

REVIEW

DEGRADATION OF PIGMENTS IN PAINT LAYERS: CHALLENGES AND SOLUTIONS FOR CULTURAL HERITAGE CONSERVATION

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Abstract. Pigment degradation in frescoes is a major challenge in cultural heritage conservation, driven by environmental stressors, material incompatibility, and past restoration interventions. This review synthesizes recent and classical studies to provide a comprehensive overview of the chemical and physical mechanisms driving pigment alteration, with particular focus on emblematic transformations such as azurite to malachite and cinnabar to metacinnabar. Both traditional and modern diagnostic techniques (optical microscopy, SEM-EDS, Raman spectroscopy, FTIR, and XRD) are compared in terms of their capacity to reveal deterioration processes and guide conservation decisions. Preventive strategies, including environmental monitoring and microclimate control, are assessed for their effectiveness in slowing deterioration. The novelty of this work lies in identifying critical research gaps, such as the absence of standardized salt-monitoring protocols and the limited integration of interdisciplinary approaches. Beyond advancing research, the review emphasizes the pedagogical value of these insights for training conservators and integrating conservation science into art and design education. By bridging material science, archaeometry, and practical restoration, the study highlights innovative eco-friendly solutions, such as biocompounds, and offers a forward-looking framework for safeguarding mural paintings.

Keywords: Fresco paintings; pigment degradation; environmental stressors; preventive conservation; interdisciplinary approaches.

1. INTRODUCTION

Fresco painting has enjoyed a distinguished status throughout history and represents one of the most durable and remarkable forms of artistic expression, transforming the architectural surfaces of historic monuments into important visual records of the past. Its artistic and documentary value, together with the extensive mural heritage preserved in many regions of the world, makes conserving fresco paintings a major concern for interdisciplinary cultural heritage research.

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From a material perspective, the fresco technique is based on the process of lime carbonation. Unlike many other painting techniques, in which pigments are fixed by means of organic binders such as oil, egg, or wax, in traditional fresco painting the pigments are applied onto fresh plaster and become integrated into the mineral matrix as the plaster dries and carbonation takes place. This integration of the pictorial layer into the mineral substrate contributes to the durability of fresco paintings, but does not protect them from the alteration and degradation processes that develop over time.

Despite the mineral system's remarkable resistance, the constituent materials of fresco paintings undergo complex, interrelated physical, chemical, and biological degradation processes. These processes are influenced both by the intrinsic characteristics of the materials (including the nature and composition of the pigments, the porosity and structure of the plaster, and the interfaces between the different layers) and by environmental conditions. Fluctuations in temperature and relative humidity, water transfer and migration, light exposure, particulate deposition, atmospheric pollutants, and microbial activity can progressively modify the physicochemical properties of the materials and accelerate degradation processes.

Pigment degradation may involve mineralogical and chemical transformations that affect both material stability and the painting's chromatic appearance. Transformations such as azurite alteration, changes involving lead-based compounds, or sulphation processes associated with exposure to atmospheric pollutants illustrate the complexity of degradation mechanisms and the need to correlate visual observations with analytical investigations. In this context, identifying alteration phases and understanding the mechanisms responsible for their formation are essential steps toward an accurate diagnosis of the conservation condition.

The conservation of fresco paintings is therefore an interdisciplinary field at the intersection of art history, conservation-restoration, chemistry, materials science, and environmental science. The selection and application of conservation treatments must take into consideration not only the current condition of the material, but also the compatibility of intervention materials, their potential secondary effects, and the long-term evolution of the system under existing environmental conditions. Consequently, the development of minimally invasive and, whenever possible, non-destructive investigation methods, together with modern conservation strategies based on a better understanding of degradation mechanisms, has become an important direction of contemporary research.

The investigation of the environment in which mural paintings are preserved is also of fundamental importance. The assessment of degradation processes cannot be separated from the characterization of microclimatic conditions and the identification of factors governing moisture transfer, salt crystallization, chemical reactions, and biological growth. Therefore, contemporary research should address not only changes within the pictorial material, but also the relationship between these changes and environmental conditions, so analytical results can be translated into effective strategies for monitoring, preventive conservation, and intervention.

This review analyses scientific research published primarily in journals indexed in the Web of Science, complemented by other relevant bibliographic sources from archaeometry, analytical chemistry, materials science, and the conservation and restoration of cultural heritage. The review aims to provide an integrated perspective on the factors influencing the degradation of pigments and the constituent materials of fresco paintings, as well as on the methods employed to investigate these processes.

Accordingly, the review examines the main categories of factors influencing pigment degradation, the impact of foreign materials and degradation agents on mural paintings, the specific degradation mechanisms affecting pigments used in fresco painting, and methods for characterizing the degradation of heritage materials. For the analytical methods, their

fundamental principles, advantages, limitations, and applicability to the assessment of degradation processes in fresco materials are discussed. Finally, several representative practical degradation studies are presented and discussed, with particular emphasis on how analytical results can contribute to diagnosis, environmental monitoring, and the development of preventive conservation and restoration strategies.

2. TECHNIQUE OF FRESCO PAINTING

The *pittura murale al fresco* technique involves painting on freshly applied wet plaster and comprises several essential layers: the *rinzaffo*, the base layer applied directly onto the masonry; the *arriccio*, an intermediate layer; and the *intonaco*, the final, uppermost layer on which pigments are applied (Fig. 1). The success of the fresco largely depends on the receptivity of the *intonaco* layer [1-11].

