Journal of Surveying, Construction and Property (JSCP) **Volume 17, 2026 Issue 1**
e-ISSN: 1985-7527

INNOVATIVE APPROACHES TO MITIGATE CLIMATE IMPACT IN BUILT ENVIRONMENTS: LABORATORY INVESTIGATIONS OF SALT CRYSTALLISATION IN CULTURE AND HERITAGE CONSERVATION

Mohd Jaki Mamat[1], Siti Norbaya Mohd Konar[2*] and Shaari Mat Saod[2]

[1]School of Housing, Building & Planning, Universiti Sains Malaysia, 11800 Gelugor, Penang, Malaysia.
[2]NTQT SDN BHD, No 29, 1, Jalan KNMP 1, Kompleks Niaga Melaka Perdana, 75450 Bukit Katil, Melaka, Malaysia

Corresponding author: *sitinorbayamohdkonar@gmail.com

ABSTRACT

Salt crystallization is one of the major causes of deterioration in heritage buildings, affecting both structural integrity and aesthetic value. This study investigates the occurrence and mitigation of salt crystallization in Sekolah Kebangsaan King Edward VII (1), a heritage building located in Taiping, Perak, Malaysia, a town commonly known as the “Rain Town” due to its exceptionally high annual rainfall and humid tropical climate. The study aims to identify the types and concentrations of soluble salts present in the building materials, assess their potential impacts on building deterioration, and evaluate the effectiveness of a poultice-based desalination treatment. Five masonry samples were collected from areas exhibiting visible signs of salt-related deterioration and analysed using ion chromatography (IC) before and after treatment. The results revealed significant concentrations of chloride, nitrate, and sulphate ions, which are known to contribute to efflorescence, spalling, cracking, and material degradation. The findings further indicate that persistent moisture ingress and repeated wetting-drying cycles facilitate salt dissolution, transport, and subsequent crystallization within porous building materials. Following the desalination treatment, the total soluble salt concentration was reduced from 36.204% to 0.237%, demonstrating a substantial reduction in salt contamination. Although the study is limited to a single heritage building and a relatively small sample size, the findings provide valuable insights into salt deterioration mechanisms and conservation challenges in tropical heritage environments. The research highlights the importance of integrating desalination treatment, moisture management, and long-term monitoring as part of sustainable heritage conservation strategies.

Keywords: Salt crystallization; Heritage conservation; Ion chromatography; Desalination treatment; Tropical climate; Building deterioration.

Received: 6 February 2026 | Revised : 12 June 2026 | Accepted: 26 June 2026

1. INTRODUCTION

A heritage building, at its core, is a structure that captivates the imagination, sparking a curiosity to explore the people and culture behind its creation. Beyond its physical presence, such a building embodies rich values including architectural, aesthetic, historical, documentary, archaeological, economic, social, political, and spiritual or symbolic dimensions (El Mansoury, 2024). Heritage buildings conservation, often referred to as historic preservation or heritage preservation, is the process of maintaining structure, buildings, landscapes, and other artifacts that hold cultural, historical, or architectural importance (Khan & Guleria, 2024). However, Heritage buildings face unique challenges such as environmental and material degradation, which can complicate preservation efforts (Idris et al., 2024).

One significant threat is salt crystallization, where soluble salts penetrate porous materials, later crystallizing and exerting pressure that leads to efflorescence, spalling, and cracking. Salt crystallization is a particularly relevant issue in the conservation of materials, such as lime-mortar used in heritage buildings (Cappai et al., 2024). King Edward VII (1) School, located in Taiping, Perak, is a prime example of a heritage building affected by salt crystallization. Established during the colonial era, this school has historical and cultural significance, representing the architectural heritage of the region. However, the building faces considerable challenges due to salt-induced damage. The primary objective of this study is to investigate the salt crystallization problems affecting King Edward VII (1) School. The research aims to identify the types and sources of salts present in the building materials, assess the extent of salt-induced damage, and evaluate the effectiveness of various conservation treatments. By conducting laboratory investigations using ion chromatography, this study seeks to provide a comprehensive understanding of the mechanisms of salt crystallization and its impact on the building's structural integrity and aesthetic value. Addressing these issues requires a multidisciplinary approach that combines traditional conservation methods with modern technology.

The primary data collection involved site visits, interviews and samples taken at the selected case study. Samples from the case study were sent to the laboratory for ion chromatography tests to determine their ion compositions and quantify the percentage of soluble salts (Ahmad & Rahman, 2010). Understanding the mechanisms and impact of salt crystallizations on heritage buildings is crucial for developing effective conservation strategies. This research not only contributes to the preservation of King Edward VII (1) School but also offers valuable insights into the conservation of other heritage buildings facing similar challenges. The findings of this study have the potential to inform best practices in heritage conservation, ensuring the longevity, buildings lifespan and integrity of these culturally significant structures.

2. LITERATURE REVIEW

2.1 Theoretical Foundations of Salt Crystallization and Its Impact on Building Materials

Salt crystallization is widely recognized as one of the most significant deterioration mechanisms affecting heritage buildings and porous construction materials. The process occurs when soluble salts dissolve in the presence of moisture, migrate through the pore network of building materials, and subsequently crystallize as water evaporates. The growth of salt crystals within confined pore spaces generates crystallization pressure that can exceed the inherent tensile strength of masonry materials, resulting in cracking, spalling, and progressive material degradation (Li et al., 2024; Ruiz-Agudo et al., 2024). The severity of damage is influenced by several factors, including the type and concentration of salts, pore size distribution, moisture availability, evaporation rates, and environmental conditions.

The deterioration process is typically governed by repeated cycles of dissolution and crystallization. During periods of high moisture availability, soluble salts dissolve and are transported through porous materials. As environmental conditions promote drying, the dissolved salts recrystallize either on the material surface as efflorescence or within the pore structure as sub-florescence. Efflorescence is generally observed as white crystalline deposits on building surfaces and primarily affects the aesthetic appearance of heritage structures. In contrast, sub-florescence occurs beneath the surface and is considerably more destructive because crystallization pressure develops within the pore network, causing internal stresses that lead to cracking, detachment, and material loss (Charola, 2000).

Salt crystallization can produce a range of physical, mechanical, and chemical deterioration processes in heritage buildings. One of the most significant impacts is the development of cracking and spalling when crystallization pressures exceed the mechanical resistance of masonry materials. Repeated dissolution and crystallization cycles can also enlarge pore structures, increase material porosity and facilitate further moisture and salt ingress. In addition, salt contamination may cause discoloration, erosion of decorative features, and chemical alteration of mineral components. Sulphate salts, for example, can react with calcium-bearing materials to form expansive compounds such as gypsum, accelerating the deterioration of plaster, mortar, and masonry surfaces (Cappai et al., 2024). Over time, these combined deterioration mechanisms can significantly reduce both the structural integrity and aesthetic value of heritage buildings.

