in the coating, localized dirt accumulation, and delamination of the pictorial layer.

Figure 3. Example of building material and degradations of archaeological assets of Madrasa (Author's figure).

The Ishikawa diagram, Figure 4 interprets the causes of damage of Marinid Madrasa, which is regrouped in three main sections; first the building constitution reason, which is related to the type of materials. Then, People intervention which represents a bad choice of conservation method, and people degradations. Lastly, an environment that encompasses biological aggression, physics-induced issues, and mechanical degradation.

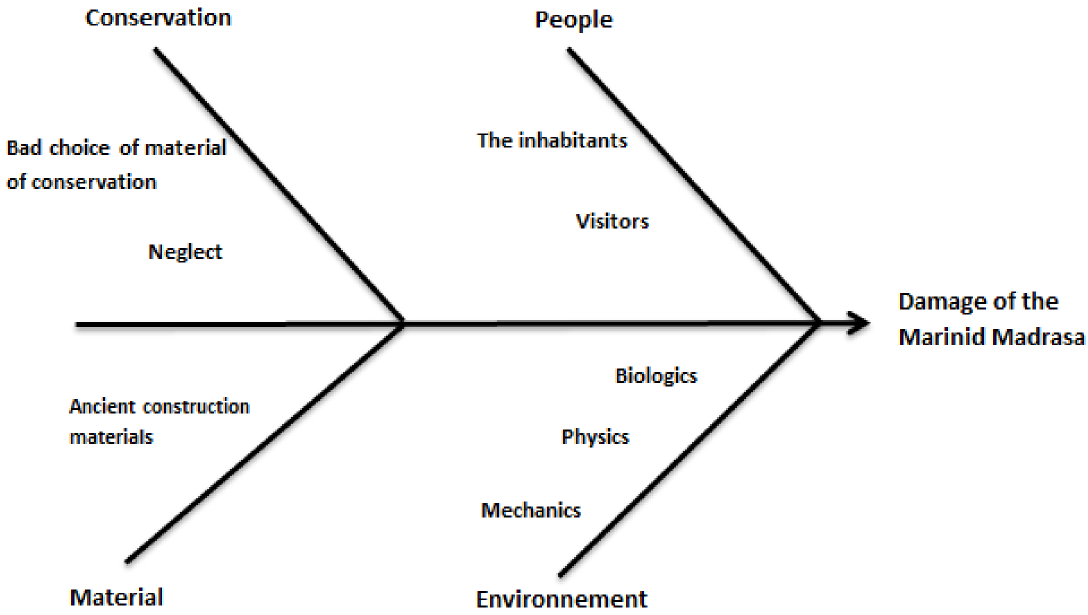


Figure 4. Ishikawa diagram of archaeological assets damage of Marinid Madrasa (Author's figure).

Building materials characterization.

The optimization of diagnostic procedures is an important scientific objective, representing the basis for sustainable monument preservation. The specific objectives of scientific diagnosis include the characterization of stone materials, quantification of stone alterations, and characterization and quantification of weathering characteristics (Theodoridou & Török, 2019). For the documentation and experimental analysis of the building materials of the Marinid Madrasa, a series of mechanical tests were applied to the adobe material extracted from the site. The methodology employed in this study demonstrates encouraging outcomes in enhancing the prediction of mechanical properties for the mix utilized in the construction and restoration of historic monuments, thereby minimizing the need for expensive experimental endeavors. To examine the morphology of a selected surface and provide a preliminary characterization of the construction materials as well as an evaluation of degradation, a scanning electron microscope was used. Specifically, a mini-Scanning Electron Microscope (mini-SEM) HIROX SH 4000M, equipped with SE (Secondary Electron) and BSE (Backscattered Electron) detectors, was employed.

Data acquisition.

The difficulty in surveying the deformation of archaeological buildings lies in finding a measurement method that is reliable, accurate, repeatable, inexpensive, and easy to implement (van Dijk, Gamstedt, & Bjurhager, 2015). Terrestrial laser scanning (TLS) may prove to be a good alternative and supplement for surveying many complex heritage constructions in a fast and safe manner, with high accuracy (Tobiasz et al., 2019). TLS has become increasingly popular for the documentation of cultural heritage due to its availability and the ability to provide dense surface models quickly, with improving accuracy and reliability (Shanoer & Abed, 2018).