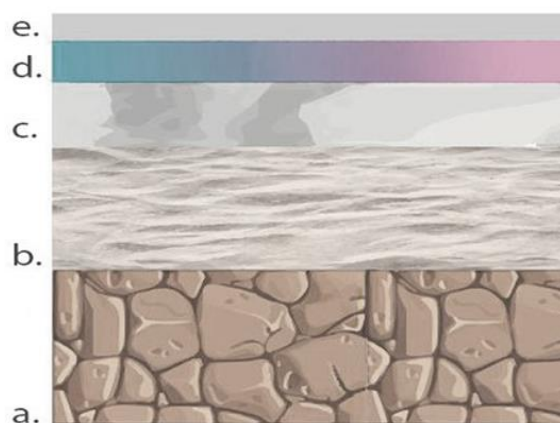


Figure 1. Structural elements of a mural painted in the al fresco technique: a – substrate (masonry); b – arriccio: 20–30 mm; c – intonaco: 5–15 mm; d – pictorial layer applied using the al fresco technique: 2–5 mm; e – calcium carbonate surface film: 1–3 mm.

Over time, lime mortar absorbs carbon dioxide from the atmosphere, and calcium hydroxide gradually transforms into calcium carbonate through carbonation. This natural process enhances the plaster's resistance to water exposure. The resulting calcium carbonate crystals not only ensure strong adhesion to the substrate and internal cohesion but also contribute to the formation of a protective surface film [9-11].

3. FACTORS INFLUENCING PIGMENT DEGRADATION

Maintaining thermal equilibrium between the ambient air and heritage objects—as well as between different zones of the same space—is essential to prevent material degradation. The primary threats are physicochemical factors, particularly humidity and temperature. Physical processes include dissolution, crystallization, and efflorescence, while chemical processes include oxidation, acid-base reactions, sulfation, chlorination, and others [12].

One example is the phase transition between mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and thenardite (Na_2SO_4). Mirabilite is sodium sulfate decahydrate, with a solubility of ~ 34 g/L at 20°C . Thenardite is the anhydrous form, a white hygroscopic powder, with a solubility of ~ 47 g/L. The transformation mirabilite $\leftrightarrow$ thenardite involves a dehydration/hydration process:

dehydration (mirabilite $\rightarrow$ thenardite) occurs above 32–35 °C and at relative humidity levels below 50%, while hydration (thenardite $\rightarrow$ mirabilite) occurs at temperatures below 25–30 °C in the presence of moisture (liquid or vapor). The rehydration of thenardite into mirabilite leads to a volume expansion of up to ~300%, generating internal stresses that result in cracking, exfoliation, and detachment. These processes are reversible and cyclical under variable moisture conditions [13–17]. However, the physical damage caused by volumetric expansion—such as cracking and exfoliation—is irreversible; only the phase transformation between the two forms of sodium sulfate is reversible, depending on temperature and humidity.

These phenomena can be identified by analyzing exfoliation or efflorescence residues using characterization techniques such as optical microscopy (OM), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), and X-ray diffraction (XRD) [18].

Preventive conservation and ongoing monitoring of restored artworks are critical to preserving heritage objects. Microclimate control and proper material handling help reduce physical and chemical degradation and slow the natural aging process. Scientific studies, along with on-site observations of heritage monuments, reveal that economic and industrial development has significantly contributed to the release of atmospheric pollutants, primarily from the combustion of fossil fuels [19, 20].

Among all degradation agents, humidity is identified as the primary cause of fresco deterioration. Water present in the structural components of monuments contributes to a wide array of degradation mechanisms—physical, chemical, and biological [21, 22]. Cyclic wetting and drying result in expansion/contraction effects, promoting micro-cracking and paint detachment. Additionally, moisture facilitates the migration of salts from the masonry into the fresco layer.

Physically, moisture can cause swelling, wrinkling, softening, and loss of adhesion in natural binders. For example, protein-based adhesives (such as animal glue) are water-soluble and can be destabilized, re-emulsified, and lose their cohesive properties under high humidity [23]. Increased humidity also promotes biological degradation by encouraging mold and fungal growth, as well as the penetration of plant roots into cracks and fissures. Artworks, particularly historical ones, are often executed on porous or organic substrates, making them highly susceptible to colonization by microorganisms such as bacteria, fungi, and algae. These organisms can severely compromise the physical structure, aesthetic appearance, and chemical composition of the pictorial layer, often resulting in irreversible deterioration.

Microbial degradation occurs through the production of organic and inorganic acids (such as oxalic, acetic, or sulfuric acid), which can solubilize certain pigments (e.g., iron oxides or chromium green), attack organic binders like gelatin, casein, or animal glue, and even decompose calcium carbonate [24, 25]. Microorganisms often form biofilms that trap dust particles and moisture, while also imparting color to the surface. For instance, microbial pigments such as melanins, carotenoids, and chlorophylls can cause darkening and significantly alter the aesthetics of the painted surface [26–29]. Certain bacterial species, such as those from the *Bacillus* or *Pseudomonas* genera, can contribute to the decohesion and cracking of pictorial layers by inducing the formation of oxalates and calcium carbonate within the substrate [30].

Several well-documented examples of biodeterioration exist: the frescoes of the Sistine Chapel were historically affected by fungi and airborne bacteria under humid conditions; the prehistoric cave paintings of Lascaux (France) suffered contamination by pigmented fungi such as *Fusarium* and *Ochroconis* following increased public access.