Recent studies have further demonstrated that environmental conditions play a critical role in controlling salt crystallization behaviour. Jannesarahmadi et al. (2024) reported that porous salt deposits formed on building surfaces can enhance evaporation rates, thereby accelerating salt migration and crystallization cycles. Consequently, understanding the mechanisms of salt crystallization is essential for diagnosing deterioration, selecting appropriate conservation treatments, and developing sustainable preservation strategies for heritage buildings, particularly those located in humid tropical environments where moisture-related deterioration is more pronounced.

2.2 Salt Crystallization in Tropical Heritage Buildings

The deterioration caused by salt crystallization is particularly severe in tropical environments where high humidity, elevated temperatures, and frequent rainfall promote continuous moisture movement within building materials. Unlike buildings located in temperate climates, heritage structures in tropical regions experience prolonged exposure to moisture, resulting in repeated wetting and drying cycles that accelerate salt transport and crystallization processes (Afif-Khouri et al., 2024). Numerous studies have documented salt-related deterioration in heritage buildings located within tropical and subtropical climates. Ahmad and Rahman (2010) reported widespread occurrences of rising damp, efflorescence, and plaster deterioration in heritage buildings in George Town, Penang, where high annual rainfall and elevated relative humidity created favourable conditions for salt migration. Similar observations have been reported in Melaka and other Southeast Asian heritage cities, where chloride, nitrate, and sulphate salts have been identified as major contributors to masonry deterioration.

The present study focuses on Sekolah Kebangsaan King Edward VII (1) in Taiping, Perak. Taiping is often referred to as the “Rain Town” of Malaysia due to its exceptionally high annual rainfall, estimated between 4,000 mm and 4,500 mm annually. The town also experiences average relative humidity levels exceeding 80% throughout the year. These climatic conditions significantly increase moisture accumulation within porous building materials, promoting the dissolution, transport, and recrystallization of soluble salts. Consequently, heritage buildings in Taiping are particularly susceptible to salt-induced deterioration, making the site a suitable case study for investigating the relationship between climate conditions and building degradation.

2.3 Sources and Transport Mechanisms of Soluble Salts

The occurrence of salt crystallization in heritage buildings is closely associated with the presence of soluble salts originating from both natural and anthropogenic sources. Groundwater is widely regarded as one of the primary sources of salt contamination in masonry structures. Through capillary action, groundwater containing dissolved chlorides, nitrates, and sulphates rises through porous materials, transporting salts into walls and foundations. As moisture evaporates, the dissolved salts remain within the material and progressively accumulate over time (Benavente et al., 2022).

Building materials themselves may also contribute to salt formation. Traditional lime mortars, bricks, stone, and cement-based materials often contain naturally occurring mineral compounds that can dissolve under moist conditions. During hydration and ageing processes, these materials may release soluble ions that subsequently migrate through the building fabric. Atmospheric pollution represents another important source of contamination, particularly in urban environments where sulphur dioxide and nitrogen oxides react with atmospheric moisture to produce sulphate and nitrate salts (Charola, 2000).

Environmental factors such as rainfall, condensation, rising damp, groundwater fluctuations, and inadequate drainage systems facilitate the movement of dissolved salts through building materials. Once transported into porous structures, salts undergo repeated cycles of dissolution and crystallization driven by changes in moisture content and environmental conditions. These processes are widely recognized as the primary causes of salt-induced deterioration in historic masonry buildings.

2.4 Conservation Treatments for Salt-Affected Heritage Buildings

The conservation of salt-contaminated heritage buildings requires an integrated approach that addresses both the source of moisture and the accumulation of salt within building materials. Moisture management is generally regarded as the most effective preventive measure because water serves as the primary transport medium for soluble salts. Appropriate interventions include improving site drainage, repairing roofs and gutters, controlling groundwater ingress, and enhancing natural ventilation to reduce internal humidity levels (Cappai et al., 2024).

Desalination treatments are commonly employed to remove existing salt contamination from affected materials. Poulticing is one of the most widely used techniques in heritage conservation and involves applying absorbent materials to extract dissolved salts through capillary action. Depending on the severity of contamination, multiple treatment cycles may be required to achieve satisfactory reductions in salt concentration. Other conservation approaches include sacrificial renders, desalination baths, and electrokinetic desalination systems, which have demonstrated varying degrees of effectiveness in different conservation contexts. The use of breathable and compatible materials is also essential in heritage conservation. Lime-based mortars and plasters are often preferred because they permit moisture evaporation while minimizing the risk of salt entrapment within the building fabric. Regular monitoring of moisture content and salt concentration is necessary to evaluate treatment effectiveness and ensure the long-term preservation of heritage structures.

2.5 Ion Chromatography in Heritage Conservation Studies

Accurate identification and quantification of soluble salts are essential for understanding deterioration mechanisms and selecting appropriate conservation strategies. Ion Chromatography (IC) has become one of the most widely adopted analytical techniques in heritage conservation due to its high sensitivity, accuracy, and ability to simultaneously detect multiple ionic species. The technique is particularly suitable for analysing chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), fluoride (F^-), and nitrite (NO_2^-) ions commonly associated with masonry deterioration. The principle of ion chromatography involves separating ions based on their interaction with a chromatographic column and subsequently measuring their concentration using conductivity detection. Compared with traditional wet chemical methods, IC offers greater precision, lower detection limits, and improved reproducibility, making it particularly useful for assessing low-level salt contamination in heritage materials.

Previous conservation studies have successfully employed ion chromatography to investigate salt deterioration in historic buildings, monuments, archaeological structures, and masonry systems. The technique enables researchers to identify dominant salt species, determine potential contamination sources, and evaluate the effectiveness of desalination treatments. As a result, ion chromatography is widely regarded as a reliable diagnostic tool that supports evidence-based conservation decision-making. In the present study, IC analysis was selected to quantify the concentrations of soluble salts before and after treatment, providing a scientific basis for evaluating the effectiveness of conservation interventions at Sekolah Kebangsaan King Edward VII (1).

2.6 Research Gap

Although salt crystallization has been extensively studied in conservation science, existing research has predominantly focused on historic buildings located in temperate and arid climatic regions, where environmental conditions differ significantly from those found in tropical environments. Previous studies have established that soluble salts such as chlorides, nitrates, and sulphates contribute to the deterioration of masonry materials through mechanisms including efflorescence, sub-florescence, cracking, and spalling (Charola, 2000; Ruiz-Agudo et al., 2024). However, there remains limited research investigating the behaviour of salt crystallization in heritage buildings located within high-rainfall tropical climates, particularly in Malaysia.