In this study, data of the Marinid Madrasa were obtained through TLS, using the Leica ScanStation 2 Laser Scanner (Figure 5), provided by the research team at the Laboratory of Applied Mechanics and Energy Recovery of Materials (LAMERN), Mohammed V University, Rabat. Multiple overlapping scans were acquired from selected positions to capture the surface details of the archaeological site, By achieving an average spatial resolution of 5-6 mm, the dense 3D point cloud acquired enables the generation of a meticulous digital model showcasing the enduring components found within the site, including the Mihrab and the North wall. This detailed representation significantly aids in the documentation of the archaeological assets present.

Figure 5. Laser data setting and capturing using Leica scan (Author's figure).

Results and Discussions.

Data exploration and visualization of numerical models.

The data obtained using TLS allows the creation of orthoimages of many durable types of construction elements in Madrasa site. The accuracy obtained after the correction of the point cloud, and then a 3D models ware produced for Mihrab and north wall of Madrasa site (Figure 6) however, these objects (Figure 7) are used as data for various conservatory analyses for damage and thematic mapping including not only qualitative information but also quantitative data. It is a very useful tool that allows saving the model in the form of virtual copy (Tsilimantou et al., 2020). The acquired models represent the sole available information regarding this archaeological site, serving as an invaluable resource for future research endeavors.

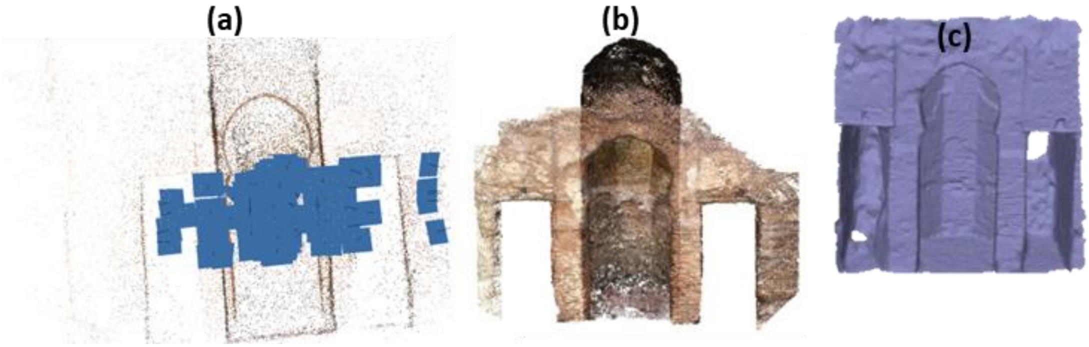


Figure 6. The process involved capturing camera positions for alignment (a), generating a dense point cloud of the Mihrab (b), and creating a 3D mesh to represent its intricate structure (c) (Author's figure).

a b

Figure 7. Orthoimages of (a) the North wall (b) the Mihrab (Author's figure).

The 2D plans corresponding to the Mihrab and the North wall are extracted from the digital models provided by the cloud points using AutoCAD. Each element of the drawing has been classified according to architectural detail, distribution of building material and type of degradation.

Building materials.

The Madrasa is located in the northeastern part of the Chellah archaeological site and comprises a prayer room, an open-air courtyard, a Minaret, and several cells for students. The damaged remains consist of a central courtyard with a beautiful basin at its center, surrounded by a scroll adorned with small columns and marble columns. On the East and West sides, there are a series of rooms. Towards the south, there is a small rectangular prayer hall with two parallel naves along the Qibla wall. In the center, there is a pentagonal Mihrab decorated with stuccoes featuring various motifs. On the opposite side, in the northern area, stands a slender Minaret (Fig. 8.d) that still retains its architectural characteristics from that period. The Minaret is square-shaped and consists of two floors. The first floor is constructed with adobe bricks, embellished with geometric motifs formed by intersecting stone lozenges. The smaller second floor is covered on all four sides with ceramic tiles of different colors.

During the in situ survey, the variations in the building materials for each type of masonry were recorded and analyzed qualitatively and quantitatively. The structural system of each architectural element was documented using thematic maps, thereby validating the architectural and historical research conducted on these elements. On the walls (Fig.8.a), it is evident that there is a higher percentage of Rammed earthen material and a lower percentage of blocks compared to the Mihrab section (Fig.8.c) and the cells (Fig.8.b), indicating the implementation of a rigid partitioned system during their construction.

A comprehensive attribute database was created, encompassing physico-mechanical characteristics data of adobe (Rammed earthen). The investigation revealed that mechanical properties, including tensile strength and modulus of elasticity, can be accurately assessed through bending tensile tests. The adobe material showcased commendable resilience against compression and tensile stress, evident in a bending strength to compressive strength ratio of 40. Furthermore, an SEM test was conducted on the fractured surfaces of the adobe material, revealing a heterogeneous microscopy with the presence of cracks and large pores (Figure 9). The significance of these findings lies in their ability to characterize the adobe material employed in constructing the walls of the Madrasa, providing essential reference values that should be taken into account when undertaking the restoration and rehabilitation of the site's buildings.