Preventive measures include strict microclimate control (maintaining stable temperature, relative humidity below 60%, and ensuring proper ventilation); enzymatic

cleaning and bioremediation using beneficial bacteria (e.g., *Pseudomonas stutzeri*) capable of degrading biofilms without harming the paint layer; and the localized application of selective biocides (such as thymol or isothiazolinones), although such treatments carry potential risks of altering original materials [31].

Increased humidity promotes biological degradation by encouraging mold and fungal growth, as well as the penetration of plant roots into cracks and fissures. The action of water on frescoes manifests in three primary forms: capillary moisture, infiltration moisture, and condensation moisture [31-37].

Color alterations, exfoliations, and efflorescence veils caused by capillary water migration originate from water movement within the structure [37].

Water rises through capillaries against gravity, sometimes reaching several meters in height. Evaporation occurs when the water vapor pressure is lower than the saturation value, determined by ambient temperature and relative humidity. As water evaporates, the ions remain on the pore surfaces and crystallize, creating intense micro-tensions that can lead to material detachment.

Using physical laws, the internal stresses caused by structural transformations involving volume changes can be estimated. For instance, in the transformation of thenardite into mirabilite—which crystallizes within the pores or micro-spaces between calcite grains in the paint layer—the molar volume of thenardite allows the calculation of internal stress values ranging from approximately 0.1 to 0.5 MPa under typical ambient conditions. These stress levels may exceed the fracture threshold of the paint layer [32].

Salt crystallization on monument walls with murals can be particularly destructive. Condensation forms when the wall surface temperature drops below that of the indoor air. This typically occurs when warm, humid air suddenly enters, such as when doors open, and condensation droplets form on cold wall surfaces [33].

The cohesion of the pictorial layer influences its degradation. The greater the cohesion between the particles of the pictorial layer, the fewer compaction defects develop, and the fewer lacunae appear [15]. Over time, the paint deteriorates through continuous loss of the layer, gradually reducing visibility (Fig. 2).

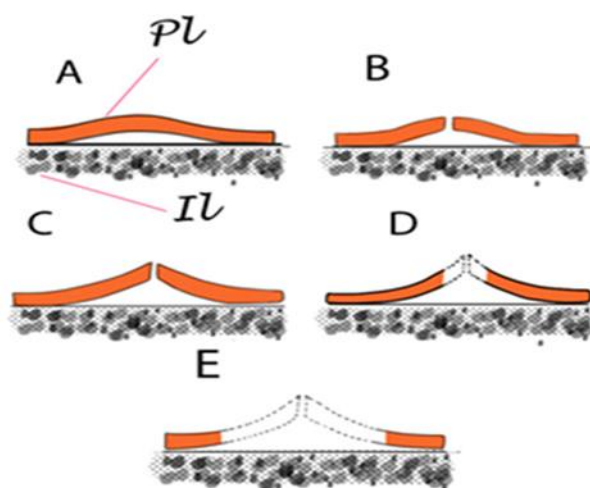


Figure 2. Mechanism of exfoliation: A – swelling of the pictorial layer and initiation of cracks; B, C – propagation and expansion of cracks; D, E – detachment and subsequent loss of the pictorial layer surrounding the initial fissure. Pl – pictorial layer; Il – intonaco layer.

The cohesion of the color layer refers to the internal binding between pigment particles, maintained by calcium carbonate. When the calcium carbonate begins to degrade, the bonds between pigment particles weaken, resulting in a loss of cohesion (Figure 3: A–E) [33-36]. As cohesion is lost, the pictorial layer becomes powdery, porous, and permeable,

making it vulnerable to abrasive actions. In advanced stages, this pulverulence gives the paint a visibly eroded appearance. If left untreated, the degradation process may progress until the painting is lost particle by particle [37].

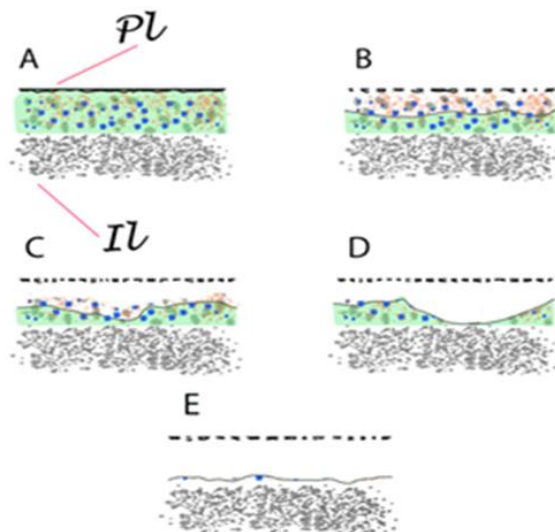


Figure 3. Mechanism of cohesion loss in the pictorial layer: A – initial thickness of the pictorial layer; B, C, D – progressive disintegration as cohesion between pigment particles weakens; E – complete disappearance of the image as material is lost. PL – pictorial layer; IL – intonaco layer.

Persistent humidity significantly affects the integrity of the paint layer, causing salt migration and recrystallization (Fig.4: A–C). Salts in masonry exhibit different solubilities: A – Soluble salts are transported by water to the mural surface, forming visible crystallizations or deposits; B – Partially soluble salts can crystallize beneath the paint layer or within its pores, weakening adhesion and cohesion; and C – Insoluble salts remain embedded without causing significant damage [37-43].