Furthermore, while various desalination and conservation treatments have been proposed in the literature, relatively few studies have quantitatively evaluated their effectiveness using laboratory-based analytical techniques such as ion chromatography. Most conservation assessments rely primarily on visual inspections and condition surveys, providing limited information regarding the actual concentration and distribution of soluble salts within building materials. Consequently, there remains a need for scientific investigations that combine laboratory analysis with conservation interventions to better understand salt contamination and treatment performance.

In the Malaysian context, studies examining salt deterioration in heritage buildings have largely focused on general moisture-related defects, with limited attention given to the identification, quantification, and monitoring of specific ionic species responsible for material degradation. Moreover, there is a lack of published research investigating salt crystallization in heritage buildings located in Taiping, Perak, despite the town's exceptionally high annual rainfall and humid environmental conditions, which may significantly influence moisture movement and salt transport within building materials. Therefore, this study addresses these gaps by applying ion chromatography to identify and quantify soluble salts present in the masonry materials of Sekolah Kebangsaan King Edward VII (1), a heritage building located in a tropical high-rainfall environment. The study further evaluates the effectiveness of a poultice-based desalination treatment through a before-and-after laboratory assessment. By integrating scientific analysis with conservation practice, this research contributes empirical evidence to support more effective and sustainable heritage conservation strategies in tropical climates.

3. METHODOLOGY

3.1 Case Study: Sekolah Kebangsaan King Edward VII (1)

Sekolah Kebangsaan King Edward VII (1), established in 1883, is the oldest-standing school in Taiping and started as the first English school in Taiping, originally known as the Central School. Today, it is primary school for Standards 1 to 6. There are three schools in Taiping with the name King Edward VII: two primary schools and one secondary school. These were initially single schools but were separated due to the increasing number of students.

The original school began with 13 students and quickly expanded, leading to the addition of a gymnasium in 1885 and physical education in 1894. By 1895, the school had 159 students, including 28 Malay boys. To accommodate this growth, additional wooden sheds were constructed. In 1901, the Central School was renamed King Edward VII School to celebrate the coronation of King Edward VII. By 1905, the school moved to its current location on the site of the first railway station in the Malay States. The new school building was inaugurated by Sultan Idris of Perak and initially enrolled 434 students.

An ornamental gate with the school's name, installed in 1908 by the Public Works Department, still stands today. Large shade trees planted in 1910 by Mr. P. Moss also remain, now over a century old. The school excelled in sports such as cricket, athletics, and gymnastics. In 1919, the Cadet Corps was introduced, followed by the formation of the first Scout troupe in 1922 and the introduction of rugby in 1923, in which the school won its first tournament against Penang Free School. During World War II, the school was occupied by Japanese forces and used as a garrison base. After the war, students continued their education in different buildings until the school reopened in 1946 with 1004 students. Classes were spread across multiple locations, including Trump Road, Museum Road, and Station Road.

In 1958, due to a growing student population, the school was divided into two primary schools (Primary I and Primary II) and a secondary school. Primary I and Primary II remained in the main building on Station Road, while secondary students moved to the Sheffield Hostel, the former Infant Department, and new buildings on Trunt Road. Today, Sekolah Kebangsaan King Edward VII (1) is stopping number 23 on the Taiping Heritage Trail, highlighting its long and storied history. The school continues to serve the community, maintaining its legacy of excellence in education and sports.

Figure 1: Sekolah Kebangsaan King Edward VII (1) Taiping, Perak

3.2 Procedure of Materials Prepping

This section outlines the systematic steps to prepare materials for assessing salt content in heritage buildings. The observed deterioration patterns and sampling locations identified during the initial site inspection are illustrated in figures 2 to 11.

3.2.1 Initial Site Inspection

An initial site inspection was carried out to systematically evaluate the physical condition of the heritage building and to identify areas affected by salt-related deterioration. The inspection began with a comprehensive visual assessment of the entire structure, including external façades, interior walls, structural elements, and areas in close contact with the ground. The objective was to detect visible indicators of salt crystallization and moisture-related decay such as efflorescence, sub-florescence, spalling, flaking, cracking, surface powdering, discoloration, and plaster detachment. Special attention was given to masonry joints, plastered surfaces, and areas showing previous repair works, as these zones are typically more vulnerable to salt accumulation.

The location, severity, and distribution of observed damage were carefully documented through high-resolution photographic recording, annotated sketches, and systematic field notes. A condition mapping exercise was conducted to categorize deterioration patterns according to their intensity (minor, moderate, or severe) and spatial distribution. Environmental factors influencing salt migration were also assessed, including proximity to drainage systems, surface runoff patterns, foundation levels, and areas exposed to direct rainfall or inadequate ventilation. Moisture-prone zones, particularly lower wall sections (up to 1.5 meters), wall-floor junctions, and areas adjacent to downpipes and roof gutters, were closely examined for signs of rising damp and water infiltration. Where necessary, preliminary moisture readings were taken to support visual observations. These assessments helped establish correlations between moisture presence and salt-related damage.

Based on the inspection findings, representative sampling locations were strategically selected to reflect varying material compositions (plaster, mortar, brick), environmental exposure conditions, and levels of deterioration. A structured sampling plan was subsequently developed, specifying the number of samples required, exact sampling coordinates, depth of material extraction, and non-destructive or minimally invasive collection techniques. Care was taken to ensure that sampling procedures minimized disturbance to the historic fabric while preserving sample integrity for laboratory analysis. This systematic inspection and documentation process provided a reliable foundation for subsequent laboratory investigations and ensured that analytical results could be accurately interpreted in relation to on-site conditions.

Figure 2: Visual Inspection of the Corridors Area

Figure 3: Visual Inspection of the Corridors Area

Figure 4: Visual Inspection of the Corridors Area

Figure 5: Visual Inspection in the Class Area

Figure 6: Visual Inspection of the Corridors Area

Figure 7: Visual Inspection of the Corridors Area

Figure 8: Visual Inspection of the Corridors Area

Figure 9: Visual Inspection of the Corridors Area

Figure 10: Visual Inspection of the Corridors Area

Figure 11: Visual Inspection of the Corridors Area

3.2.2 Sample Preparation

Ensure that all equipment, containers, and solvents used in the sample preparation process are clean and free from contaminants. Use blanks (solvent without sample) to check for any background contamination. Figure 12 shows the equipment used for data preparation

Figure 12: Equipment Used for Data Preparation

Representative samples should be systematically selected and collected from various locations within the heritage building, with particular attention to areas susceptible to salt crystallisation. These include walls, plasters, and other masonry materials. The precise location and condition of each sample should be meticulously documented, a process referred to as mapping. The presence of salt in building materials plays a critical role in influencing their moisture content, as salts possess hygroscopic properties that attract and retain moisture. This process can result in the crystallisation of salt, leading to significant material damage and degradation over time. When collecting samples for ion chromatography (IC) analysis, priority should be given to areas within the building exhibiting elevated moisture content. The moisture assessment activities and the identification of sampling locations are illustrated in figures 13 and 14.