Due to the advanced state of degradation of the monument, non-destructive testing (NDT) techniques were employed in the study conducted by S. Belhaj and colleagues (Belhaj, El Ghazali, Bahi, Akhssas, 2019),s to assess the Medersa Marinid site located in Chellah. The objective was to determine the primary cause of these deteriorations by examining the internal and external faces, adobe material within the walls, as well as the chaining stones and bricks. A comprehensive sampling approach was undertaken to cover all the existing structures within the Chellah enclosure, which, combined with the diagnostic process, enabled the identification and characterization of degraded areas within the overall Chellah monument and specifically the Medersa Marinid.

The representation and distribution of building materials at the surface level, particularly on the Mihrab and the minaret, were illustrated using visual inspection, NDT evaluation, and digital models generated through terrestrial photogrammetry. The integration of NDT and visual inspection facilitated the identification of construction materials on the Mihrab's façade, which consists of red bricks interspersed with clay, adobe in the upper part of the Mihrab, and remnants of lime. The minaret's façades feature adobe bricks and persisting zellige patterns.

a b

c d

Figure 8. Different archaeological parts of Marinid Madrasa (Author's figure): North wall (a), Remains of chambers (b), The Mihrab (c), The Minaret (d).

For a qualitative and quantitative survey, the distribution of various types of masonry was analyzed, as shown in Figure 10. The wall exhibits a higher percentage of adobe (Rammed earthen) and a smaller proportion of adobe bricks compared to the remaining preserved sections, as it represents the thickest wall within the Medersa building. Conversely, the façades of the Mihrab predominantly consist of adobe brick materials, while the Minaret exhibits a high percentage of red bricks.

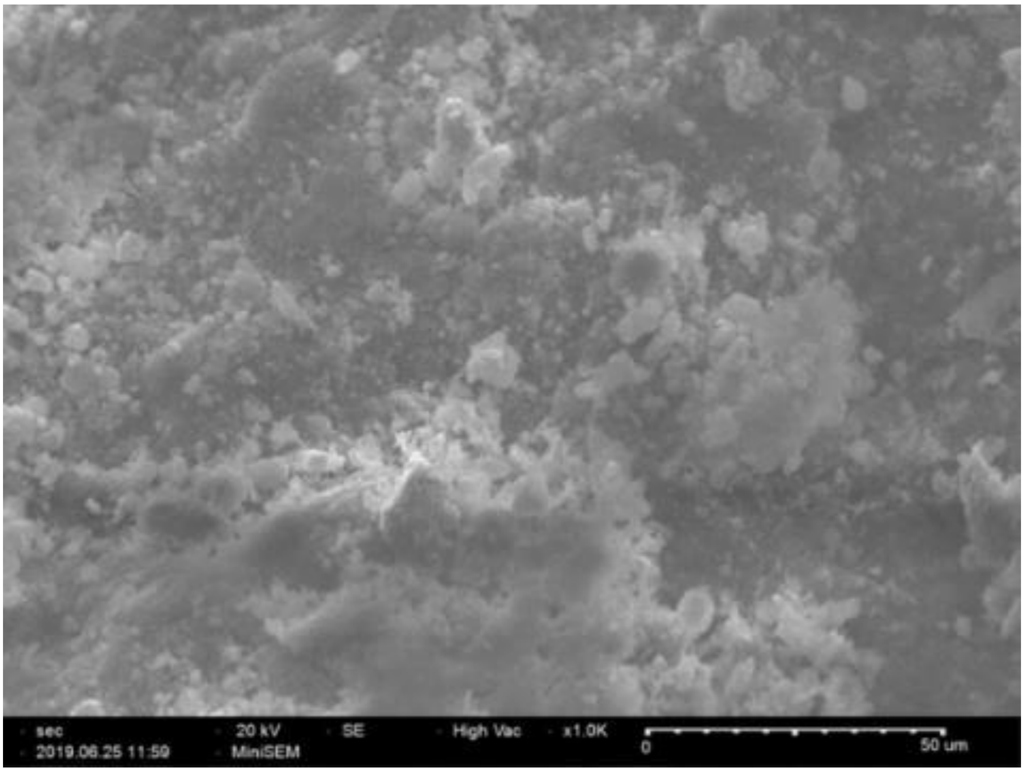


Figure 9. SEM image of fracture surface (50μm) (Author's figure).