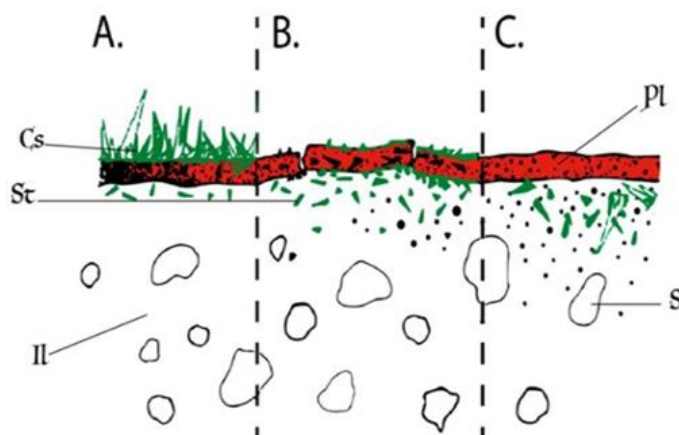


Figure 4. Influence of salt solubility in water on fresco stability: A – highly soluble; B – slightly soluble; C – almost insoluble. Cs – crystallized salts; Pl – pictorial layer; Il – intonaco mortar layer; S – sand; St – salts within the intonaco.

Surface evaporation leads to efflorescences, while evaporation within the pores results in cryptoflorescences [36-38]. Efflorescences also degrade calcium carbonate, weakening the pigment-binder network and causing cohesion loss. Cryptoflorescences can push the pictorial layer outward and cause loss of adhesion between the paint and its substrate [39-48]. Large temperature fluctuations can trigger rapid water evaporation, salt crystallization, and material

contraction. Freeze–thaw cycles further exacerbate damage by fracturing plaster layers and causing color layer decohesion, particularly in exterior murals.

4. THE IMPACT OF FOREIGN MATERIALS AND DEGRADATION AGENTS ON MURAL PAINTINGS

The accumulation of foreign materials on the painting's surface forms an independent layer that reacts differently from the color layer to environmental conditions and degradation agents. This layer may expand and contract at different rates, creating tensions within the color structure. When these deposits detach, they can carry away fine pigment particles, further contributing to the deterioration of the painting [49].

The loss of adhesion and cohesion in the color layer can also be caused by atmospheric pollution. Carbon dioxide from the atmosphere attacks calcium carbonate, leading to pulverization. Sulfur dioxide from pollutants causes sulfation of the pictorial layer, resulting in calcium sulfate (gypsum crystals), which severely reduces cohesion [46-49]. During mortar polishing, calcium hydroxide rises to the surface and, through carbonation, incorporates the applied pigments [50-56]. Insufficient carbonation compromises the integrity of the color layer, making it more vulnerable to external degradation factors [57,58].

Temperature, as a degradation factor, affects mural paintings in three main ways: influencing relative humidity, which affects the absorption and release of moisture by materials; causing dimensional changes, such as expansion and contraction, depending on the nature of the material; and activating various chemical processes, including carbonation and sulfation [48]. Temperature fluctuations indirectly affect the painting by altering humidity levels, causing volume variations, and leading to material deformation, cleavage, and contact erosion. A balance is established between the temperature and humidity of the environment and the moisture content within the fresco.

A study monitoring a Renaissance fresco restored in 2006 in a cathedral in Valencia found that variations exceeding these recommendations did not appear in recorded data [47]. Churches, cathedrals, and historical monuments represent valuable cultural heritage and require microclimatic conditions similar to those in museums. Researchers have monitored temperature (T_a) and relative humidity (RH) in churches across Russia [40,41], the Baltic States [42-43], Italy [44-46], Cyprus [47], and Poland [48]. Temperature fluctuations can occur locally due to artificial or natural lighting, with the sun being the primary source of thermal energy. The amount of radiation absorbed by walls depends on the construction material, which requires the regulation of indoor temperatures, particularly between rooms with exterior walls and those without direct exposure to the environment.

The introduction of heating systems in places of worship has created complex problems, affecting both the structural integrity of buildings and mural paintings. Heating systems are often used intermittently, causing sudden fluctuations in temperature and humidity. Temperature differences between the interior and exterior of churches can lead to condensation of water vapor on cold surfaces, forming whitish deposits [49-54].

5. SPECIFIC DEGRADATION OF PIGMENTS IN FRESCO

Various research studies and restoration interventions on heritage monuments have analyzed the pigments used in mural painting and their deterioration through physico-

chemical techniques and characterization methods. Studies on mural paintings reveal that chemical alteration of pigments occurs in all monuments, in one form or another.

Humidity is the primary factor responsible for pigment alteration. However, pigment deterioration can also result from other factors, such as solar radiation (especially ultraviolet rays, which affect cinnabar red and lead white), thermal stress caused by fires or lightning, and air pollution, particularly sulfur compounds. These issues are often exacerbated by technical flaws, the nature of the pigments (both organic and mineral), and improper restoration interventions over time.

To better understand these phenomena, it is essential to discuss the main pigments used in fresco and the specific forms of alteration identified during restoration processes. Although these chromatic transformations can sometimes be prevented, once they occur, they permanently alter the original image. Below, we briefly mention two of the most common chromatic transformations found in fresco mural painting—changes directly influenced by human negligence.