Figure 13: Measure the Moisture Content Before Pointing the Place to take the Materials

Figure 14: Assist by Conservator to Measure the Moisture

Gently clean the surface of the samples to remove any loose debris, dust, or contaminants that could affect the analysis. Use a soft brush or a lint-free cloth to avoid introducing new contaminants. If the samples are solid, such as pieces of plaster or brick, they need to be crushed and ground into a fine powder. Use a mortar and pestle or a mechanical grinder to achieve a consistent and fine powder. This increases the surface area and ensures a more efficient extraction of salts. The sample extraction and material crushing procedures are illustrated in figures 15 to 18.

Figure 15: Crushing the Point Selected to Collect the Sample

Figure 16: Crushing the Point Using the right Technique and Tools

Figure 17: Hold the Sample Using Clean Board to Avoid Sample Fell to the Floor

Figure 18: Collect Specific Amount of Sample and Put in the Zip Bag with Tagging

Accurately weigh a known quantity of the ground sample (typically a 5 grams) using a precise analytical balance. Record the weight for each sample to ensure accurate concentration calculations. Clearly label each sample with relevant information, including the location, date of collection, and any pertinent observations.

Five sampling locations were selected from areas exhibiting visible signs of moisture-related deterioration. Location B106/13A/1 was situated at the lower corridor wall adjacent to an external drainage channel. Location B106/13A/2 was located near a wall-floor junction showing severe efflorescence. Location B106/13A/3 was sampled from an internal classroom wall affected by rising damp. Location B106/13A/4 represented the most severely deteriorated masonry section with extensive plaster detachment and salt deposits. Location B106/13A/5 was collected from a corridor column base exposed to frequent rain splash. The tagging, sample identification, and collection procedures for all sampling locations are illustrated in Figures 19 to 24.

Figure 19: Tagging Process

Figure 20: Tagging Sample 1

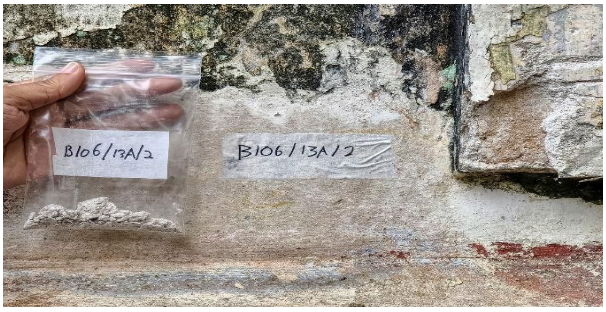

Figure 21: Tagging Sample 2

Figure 22: Tagging Sample 3

Figure 23: Tagging Sample 4

Figure 24: Tagging Sample 5

Prepare a solvent, typically high-purity deionized water (DI water), to extract soluble salts from the collected heritage material samples. The solvent plays a critical role in ensuring the reliability and accuracy of the ion chromatography (IC) analysis, as any background ionic contamination may significantly distort the analytical results. Therefore, laboratory-grade deionized water with a resistivity of at least ≥18 MΩ·cm should be used to minimize the presence of residual ions such as chloride, nitrate, sulphate, or carbonate that could interfere with detection and quantification. Prior to extraction, the deionized water should be tested as a blank sample using the ion chromatography system to verify that it produces negligible or undetectable background ion signals. This blank verification step ensures that any detected ions in subsequent analyses originate solely from the heritage material samples and not from the solvent itself. The solvent must be stored in clean, chemically inert containers such as polypropylene or borosilicate glass bottles that have been pre-rinsed with deionized water to eliminate contamination risks. Strict laboratory handling protocols should be observed during solvent preparation, including the use of powder-free gloves, sterilized measuring cylinders, and contamination-free stirring rods. All containers used for extraction must be thoroughly cleaned and dried prior to use. It is also recommended to prepare the solvent immediately before extraction to reduce the possibility of atmospheric contamination, particularly in humid laboratory environments. The solvent preparation, blank verification, and extraction procedures are illustrated in Figures 25–28.

Figure 25: Organized The Sample Before Proceed to the Next Step

Figure 26: Place Deionized Water into Measured Jug to Easy Put in the Beaker (20 ml)

Figure 27: Place Deionized Water in the Beaker (20 ml)

Figure 28: Deionized Water in the Beaker (20 ml)

Place the weighed samples into clean, inert containers (e.g., plastic or glass beakers). Add an appropriate amount of solvent to each container (10 ml of deionized water per gram of sample). Stir or shake the mixture gently to ensure thorough contact between the solvent and the sample. Allow the samples to soak in the solvent for a sufficient period, usually 24-48 hours, to ensure complete extraction of the salts. After the extraction period, filter the solution to remove any undissolved particles. Use fine filter paper or a membrane filter with an appropriate pore size (e.g., 0.45 micrometres) to ensure that only the liquid containing dissolved salts passes through. Collect the filtrate in a clean container and check the pH level before placing the solution in the clean bottle. The soaking, filtration, pH measurement, and filtrate preservation procedures are illustrated in Figures 29 to 35.

Figure 29: Place Specific Amount of the Sample in the Beaker with Deionized Water (20 ml)

Figure 30: Sample in the Beaker with Deionized Water (20 ml)

Figure 31: Stir the Sample in the Beaker with Deionized Water (20 ml)

Figure 32: Filter the Solution to Remove any Undissolved Particles

Figure 35: Check the Ph Level Before Place the Solution in the Clean Bottle

After filtration, the extracted solutions were transferred into clean, labelled containers for storage and subsequent ion chromatography analysis. Proper labelling is important to avoid sample misidentification and to maintain the integrity and reliability of the laboratory results. The transfer of filtered solutions into storage containers and the sample bottle labelling procedures are illustrated in Figures 36 and 37.

Figure 36: Place Solution into the Clean Bottle

Figure 37: Tagging Sampling Bottle

If immediate analysis is not possible, preserve the filtrate by storing it in clean, airtight containers. Refrigerate the samples if necessary to prevent any changes in their composition. These steps ensure that the samples are prepared accurately and consistently, providing reliable data for the subsequent chromatography analysis. Proper sample preparation is crucial for obtaining accurate and meaningful results that can inform effective conservation strategies. The final sample preservation and storage procedures are illustrated in Figure 38

Figure 38: Preserve The Filtrate by Storing It in Clean, Airtight Containers

3.3 Ion Chromatography Set-Up

This section describes the ion chromatography (IC) system and analytical procedures used to determine the concentration of soluble salts present in the heritage building materials. Ion chromatography was selected because it provides accurate, reliable, and sensitive quantification of ionic species commonly associated with salt deterioration, including chloride, nitrate, sulphate, fluoride, and nitrite ions. The analytical procedures included instrument calibration, preparation of standards and blanks, sample injection, chromatographic separation, data acquisition, and post-analysis verification. The ion chromatography instrument used for the laboratory analysis is illustrated in Figure 39.