In the Marinid stone (Figure 11.a), the percentage of calcium oxide is excessively high, reaching 51%, while clay minerals account for 17%. The loss on ignition is estimated at 30,5%, indicating significant alteration. The rock's alteration is confirmed by both the loss on ignition and observations under the optical microscope. The predominant elements in the rock are carbon, oxygen, and calcium. The Marinid brick (Figure 11.b) is found in the domes of the towers and the Mihrab. The study conducted under the optical microscope revealed that it is a sandstone clay with a low carbonate content and large sandy grains, likely derived from sea sand or Oued Bouregreg. The dispersion of grains indicates a poor element composition and therefore low quality. The composition consists of 10 to 15% of quartz grains measuring 50 to 100μm in diameter, which are sub-rounded in shape, and 5% of joined quartz with a diameter of 0.5 to 1 mm. The matrix is predominantly clayey with occasional patches of calcite. The archaeological monument Madrasa of Chellah includes building materials such as; brick, stone, clay, mud, wood, plaster, zellige, steel and as a method of construction adobe masonry.

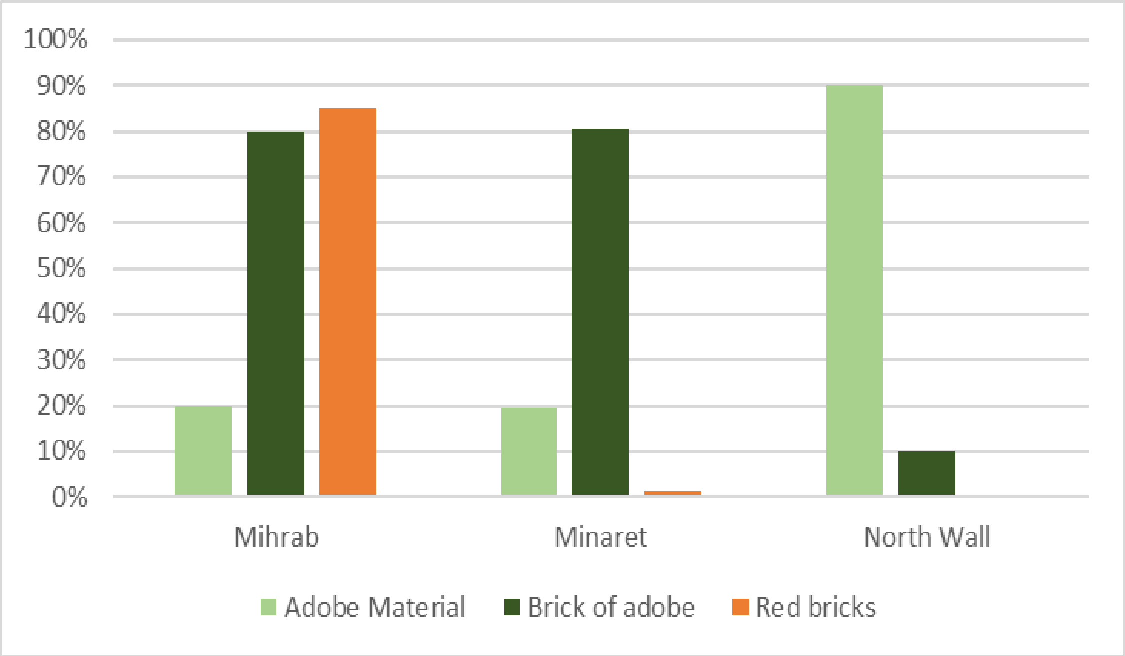


Figure 10. Diagram of the percentage of building materials in North wall, Mihrab, and Minaret (Author's figure).