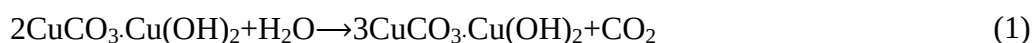
Slaked lime (Ca(OH)_2) is a key component in fresco painting [20]. Typically, lime white is chemically stable. However, air pollution from acidic compounds like sulfur dioxide and carbon dioxide, combined with high environmental humidity (acid rain, wall moisture, vapor condensation), can trigger harmful chemical reactions. These reactions form salts, such as sulfates and acidic carbonates, that crystallize on the paint layer, creating white veils or more severe micro-karst-like degradation, including hard carbonate crusts [20]. The pigment obtained from sun-carbonated lime paste or from ground old fresco plaster was traditionally applied to fresh painting surfaces, valued for its compatibility with fresco substrates and its resilience in harsh environmental conditions [55, 56].

Blue Pigments. Due to their chromatic properties, blue pigments have been used from Antiquity to the present day. Among these, azurite, i.e., a natural pigment derived from the mineral azurite (basic copper carbonate, $2\text{CuCO}_3 \cdot \text{Cu(OH)}_2$) was frequently employed in both interior and exterior mural paintings of churches [54]. The diversity of blue pigments and their alteration products allows for the determination of the chronology of mural painting layers, as well as for the identification of retouching and repainting interventions [56, 57].

Under the influence of humidity, azurite can transform into green malachite ($\text{CuCO}_3 \cdot \text{Cu(OH)}_2$), another basic copper carbonate. In the presence of chlorides originating from the intonaco, its color may change to green due to the formation of basic copper chlorides, such as atacamite and paratacamite ($\text{CuCl}_2 \cdot 3\text{Cu(OH)}_2$). Exposure to sulfurous gases causes azurite to darken through the formation of copper sulfide (CuS). Additionally, blackening may occur in alkaline environments or as a result of heating at approximately 410°C , when azurite decomposes into copper oxide (CuO , tenorite).

A notable example of blue pigment alteration was observed at the Horezu and Sucevița monasteries, where the original intense blue layers underwent significant transformation, resulting in a range of altered hues that extended to chalky white–cream tones. Although azurite carbonation is generally slow and can be isolated from plaster alkalinity, sulfurous gases accelerate chromatic alteration, leading to blackening through the conversion of azurite into copper sulfide [20].

Additionally, under prolonged humidity exposure, azurite transforms into malachite ($\text{CuCO}_3 \cdot \text{Cu(OH)}_2$), a basic copper carbonate also known as *verderame*, according to the reaction [59, 60]:



A famous example of this transformation is found on the southern facade of the Voroneț Monastery Church [61]. Raman spectroscopic analysis of certain green-toned areas associates them with a copper arsenate, either conichalcite, $\text{CaCu(AsO}_4\text{)(OH)}$, or duftite,

PbCu(AsO₄)(OH), both relatively common green arsenate minerals. However, it remains unclear whether their presence is due to degradation processes of originally applied materials or if they were intentionally used as pigments [62,63].

Investigations using optical microscopy and SEM-EDS on a green fresco from a 15th-century former church in Piedmont (Italy) revealed, beneath three layers of limewash, the presence of two superimposed green layers: an upper layer made of copper-based green pigment and lead white, and a lower layer composed of silicates of potassium, magnesium, iron, and aluminum [64]. Spectrophotometric analyses conducted after removing the layers confirmed the presence of the green pigment malachite. Lead white influences malachite's spectral behavior, increasing reflectance values without altering the green pigment. This suggests a possible dilution of the pigment.

Earth pigments are very stable, and these include lime white and kaolin; for yellow, red, and brown, various shades of ochre and sienna, caput mortuum, and umbra; for green, malachite and earth green; and for blue, lazurite (also called lapis lazuli or ultramarine). Unstable mineral pigments include, for example, lead white and red-orange tetroxide called minium, both turning brown; azurite, which in the presence of moisture transforms into malachite green and in the presence of sulfur turns black; verdigris, which in the presence of moisture changes to whitish or pinkish crusts; and finally, cinnabar, which under the action of moisture and sunlight turns black: [65]

High temperatures from open flames such as candles, oil lamps, or fires can devastate mural paintings, causing alterations with consequences that are difficult or impossible to remedy through restoration. At these temperatures, calcium carbonate transforms into calcium oxide, changing volume and causing the plaster to disaggregate and the tones to shift. Yellow or green earth pigments can turn red or brown through dehydration. This is why the halos in altars have acquired red or dark tones, contrasting with those in the rest of the church.

Yellow earths begin to shift to red at temperatures of around 250°C, become red-brown up to 500°C, and continue to darken up to 750°C, after which no further chromatic changes are observed [1]. The thermal action generated by fires or the burning of candles near painted surfaces leads to irreversible chromatic transformations of some pigments, as a result of the loss of hydration water or the crystallization of the constituent compounds [66].

Through heating, yellow ochre (goethite, FeO(OH)) loses its crystallization water and transforms into red ochre (hematite, Fe₂O₃). Anhydro Faria and Lopes showed that it is not possible to distinguish heated goethite from other disordered hematites [67]. Pomiès, Morin, and Vignaud used X-ray diffraction to study the goethite-to-hematite transformation through the effects of heating on structure [68,50]. Brown ochre is a mixture of Fe₂O₃ and FeO(OH). The shades of these clay pigments vary significantly depending on the degree of hydration and the content of iron and manganese oxides, with manganese oxides imparting brown hues [68].