Figure 39: Setup Instrument for Ion Chromatography Testing

3.3.1 Calibration of Ion Chromatography Equipment

Calibration of the ion chromatography (IC) system is a critical step to ensure accurate and reliable quantification of ionic species present in the samples. A multi-point calibration curve was established using a series of standard solutions with known concentrations of target ions, including chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), fluoride (F^-), and nitrite (NO_2^-). These standard solutions were prepared at different concentration levels, covering the expected analytical range of the samples to ensure linearity and precision.

Each standard solution was injected into the IC system under controlled operating conditions, and the detector response (peak area or peak height) was recorded. A calibration curve was then generated by plotting detector response against known ion concentrations. Linear regression analysis was performed to obtain the calibration equation and correlation coefficient (R^2), ensuring that the curve demonstrated strong linearity (typically $R^2 \geq 0.99$).

To maintain analytical accuracy, calibration verification was conducted periodically using midrange standard solutions. Any deviation beyond acceptable limits required recalibration of the instrument. This process ensures that detector signals are consistently converted into accurate concentration values and minimizes systematic errors during analysis.

3.3.2 Preparation of Standards and Blanks

Standard solutions for each target ion were prepared using certified reference materials and high-purity deionized water to ensure precision and reproducibility. The prepared standards covered a concentration range that reflects both low-level and high-level salt contamination expected in heritage building materials. Proper dilution techniques were applied using calibrated volumetric flasks and pipettes to ensure concentration accuracy.

Blank samples were prepared using only high-purity deionized water without any analyte. These blanks were analyzed periodically throughout the testing sequence to detect potential background contamination, carryover effects, or instrumental drift. The inclusion of blanks allows for correction of baseline signals and ensures that measured ion concentrations originate exclusively from the sample extracts.

In addition to blanks, quality control (QC) standards were included at regular intervals during the analytical run to verify instrument stability and consistency. This systematic approach to standard and blank preparation enhances the reliability of ion quantification and strengthens the validity of laboratory findings related to salt crystallization in heritage building materials. The certified reference standards and blank solutions used for ion chromatography analysis are illustrated in figure 40.

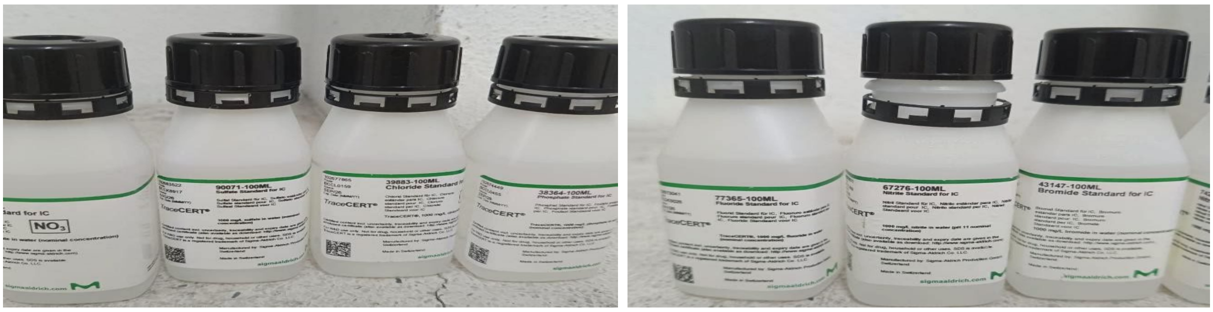

Figure 40: Standards and Blanks Used for Ion Chromatography Testing

3.3.3 Instrument Setup

The ion chromatography (IC) system was carefully configured prior to analysis to ensure optimal separation and accurate detection of target anions. An appropriate analytical column was selected based on the ionic species to be measured (e.g., chloride, nitrate, sulphate, fluoride, and nitrite). The column was inspected, cleaned if necessary, and properly conditioned according to the manufacturer's guidelines to stabilize the stationary phase and ensure consistent performance. The eluent (mobile phase) was prepared using high-purity reagents and deionized water, following the instrument's recommended concentration and pH specifications. The composition and pH of the eluent are critical parameters, as they directly influence ion retention time, peak resolution, and separation efficiency. The flow rate, suppressor settings (if applicable), and column temperature were adjusted according to the operational guidelines to maintain reproducibility and analytical precision. The system was allowed to equilibrate until a stable baseline was achieved before sample injection.

3.3.4 Sample Preparation

Prior to analysis, the filtered extract solutions were examined to ensure suitability for ion chromatography. If ion concentrations exceeded the calibration range, appropriate dilution was performed using high-purity deionized water to bring the concentration within the instrument's optimal detection range. Accurate dilution factors were recorded to allow correct back-calculation of final ion concentrations. To protect the chromatography column and maintain analytical integrity, all samples were filtered through a 0.45 µm membrane filter to remove residual particulate matter. This step prevents column clogging, reduces backpressure, and ensures stable peak shapes during analysis. Samples were handled carefully to avoid contamination and were stored in clean, inert containers prior to injection.

3.3.5 Injection of Sample

Prepared samples, calibration standards, and blank solutions were transferred into clean, airtight vials compatible with the ion chromatography autosampler system. Each vial was clearly labeled to prevent misidentification. When using an autosampler, the injection sequence was programmed systematically to include blanks, standards, quality control samples, and unknown samples in a controlled order. This sequence helps monitor instrument drift and verify analytical consistency throughout the run. For systems requiring manual injection, calibrated and contamination-free syringes were used to inject a precise and consistent sample volume into the instrument. Care was taken to avoid introducing air bubbles or contaminants during the injection process, as these could affect detector response and peak accuracy.

3.3.6 Running the Analysis

The chromatographic analysis was initiated according to the established analytical method. During the run, chromatograms were continuously monitored to ensure proper ion separation, stable baseline conditions, and well-resolved peaks. Retention times were compared against standard references to confirm ion identification. Quality control (QC) samples were included periodically throughout the analytical sequence to verify instrument accuracy, repeatability, and precision

Any abnormal peak shapes, baseline instability, or unexpected retention shifts were investigated immediately to maintain data reliability. Upon completion of the run, data were recorded and prepared for quantitative interpretation using the previously established calibration curve. The ion chromatography analytical run and data acquisition process are illustrated in Figure 41.