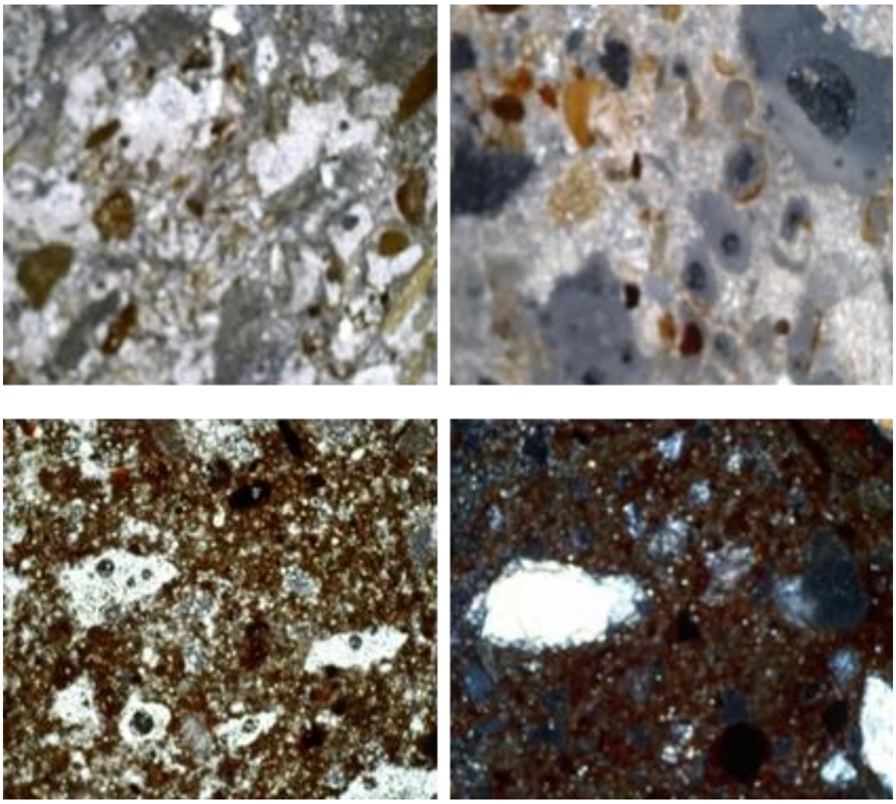


Figure 11. (a) Building stone and (b) The Marinid brick, under white light and polarized under 4X objective. (Author's figure).

The development of lichens (Marked with blue circle) on the wall causes physic-chemical damage because of their metabolic activity (production of oxalic acids) and an aesthetic inconvenience Figure 12-a. The development of lichens causes physic-chemical alterations and aesthetic inconvenience (Minaret of Chellah) Figure 12-b.

a b

Figure 12. (a) North wall and (b) Minaret of Madrasa with the evolution of lichens (Author's figure).

Also, the roots of plants (Marked with the red circle) in addition to the former exert mechanical thrusts causing fractures. The excrements of birds (oxpeckers and storks) also cause chemical degradation (Chellah lichen). The issues encountered on this site are related to humidity, the presence of water, atmospheric pollution, vegetation growth, lack of sanitation inside and outside the site, the primary construction technique and the previous rehabilitation and conservation processes.

Elaboration of thematic maps of decay and building material distribution.

Thematic maps depicting the distribution of building materials in the Madrasa were developed (Figure 13).

The selection of the Mihrab and the North wall was based on their representation of the various building materials and construction phases found throughout the Madrasa. The data pertaining to building materials and decomposition schemes consist of attribute data sets that comprehensively depict the characteristics of the registered spatial features found within the site. To create the thematic maps, GIS tools were utilized, making use of the results obtained from the degradation diagnostics. GIS is capable of recording, aggregating, analyzing and managing large volumes of spatially referenced data and associated attributes. These results form the basis of a database that facilitates the analysis and preservation of the state of the archaeological assets at the Medersa site. Figure 14 represents the thematic map showcasing the decay of building materials in the Mihrab, based on visual inspection, macroscopic tests, and digital models generated by terrestrial photogrammetry.

The decay in the Mihrab is significant, with a noticeable detachment of building materials on the upper part and facade. This detachment indicates rising humidity, although significant structural cracks are not observed. The lime coating has disappeared, revealing the building bricks, which exhibit flaking and material loss. The wood is completely degraded, and a large portion of the plaster decoration has vanished. The most dominant building material observed is red brick (12 cm long and 3 cm wide), intercalated with a layer of clay, with remnants of rammed earth visible in the upper part.