Cinnabar Red (HgS). Cinnabar red, or mercury sulfide (vermilion) [57], is a natural or artificial pigment used since ancient times in mural painting. It is distinguished by its unparalleled intensity and excellent covering power, which increases as particle size decreases during grinding [69]. Although generally stable under most environmental conditions, vermilion (α -HgS) undergoes color changes over time due to exposure to sunlight, humidity, and atmospheric pollutants [50,54,68]. The primary degradation pathway is a photoinduced allotropic transformation:

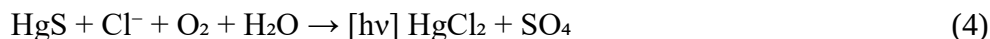


Red α -HgS (vermilion) has a hexagonal crystalline structure and is glossy and bright, while the degraded β -HgS (metacinnabar) is cubic, black-grey, opaque, and lacks luster. This transformation involves crystalline rearrangement without chemical composition change.

Additionally, photooxidation of HgS in the presence of oxygen generates toxic metallic mercury (Hg⁰) and sulfur dioxide:



Hg⁰ may appear as grey-silver droplets, and SO₂ can further interact with the paint layers. Photochemical reactions with airborne pollutants also contribute to degradation. In humid, slightly acidic atmospheres (e.g., acid rain), under light exposure:



The resulting HgCl₂ is colorless and soluble, potentially leading to whitish stains or efflorescence. Vermilion may also darken through interactions with lead compounds or light-induced decomposition, forming grey metallic mercury spots.

6. METHODS FOR CHARACTERIZING THE DEGRADATION OF HERITAGE MATERIALS

In analytical projects studying cultural heritage objects, the first essential step is to establish a protocol that addresses the nature of the problem, the purpose of the study, the required analysis, and the appropriate analytical techniques. These aspects also determine the minimum sample quantity, the required number of samples, and their location. It is crucial for the samples to be representative and for the way the results will be used to be clearly defined [70].

The first characterization technique is macroscopic analysis, which is indispensable before sample collection. It is performed on site with the naked eye or a magnifying glass. This allows for the correct establishment of the sampling area and an initial characterization of the fresco surface: the adherence of the fresco to the supporting layer, the presence of layers on the fresco surface from various interactions with environmental factors or aggressive agents, and the degree of degradation of the fresco both in depth and on the surface.

Optical microscopy (OM) is frequently used to characterize heritage materials and objects [71]. It analyzes the morphology, size, and type of aggregates, inclusions, compaction defects, and interfaces [72]. Its main advantage is that it shows the object as it is, without additional processing or secondary treatments. Another important aspect is that it is the oldest type of microscopy, has reached a mature technological stage, and has relatively low costs compared to other methods.

Polarized light optical microscopy is used to examine the microstructure and defects in the paint layer, stratigraphy, and layer morphology. By analyzing the sample surface, the paint layer appearance, application method, and pollution phenomena are determined. In section analysis, its thickness and uniformity are assessed, as well as the quality of the interface between the paint layer and mortar. Stratigraphies allow for understanding how the color was applied, the number of layers, and the composition of the pigments [73-79].

SEM-EDS analyses allow for both surface and cross-sectional morphological characterization, determination of layer thickness, and elemental chemical characterization. Bibliographic studies show that Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS), because of their excellent resolution and precise elemental composition determination, are essential for characterizing fresco materials. The study of the surface morphology enables the analysis of structural details (cracks, exfoliations, or

porosities on a micrometric and nanometric scale) and can reveal the techniques used by the artist [19,80,81].

The composition of the pigments can be identified through the chemical elements present (e.g., Pb for lead white, Fe for ochre pigments, Cu for azurite or malachite), as well as aggregates, inclusions, and impurities that can indicate the source of the raw materials [72,82].

In assessing degradation processes, SEM and EDS can detect products of chemical alteration, such as the formation of secondary compounds (gypsum – $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or metal oxides, resulting from pollution or other environmental factors. These techniques also provide information about the degradation of pigments through chemical reactions that lead to color changes or material loss [11].

Cross-sectional analysis enables determination of the layered structure of frescoes, interface quality, and interactions between layers, including salt migration or reactions between pigments and the substrate. To identify restoration interventions, SEM and EDS can highlight differences in material composition, revealing the use of modern materials in restoration processes [83].

FTIR Spectroscopy is useful for identifying chemical bonds and the composition of degraded pigments. By using a microscope coupled with FTIR equipment, IR microscopy becomes extremely efficient in identifying organic and inorganic pigments, contaminants, binders, varnishes, and characterizing natural resins (varnishes, amber) [70,84].

X-ray Diffraction (XRD) allows for the determination of the crystalline phases of pigments and salts formed on the surface of frescoes. This qualitative and semi-quantitative method enables analysis of crystalline components (organic and inorganic), providing information on the crystalline structure, chemical composition, and physical properties of materials [70,83-89]. X-ray diffraction can also help the restorer understand materials. Analyzing salt segregation provides valuable knowledge for the conservation of frescoes. The analysis of the mortar can also provide valuable information regarding both the original materials and preparation techniques, as well as the choice of conservation techniques.

The crystalline structure of lime (calcite) in the mortar composition indicates its origin: slaked lime or limestone powder, or even marble dust. If the lime (calcium carbonate) is present as aragonite rather than calcite, it indicates that it was obtained from ground shells. In addition to the calcium carbonate obtained by burning limestone, the lime in the composition also contains magnesium carbonate (magnesite) from higher-magnesium limestone. This helps, on the one hand, identify potential source mines and, on the other hand, warns of the mortar's high sensitivity to the harmful effects of acidic, sulfate-rich moisture [90].