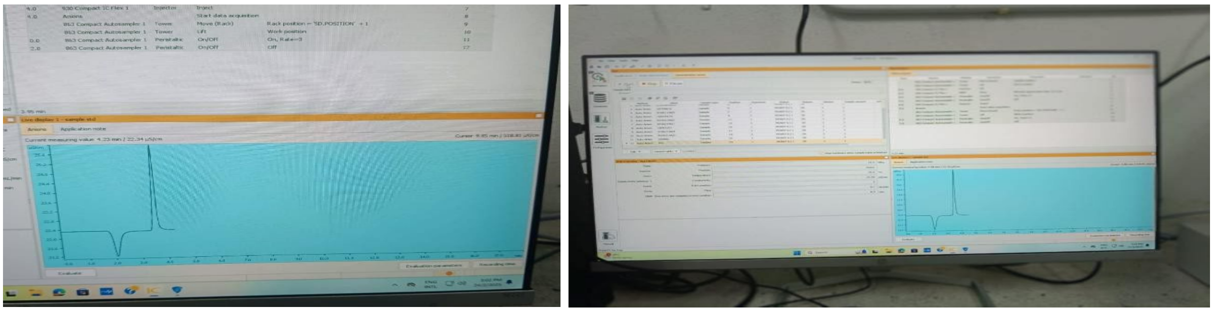

Figure 41: Running the Sample for Ion Chromatography Testing

3.3.7 Data Collection and Analysis

Upon completion of the chromatographic run, the resulting chromatograms were carefully examined to identify ion peaks based on their characteristic retention times. Each detected peak was compared with the retention times obtained from the calibration standards to ensure accurate ion identification. Peak areas were integrated using the instrument's data processing software to obtain quantitative measurements of detector response.

The established calibration curve was then applied to convert peak areas into corresponding ion concentrations. Where sample dilution was performed, appropriate correction factors were applied to calculate the actual concentrations in the original extract. Data quality was assessed by evaluating baseline stability, peak symmetry, signal-to-noise ratio, and resolution between adjacent peaks. Only well-resolved peaks with stable baselines were considered valid for quantification.

Quality control standards and blank samples were also reviewed to confirm analytical precision and detect any background contamination or instrumental drift. Replicate analyses, where applicable, were used to verify repeatability and ensure consistency of results. This systematic data validation process enhances the reliability of ion concentration measurements and supports accurate interpretation of salt contamination levels in heritage building materials.

3.4 Salt Treatment Procedure

A poultice-based desalination treatment was applied to reduce the concentration of soluble salts present within the masonry materials of Sekolah Kebangsaan King Edward VII (1). Prior to treatment, all affected surfaces were carefully inspected and documented. Loose plaster, dust, surface contaminants, and visible salt deposits were gently removed using non-metallic brushes to avoid damaging the historic fabric. The poultice mixture was prepared using absorbent clay and cellulose fibre materials combined with deionized water to form a workable paste. The use of deionized water ensured that no additional salts or contaminants were introduced during the treatment process. The prepared poultice was applied uniformly to affected masonry and plaster surfaces at an approximate thickness of 15–20 mm, ensuring complete coverage of areas exhibiting visible signs of salt contamination, efflorescence, and moisture-related deterioration.

Once applied, the poultice was left in place for approximately 48 hours to allow capillary extraction of soluble salts from the pore structure of the building materials. During this period, dissolved salts migrated from the masonry into the poultice as moisture moved through the absorbent layer. After the drying period, the poultice was carefully removed and visually examined for evidence of extracted salts. To maximize salt removal efficiency, the treatment process was repeated for three consecutive cycles. Following completion of the desalination treatment, new material samples were collected from the same locations as the pre-treatment investigation. These samples were subjected to ion chromatography (IC) analysis to determine the remaining concentrations of soluble salts and evaluate the effectiveness of the treatment. The comparison between pre-treatment and post-treatment salt concentrations provided a quantitative assessment of the desalination process and its suitability as a conservation intervention for heritage buildings affected by salt crystallization.

4. RESULTS AND DISCUSSION

The ion chromatography results presented in Table 3 indicate a significant accumulation of soluble salts within the masonry materials of Sekolah Kebangsaan King Edward VII (1) prior to treatment. The total salt concentration recorded was 36.204%, confirming substantial salt contamination throughout the investigated areas. Among the detected ions, nitrate was the dominant salt species, with a cumulative concentration of 20.294%, followed by sulphate (6.520%) and chloride (3.744%). The highest level of contamination was observed in sample B106/13A/4, which recorded a total salt concentration of 15.055%, comprising elevated concentrations of nitrate (8.7033%), chloride (3.8366%), and sulphate (3.0726%). Similarly, sample B106/13A/2 exhibited a high total concentration of 11.079%, largely attributed to nitrate accumulation (7.8649%). The predominance of nitrate, chloride, and sulphate suggests that moisture movement, rising damp, and environmental exposure are the principal mechanisms contributing to salt transport and accumulation within the building fabric.

Table 3: Raw Data of the Concentrations in Percentages of Materials

Ident	Pressure (MPa)	Temp. (°C)	Fluoride (%)	Chloride (%)	Nitrite (%)	Bromide (%)	Nitrate (%)	Phosphate (%)	Sulphate (%)	Total
B106/13A/1	13.34	27.20	0.0124%	0.8824%	0.0031%	-	0.5308%	-	0.4489%	1.8776
B106/13A/2	13.23	27.60	0.0075%	1.2633%	0.0114%	-	7.8649%	-	1.9315%	11.079
B106/13A/3	13.18	27.70	0.0078%	0.4337%	0.0049%	-	0.1418%	-	0.1558%	0.7440
B106/13A/4	13.46	27.10	0.0088%	3.8366%	0.320%	0.0017%	8.7033%	-	3.0726%	15.055
B106/13A/5	13.29	27.40	0.0112%	0.8278%	0.00497%	-	2.9532%	-	0.9116%	7.449
TOTAL (%) BEFORE TREATMENT										**36.204**

The elevated nitrate concentrations are of particular concern as these salts are highly soluble and readily migrate through porous materials, promoting efflorescence and indicating persistent moisture ingress. Chloride contamination presents additional risks due to its potential to accelerate corrosion of embedded metallic elements, while sulphate salts may react with calcium-based masonry materials, forming expansive compounds that contribute to cracking, spalling, and material deterioration. The heterogeneous distribution of salts observed among the samples indicates localized moisture conditions and varying exposure levels throughout the building.

Following the implementation of the poultice-based desalination treatment, the ion chromatography results presented in Table 4 demonstrate a substantial reduction in overall salt concentration. The cumulative salt content decreased from 36.204% before treatment to 0.23734% after treatment, representing a reduction of approximately 99.3%. Significant reductions were observed across all measured ions. Nitrate and bromide were completely removed from all samples, while fluoride and nitrite concentrations were reduced to negligible levels. Chloride concentrations decreased considerably, ranging from 0.01002% to 0.03986%, while sulphate concentrations were reduced to between 0.01004% and 0.03780%.