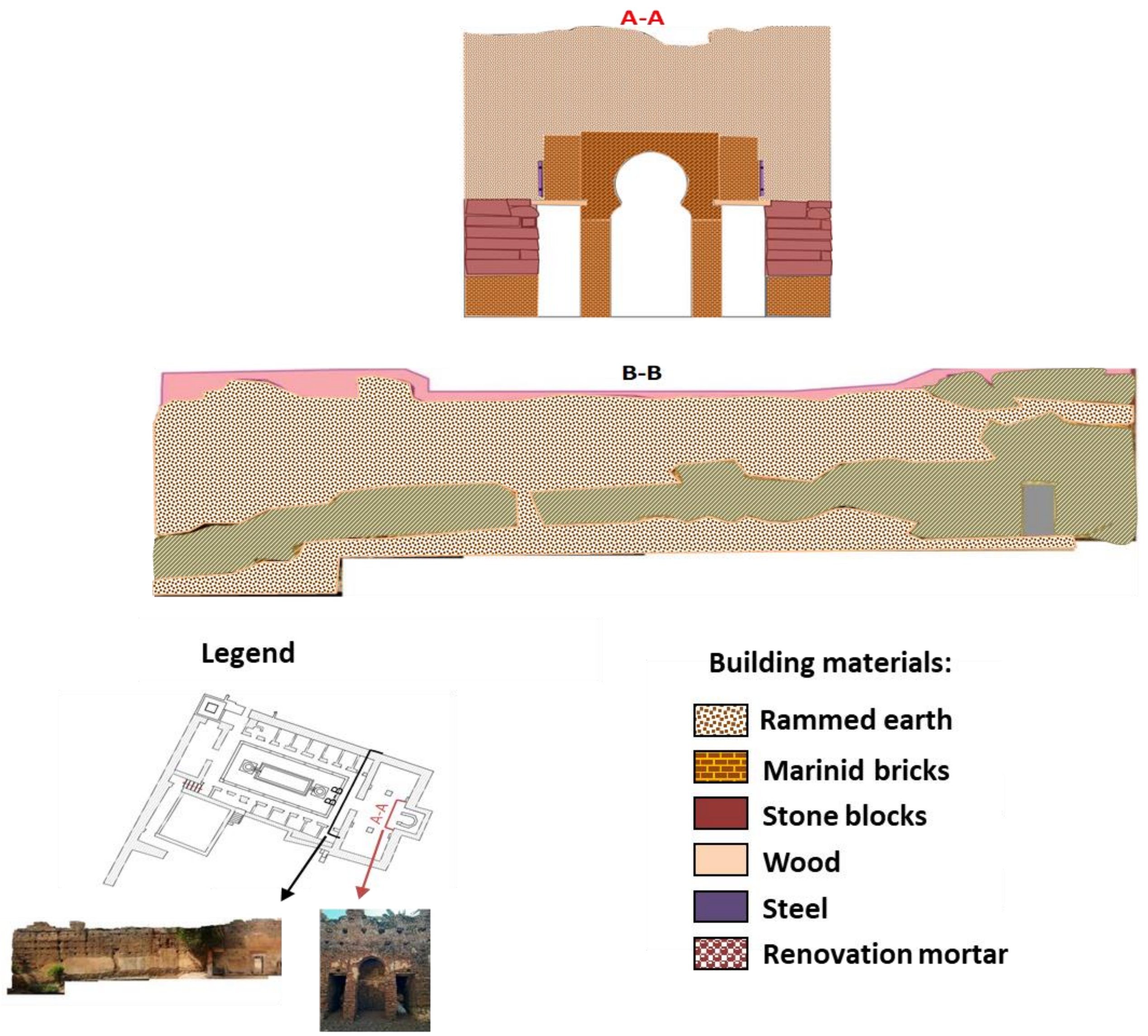


Figure 13. Thematic map of building material distribution on (A-A) the Mihrab and (B-B) North wall (Author's figure).