Pigment analysis can provide objective information regarding dating, as the distribution of pigments over time and space is generally well known. The base layer of paintings is typical of the artist or the era, and the white pigment in the base is easily identifiable, complementing pigment analysis. The analysis of the adjacent ores in the composition of the lapis lazuli pigment has been successfully used to determine the place of origin. Regarding the greenish discoloration of azurite in frescoes, further analyses of as many cases as possible are needed. In the case of patinated or discolored color layers, identifying pigment residues would be extremely useful in reconstructing the original color scheme [91].

Raman analysis is a non-destructive technique essential for identifying pigments and their degradation-related modifications. Micro-Raman spectroscopy has proven useful for analyzing various cultural heritage artifacts, from painted materials to natural or synthetic fibers, ceramics, glass, mural paintings, and corrosion products. The main advantages of this method include non-destructiveness, the need for very small samples, and high sensitivity, making it one of the most important diagnostic techniques [70,92].

Atomic Force Microscopy (AFM) is an advanced and versatile technique used in the analysis and characterization of historical frescoes. It provides detailed information about surface topography and the physico-chemical properties of materials, without invasive sample preparation. Here is an overview of the use of this technique in fresco characterization: AFM allows the analysis of topography and microstructure (detailed investigation of the surface texture of frescoes, identification of cracks, exfoliations, or other damage at the nanometric scale), determination of topography, artistic techniques used, and traces of previous restorations [72,93-95].

Cathodoluminescence Microscopy (CL) is used in fresco characterization to identify natural or artificial pigments based on their specific optical signature and the materials used, including their provenance and purity (limestone, quartz). CL highlights variations caused by manufacturing or degradation processes due to environmental interactions (salt formation, sulfation, oxidation). Through CL, differences between original materials and those used in later interventions can be identified, revealing modifications made by restorers [72,82,94-99].

7. PRACTICAL DEGRADATION STUDIES

The scientific literature in chemistry and archaeometry has extensively documented the degradation processes of fresco painting layers from various historical periods. The practical knowledge accumulated over centuries has allowed artists to choose materials less susceptible to alteration or degradation [100]. Additionally, environmental influences, seasonal climate changes, extreme conditions (floods, fires), and increasing pollution with sulfur and nitrogen compounds (SO_2 , SO_3 , NO_x) have significantly affected these materials [101].

Most studies focus on characterizing different inorganic pigments used in frescoes [102–108], including pigments such as black [109], white (lead white and calcium carbonate), yellow (ochre), red-orange (vermilion, red lead), lapis lazuli [85], blue (ultramarine, azurite), and green (malachite).

Various advanced techniques such as macroscopic analysis, optical microscopy, XRF, FTIR, UV-Vis spectroscopy, SEM-EDS, AFM, XRD, and Raman spectroscopy have been used to characterize vulnerable material areas, providing insights into degradation phenomena and alterations caused by key factors (climate, environmental conditions, material selection, biological activity).

This detailed material characterization enables the proper selection of conservation and restoration treatments. Cathodoluminescence microscopy of fresco fragments helps determine petrographic constituents and stratigraphy and evaluate degradation processes through pore and crack analysis. The pigments used in mural painting and their degradation have been identified through physico-chemical analyses and characterization techniques in various studies and interventions conducted on heritage monuments.

A detailed analysis of the Renaissance mural frescoes of Casas Pintadas in Évora (Portugal) identified various microorganisms, including bacteria, yeasts, and fungi (*Aspergillus*, *Cladosporium*, and *Penicillium*). This microbial population is responsible for the alteration of the mural paintings and can significantly influence the overall degradation process [110–114].

SEM analysis of microfragments of mortar confirmed microbiological contamination, highlighting the ability of microorganisms to develop within the pictorial layer. In the mortar microstructure, fungal hyphae were observed proliferating on the surface, which may explain the detachment and cracking seen in some areas of the painted layer [115].

The mycelial structures of filamentous fungi were found forming a biofilm on the mortar surface, covering certain painted areas, which can induce chromatic alterations due to the metabolic activity of the microorganisms on the wall surfaces [112, 116–118].

Rosado et al. [117,118] proposed a multi-analytical approach to mural paintings, integrating material characterization with the investigation of biodeterioration and the assessment of conservation treatments. In their study of the Renaissance frescoes at Santo Aleixo, material characterization involved optical microscopy, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS), and micro-X-ray diffraction (μ -XRD), complemented by micro-Raman spectroscopy. These techniques enabled the identification of the pictorial palette, consisting of red and yellow ochres, malachite, azurite, and bone black, as well as the detection of a localized transformation of malachite into tenorite. Electron microscopy also provided information on the microstructure of the paint layers and mortar and enabled the observation of microbial proliferation.

Biodeterioration was assessed by isolating and characterizing bacteria, yeasts, and filamentous fungi, along with SEM observations and determination of dehydrogenase enzymatic activity. This method was particularly relevant because it assessed the metabolic activity of the microbial community rather than merely confirming the presence of microorganisms. The results indicated an association between microbial activity and the physical disruption of the paint layers and mortars. Subsequently, the researchers tested commercial biocides to identify effective treatments against predominant microorganisms.

In the study of the mural paintings at Casas Pintadas in Évora, the methodology was further extended towards an integrated conservation and intervention approach. Preliminary in situ analyses using X-ray fluorescence (XRF) and colorimetry were employed for the overall characterization of the paintings and for the selection of sampling locations. Stratigraphic sections were examined by optical microscopy and SEM-EDX, including two-dimensional elemental mapping (Table 1). An important aspect of the study [118] was the transition from diagnosis to intervention.