Table 4: Raw Data of the Ion Chromatography Materials in Parts Per Million (ppm) in Percentage

Ident	Pressure (MPa)	Temp. (°C)	Fluoride (%)	Chloride (%)	Nitrite (%)	Bromide (%)	Nitrate (%)	Phosphate (%)	Sulphate (%)	Total
B106/13A/1	13.85	27.50	0.00121	0.01002	0.0007	-	-	-	0.01523	0.02716
B106/13A/2	13.74	27.40	0.00007	0.02850	0.00022	-	-	-	0.03780	0.06659
B106/13A/3	13.85	27.20	0.00004	0.02459	0.00001	-	-	-	0.01004	0.03468
B106/13A/4	14.02	27.10	0.00001	0.02426	0.00003	-	-	-	0.01199	0.03656
B106/13A/5	13.68	27.70	0.00003	0.03986	0.00002	-	-	-	0.03244	0.07235
TOTAL (%) BEFORE TREATMENT										**0.23734**

The effectiveness of the treatment is particularly evident in sample B106/13A/4, where the total concentration decreased from 15.055% before treatment to 0.03656% after treatment. Similar reductions were recorded in all other samples, confirming the effectiveness of the desalination process in extracting soluble salts from the masonry materials. Although small quantities of chloride and sulphate remained after treatment, their concentrations were substantially lower than those recorded prior to intervention.

The comparison between pre-treatment and post-treatment results confirms that the poultice-based desalination treatment was highly effective in reducing salt contamination within the heritage building materials. The significant reduction in nitrate, chloride, and sulphate concentrations indicates a corresponding decrease in the risk of efflorescence, crystallization pressure, moisture retention, and salt-induced deterioration. Nevertheless, the continued presence of residual chloride and sulphate salts highlights the importance of long-term monitoring, moisture control measures, and periodic maintenance to prevent future salt accumulation. These findings demonstrate the value of integrating laboratory-based chromatography analysis with conservation treatments to support evidence-based heritage conservation practices in tropical environments.

To evaluate the effectiveness of the poultice-based desalination treatment, a comparison of the total salt concentrations before and after treatment was conducted for each sampling location. The results are presented in Table 5.

Table 5: Comparison of Total Salt Concentration Before and After Treatment

Sample ID	Before Treatment (%)	After Treatment (%)
B106/13A/1	1.8776	0.02716
B106/13A/2	11.079	0.06659
B106/13A/3	0.7440	0.03468
B106/13A/4	15.055	0.03656
B106/13A/5	7.449	0.07235

The comparison demonstrates a substantial reduction in total salt concentration across all sampling locations following the poultice-based desalination treatment. Prior to treatment, the highest contamination level was recorded at sample B106/13A/4 (15.055%), followed by B106/13A/2 (11.079%) and B106/13A/5 (7.449%). After treatment, all samples exhibited significant reductions in salt concentration, with residual concentrations ranging from only 0.02716% to 0.07235%. Sample B106/13A/4 recorded the greatest improvement, showing a reduction of approximately 99.76%, while sample B106/13A/3 exhibited the lowest reduction percentage of 95.34%, although its initial salt concentration was comparatively low. Overall, the total salt concentration decreased from 36.204% before treatment to 0.23734% after treatment, representing an overall reduction of approximately 99.34%.

The substantial decrease in soluble salt content confirms the effectiveness of the poultice-based desalination treatment in extracting harmful salts from the masonry materials. The reduction of nitrate, chloride, and sulphate salts is particularly important because these ions are closely associated with efflorescence, moisture retention, crystallization pressure, cracking, and material deterioration. These findings are consistent with previous conservation studies that reported the effectiveness of poultice treatments in reducing salt contamination within historic masonry structures (Cappai et al., 2024).

It should be noted that the present study employed a before-and-after assessment approach using samples collected from the same affected locations. A separate untreated control sample was not included due to conservation constraints and the need to minimise intervention on the historic fabric. Consequently, treatment effectiveness was evaluated through comparative ion concentration measurements obtained before and after the desalination treatment.

Due to the limited sample size (n = 5), inferential statistical analysis was not performed in this study. The effectiveness of the poultice-based desalination treatment was therefore evaluated through descriptive comparison of ion concentrations before and after treatment. While the observed reductions indicate a substantial decrease in soluble salt contamination, future studies involving larger sample sizes and multiple case study buildings should incorporate statistical analyses, such as paired t-tests or non-parametric tests, to determine the significance and reproducibility of treatment effects.

5. RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed to mitigate salt-induced deterioration and enhance the long-term preservation of heritage buildings in humid tropical environments. The results demonstrate that moisture ingress is the primary factor facilitating the transport and accumulation of soluble salts within masonry materials. Therefore, effective moisture management should be prioritised through the improvement of drainage systems, regular maintenance of roofs and gutters, and the installation of appropriate surface water diversion measures to minimise rising damp and water penetration. The use of breathable and compatible conservation materials is strongly recommended. Lime-based mortars and plasters should be preferred over impermeable cement-based materials, as they allow moisture vapour to escape while reducing the risk of salt accumulation within the building fabric. Such materials also maintain compatibility with historic masonry and contribute to the long-term durability of conservation interventions.

For buildings already affected by salt contamination, desalination treatments such as poulticing should be implemented to extract soluble salts from masonry materials. The findings of this study demonstrate that poultice-based desalination can significantly reduce salt concentrations and minimise the risks associated with efflorescence, crystallization pressure, cracking, and material deterioration. However, treatment effectiveness should be periodically evaluated through laboratory analysis and condition monitoring to ensure long-term performance. Regular monitoring programmes should be established to assess moisture content, environmental conditions, and salt concentrations within heritage structures. The integration of diagnostic tools such as moisture meters, environmental sensors, and ion chromatography analysis can support evidence-based decision-making and facilitate early intervention before severe deterioration occurs.

In the context of climate change, conservation strategies should adopt a climate-responsive approach that considers increasing rainfall intensity, prolonged humidity, and changing environmental conditions. Improving building ventilation, enhancing drainage infrastructure, and implementing sustainable maintenance practices can strengthen the resilience of heritage buildings against moisture-related deterioration. By integrating scientific analysis with preventive conservation measures, heritage managers can reduce future maintenance requirements, preserve cultural significance, and support the sustainable conservation of historic buildings.