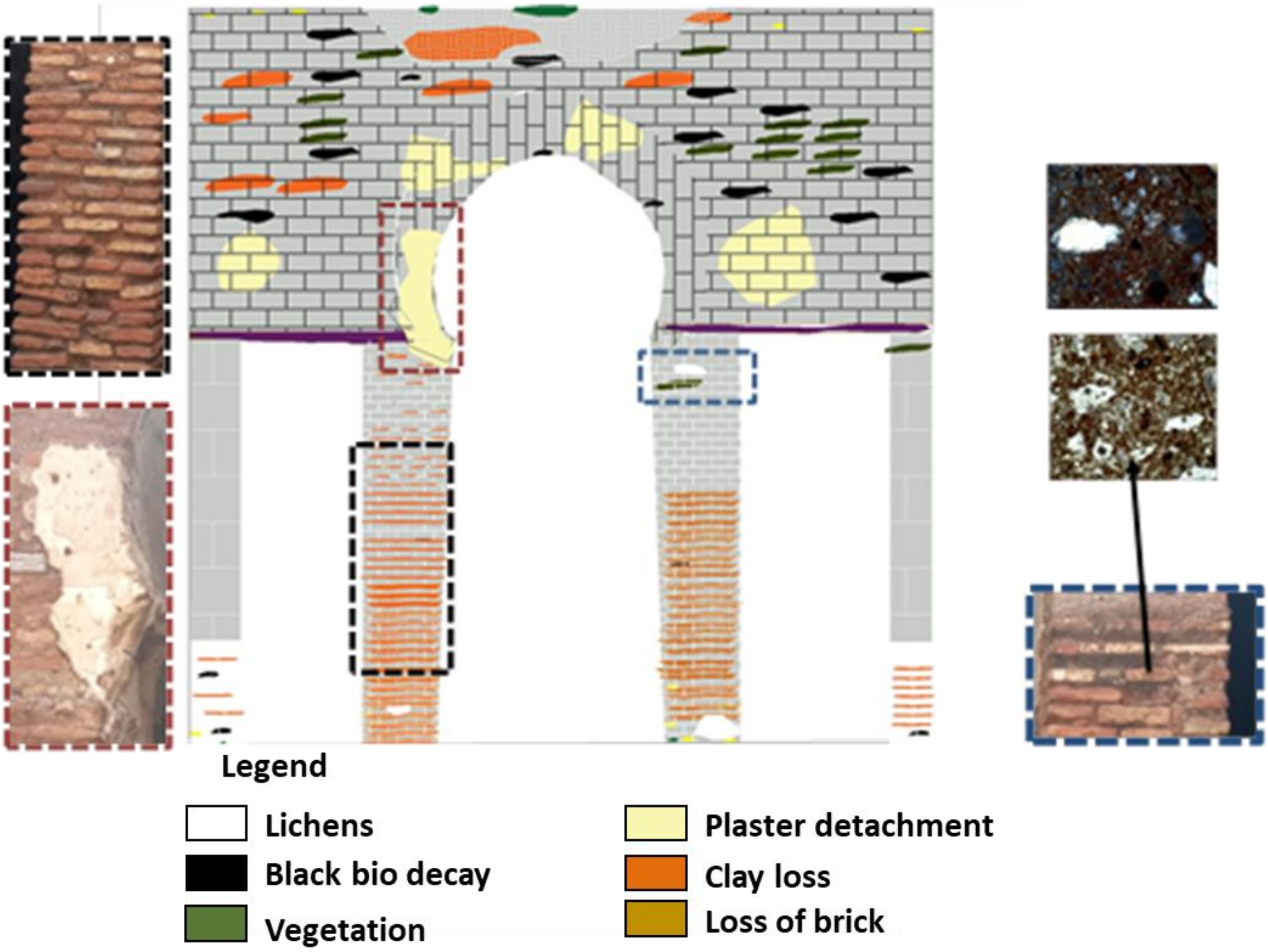


Figure 14. Thematic map of decay on the archaeological Mihrab (Author's figure).

Conclusions.

The multi-criteria approach presented in this paper aims to establish correlations between different data in order to create multidisciplinary thematic maps (Figure 15). This approach relies on in-situ investigations, numerical documentation, and the characterization of building materials in archaeological assets. The first step involves collecting and processing data and information in a careful, balanced, and thoughtful manner to develop a comprehensive action plan. Conservation practices for an archaeological site require a thorough understanding of the structure's characteristics and materials. It is crucial to gather information about the asset in its original and early state, the construction techniques employed, the endured alterations and their effects, the occurred phenomena, and its present condition. The chosen site contains archaeological remains, which poses specific challenges as stabilization must be carried out simultaneously with the excavations while information is still incomplete. A diagnosis was conducted using qualitative and quantitative methods, with historical research relying on structural damage and material decay observations, as well as historical and archaeological investigations. The quantitative aspect involved testing building materials, non-destructive testing (NDT), and geometric data generated through photogrammetry. Based on the obtained data, thematic maps were created, serving as a foundation for restoration efforts and the management of disciplinary information. These maps contribute to the planning and decision-making processes regarding interventions on the site's remains.