6. CONCLUSION

This study investigated the occurrence and impact of salt crystallization in the heritage building of Sekolah Kebangsaan King Edward VII (1), Taiping, Perak, through laboratory analysis using ion chromatography. The findings confirmed the presence of significant concentrations of soluble salts, particularly nitrate, chloride, and sulphate ions, which contribute to deterioration mechanisms such as efflorescence, cracking, spalling, and material degradation. The results further demonstrated the strong relationship between moisture ingress and salt accumulation, highlighting the influence of Taiping’s high rainfall and humid tropical climate on the deterioration of historic masonry materials. The study also evaluated the effectiveness of a poultice-based desalination treatment through a comparative assessment of salt concentrations before and after treatment. The ion chromatography results indicated a substantial reduction in total salt content, from 36.204% before treatment to 0.23734% after treatment, representing an overall reduction of approximately 99.34%. These findings demonstrate that desalination treatment can effectively reduce soluble salt contamination and contribute to the mitigation of salt-related deterioration in heritage buildings. The research contributes to the growing body of knowledge on climate-related deterioration of heritage structures in tropical environments by providing scientific evidence on the relationship between moisture, salt crystallization, and material degradation. The integration of laboratory-based diagnostics with conservation treatment evaluation offers a practical framework for evidence-based heritage conservation and supports the development of more sustainable maintenance strategies for historic buildings.

However, this study was limited to a single case study building and a relatively small number of samples. Therefore, the findings should be interpreted within the context of the site investigated and may not be directly generalised to all heritage buildings. Future research should incorporate larger sample sizes, multiple case studies, long-term monitoring programmes, and untreated control samples to further validate treatment effectiveness and improve understanding of salt crystallization processes under varying environmental conditions. Overall, the study demonstrates that effective moisture management, regular monitoring, and scientifically informed desalination treatments are essential components of sustainable heritage conservation. By addressing salt-induced deterioration at its source, conservation practitioners can enhance the resilience of heritage buildings against climate-related impacts while preserving their historical, cultural, and architectural significance for future generations.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to NTQT Sdn. Bhd., Melaka, Malaysia, for providing financial support, technical assistance, and access to the case study site that made this research possible. Special appreciation is extended to Mr. Shaari Mat Saod, Registered Conservator of the Department of National Heritage Malaysia and Director of NTQT Sdn. Bhd., for his generous funding, professional guidance, and continuous support throughout the implementation of this study. The authors also wish to acknowledge Dr. Mohd Jaki Mamat, Senior Lecturer at the School of Housing, Building and Planning, Universiti Sains Malaysia, for his invaluable academic guidance, constructive comments, expert supervision, and scholarly insights that significantly contributed to the development and completion of this research. Appreciation is further extended to the Department of Building Surveying, Faculty of Built Environment, Universiti Malaya, for providing academic support and research facilities throughout the study. The authors are also grateful to all individuals involved in the field investigation, sample collection, laboratory testing, and data analysis undertaken at Sekolah Kebangsaan King Edward VII (1), Taiping, Perak. Finally, the authors acknowledge the contributions of all parties whose support, expertise, and collaboration have contributed to the successful completion of this research on salt crystallization and heritage building conservation.

7. REFERENCES

Afif-Khouri, E., Lozano-Martínez, A., López de Rego, J. I., López-Gallego, B., & Forjan-Castro, R. (2024). Capillary rise of soluble salts and its effect on the degradation of calcareous material used in historical monuments. In *REHABEND 2024 Proceedings* (pp. 448–454). https://doi.org/10.20944/preprints202409.2304.v1

Ahmad, A. G., & Rahman, H. F. A. (2010). Treatment of salt attack and rising damp in heritage buildings in Penang, Malaysia. *Journal of Construction in Developing Countries, 15*(1), 93–113.

ASTM International. (2011). *ASTM D4327-11: Standard test method for anions in water by chemically suppressed ion chromatography*. ASTM International.

Benavente, D., Pla, C., Gil-Oncina, S., Ruiz, M. C., Blanco-Quintero, I. F., Huesca-Tortosa, J. A., Spairani-Berrio, Y., & Sanchez-Moral, S. (2022). Monitoreo de la calidad del aire para la conservación preventiva del patrimonio construido deteriorado por cristalización de la sal. *Geosciences, 12*(9), 1–16.

Cappai, M., Casti, M., & Pia, G. (2024). Salt crystallization in limestone: Materials decay and chemomechanical approach. *Materials, 17*(16), Article 3986. https://doi.org/10.3390/ma17163986

Charola, A. E. (2000). Salts in the deterioration of porous materials: An overview. *Journal of the American Institute for Conservation, 39*(3), 327–343.

European Committee for Standardization (CEN). (2014). *EN 16455:2014 conservation of cultural heritage—Extraction and determination of soluble salts in natural stone and related materials*. CEN.

El Mansoury, M. E. T. E. M. (2024). Sustainable conservation of heritage buildings. *International Journal of Advanced Research on Planning and Sustainable Development, 6*(1), 14–30. https://doi.org/10.21608/ijarpsd.2024.274887.1004

Godts, S., Steiger, M., Orr, S. A., Stahlbuhk, A., Desarnaud, J., De Clercq, H., Cnudde, V., & De Kock, T. (2022). Modeling salt behavior with ECOS/RUNSALT: Terminology, methodology, limitations, and solutions. *Heritage, 5*(4), 3648–3663. https://doi.org/10.3390/heritage5040190

Idris, M. L., Abdul Rahman, A. R., Ishiyaku, B., & Alias, A. R. (2024). Preserving heritage buildings with building information modelling: Addressing the challenges and opportunities. *Smart and Green Materials, 1*(1), 33–43. https://doi.org/10.70028/sgm.v1i1.5

Jannesarahmadi, S., Aminzadeh, M., Helmig, R., Or, D., & Shokri, N. (2024). Quantifying salt crystallization impact on evaporation dynamics from porous surfaces. *Geophysical Research Letters, 51*(22), 1–10. https://doi.org/10.1029/2024GL111080

Khan, M. A., & Guleria, D. S. (2024). A bibliometric study analyzing research contributions and patterns in heritage conservation. *Educational Administration: Theory and Practice, 30*(4), 5870–5880. https://doi.org/10.53555/kuey.v30i4.2307

Li, Q., Wang, Z., Guo, H., Zhao, J., Luo, H., & Huang, X. (2024). A perspective view of salt crystallization from solution in porous media: Morphology, mechanism, and salt efflorescence. *Scientific Reports, 14*(1), 1–12. https://doi.org/10.1038/s41598-024-74645-5

Ruiz-Agudo, E., Ibañez-Velasco, A., Ruiz-Agudo, C., Bonilla-Correa, S., Elert, K., & Rodríguez-Navarro, C. (2024). Damage of porous building stone by sodium carbonate crystallization and the effect of crystallization modifiers. *Construction and Building Materials, 411*, Article 134591. https://doi.org/10.1016/j.conbuildmat.2023.134591