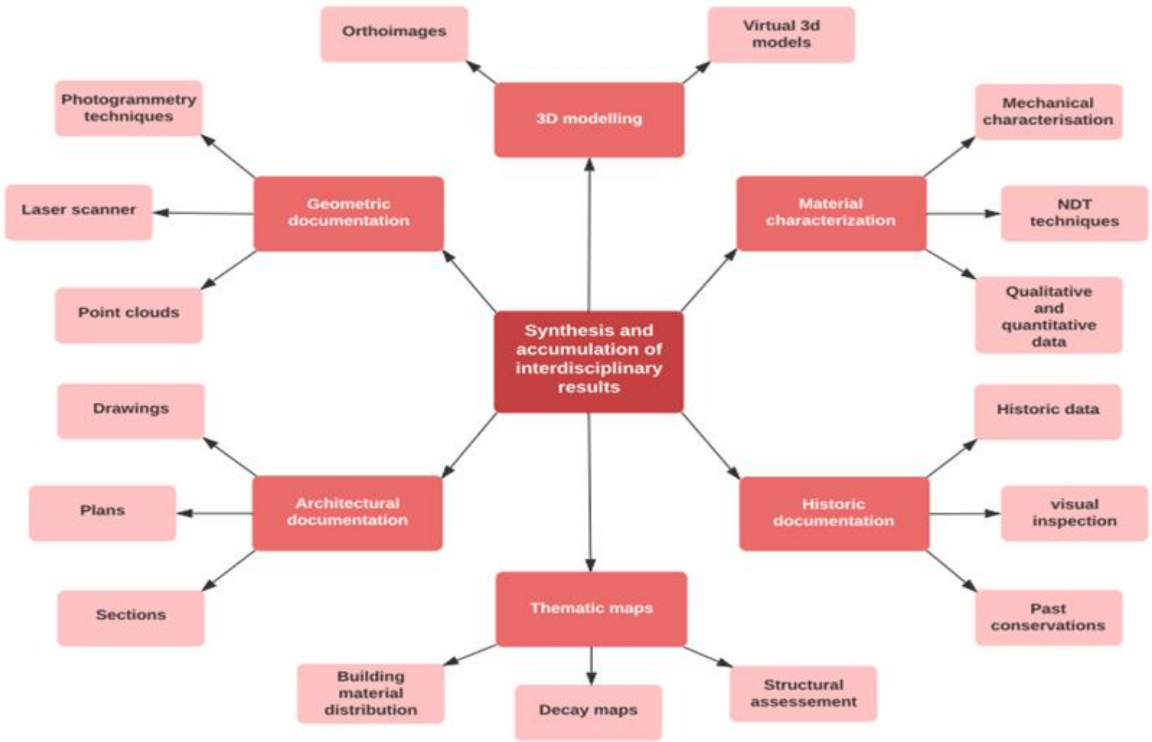


Figure 15. Diagram of the synthesis and accumulation of interdisciplinary results incorporating various data (Author's figure).

Conflicts of interest.

The authors declare no conflict of interest.

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Синергія багатокритеріальної діагностики для збереження культурної спадщини та відновлення зниклої спадщини: Історичне дослідження в науці, техніці та археології

Анотація. *Нагальна потреба збереження культурної спадщини на сучасному етапі розвитку суспільства стає надзвичайно важливою, особливо гостро в Марокко, де його багата культурна спадщина стикається з непередбачуваними загрозами. Швидкі сили урбанізації та нескінченного економічного розвитку зіткнулися, що призвело до тривожної депреціації та необоротного погіршення стану значної частини цієї безцінної спадщини. У цьому контексті деяким видатним пам'яткам вдалося витримати плив часу. Одним з таких зразків є Маринідська медресе, архітектурне диво 4 століття, розташоване на території археологічного об'єкту Шелла у Рабаті, Марокко. Поза своєю фізичною величчю, медресе відіграє ключову роль як канал між минулим та майбутнім, сприяючи передачі культурної спадщини нащадкам, які ще народяться. Ця робота розпочинає багатодисциплінарну подорож, використовуючи передові техніки, такі як земельна фотограметрія, числове моделювання та спеціалізована археологічна характеризація, для проведення комплексного діагностичного дослідження. Злиття цих різноманітних методик створює міцну основу для всебічного діагностичного дослідження. Ці зусилля будуть слугувати не лише академічній цікавості, але й стануть кутовим каменем, на якому будуються стратегії сумісних консерваційних та реставраційних втручань. У складній взаємодії між збереженням історичного спадку та імперативами прогресу ці методики утворюють міст. Цей міст зв'язує архітектурну велич медресе з необхідністю збереження її в швидкозмінному світі. Остаточною метою цього багатодисциплінарного* *підходу є: забезпечити довготривалий захист Маринідської медресе та інших археологічних залишків від руйнівних сил часу та міського розвитку, а також сформувати наратив, що чутливо реагує на виклики збереження культурної спадщини перед сучасністю. У цьому зусиллі передові технології переплітаються з глибоким визнанням історичного, соціального та культурного значення цих місць, нарешті, прокладаючи шлях, який не лише зберігає архітектурний блиск, але й вшановує глибокі історії, які вони вміщують через епохи.*

Ключові слова: *культурні цінності; матеріальний аналіз; реставрація; античність; археологія; 3D-технологія*

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