Table 1. Comparative synthesis of characterization techniques used in [117–118].

Technique	[117] Santo Aleixo	[118] Casas Pintadas	Main role
Optical microscopy	✓	✓	Stratigraphy, morphology and sample selection
SEM	✓	✓	Microstructure and biodeterioration
SEM-EDS/EDX	✓	✓	Elemental composition
μ -XRD	✓	—	Identification of crystalline phases
Micro-Raman spectroscopy	✓	— / complementary	Pigment identification
In situ XRF	—	✓	Non-invasive elemental characterization
Colorimetry	—	✓	Colour characterization and changes
Dehydrogenase assay	✓	—	Microbial metabolic activity
Microbiological culturing	✓	✓	Isolation of microorganisms
Microbial morphology	✓	✓	Preliminary identification
ITS sequencing	—	✓	Molecular identification of fungi
SEM imaging of biofilms	✓	✓	Localization and penetration of microorganisms
Biocide testing	✓	✓	Treatment selection
T/RH monitoring	—	✓	Preventive and post-intervention conservation
Photogrammetry/photography	—	✓	Monitoring of deterioration progression

The identified microorganisms were used to assess the efficacy of commercial biocides, and, after verifying chromatic compatibility, the treatments were progressively applied to the affected surfaces. In parallel, biotechnological alternatives based on lipopeptides produced by *Bacillus* were investigated to develop safer, less toxic antimicrobial treatments. Following the intervention, preventive conservation was supported by long-term monitoring of temperature, relative humidity, surface condition, newly formed alteration products, and microbial communities. Because of the microbial diversity present, developing combined biocide applications was necessary to prevent further proliferation.

As part of the research, safer alternative biocides were investigated, and new biocompounds isolated from bacterial cultures showed effective inhibition levels. These represent an innovative, environmentally friendly option compared with commercially available toxic compounds. This encourages applying these biocompounds to biocontaminated cultural heritage objects to prevent recolonization.

In conclusion, effectively eliminating and controlling the development of microorganisms involved in the biodegradation process requires an in-depth understanding of degradation mechanisms and remediation solutions before conservation-restoration interventions. Additionally, it is essential to develop preventive monitoring programs to ensure the longevity of interventions and the safeguarding of artworks [116-120]. Mizutani et al. [122,123] conducted extensive studies on the influence of moisture on the mural paintings of Hagia Sophia Cathedral in Istanbul. In article [122], Mizutani et al. further investigated the relationship between rainwater absorption, water accumulation and evaporation, and the deterioration of the mural paintings, with particular attention to the distribution of evaporation within the wall stratigraphy. The study highlighted a correspondence between areas with high evaporation rates and areas with severe flaking. Article [123], also published by Mizutani et al., provides a broader investigation and focuses primarily on the influence of infiltrated rainwater on wall deterioration. The study combines a long-term monitoring campaign with numerical modeling of coupled heat and moisture transfer to identify the underlying deterioration mechanism and to establish a scientific basis for the conservation of the mural paintings. Table 2 presents a synthesis of the characterization methods and techniques employed in these studies.

Table 2. Summary of characterization techniques used by Mizutani et al. [122,123].

Technique / Method	What it characterizes	Role in the degradation study
Visual inspection/degradation documentation	Flaking, deterioration, and affected areas	Localization and assessment of degraded areas
TDR moisture measurement	Water content within the wall	Identification of areas with moisture accumulation
Moisture mapping	Spatial distribution of water	Correlation of moisture distribution with deterioration
Rainfall monitoring	Amount of rainfall	Identification of external moisture sources
Wind-driven rain analysis	Water input to exterior surfaces	Explanation of differences between exedrae
Determination of material transport properties	Liquid-water diffusivity	Parameterization of the water-transport model
Heat–moisture transfer modelling	Water movement and accumulation within the wall	Explanation of the degradation mechanism
Saturation modelling	Seasonal distribution of moisture	Identification of permanently damp areas
Evaporation modelling	Location and intensity of evaporation	Identification of areas favorable for salt crystallization
Correlation of model predictions with observed deterioration	Relationship between evaporation and deterioration	Validation of the proposed degradation mechanism

The main role of the characterization techniques employed by Mizutani et al. was to transform the phenomenological observation of deterioration into a process-based explanation grounded in physical mechanisms. Moisture measurements enabled the localization of water within the wall, rainfall analysis helped identify its external source, characterization of transport properties provided insight into water migration through porous materials, while hygrothermal modeling enabled the identification of areas of moisture accumulation and evaporation. The integration of these methods provided a scientific basis for identifying the causes of deterioration and for developing preventive conservation strategies for mural paintings.

The Church of St. Stephen in Nessebar (Bulgaria) was restored in 1975, but severe deterioration of the wall paintings was observed just a few years later. Investigations revealed major errors in the design and construction of the waterproofing and drainage system [124]. Porosity measurements of the plaster indicate that special attention is needed because of the presence of soluble salts. Before restoration, these salts must be removed, and special precautions should be taken to mitigate their effects [39].

Bernardi et al., in their work [124], emphasize the importance of the integrated characterization of the microclimate and material properties for assessing the conservation status of mural paintings. The methodology included monitoring temperature, relative humidity, specific humidity, and the dew point difference within a spatial measurement network, complemented by two-dimensional cartographic representations. These investigations enabled the identification of thermo-hygrometric gradients and the evaluation of condensation risks. Additionally, analysis of substrate porosity highlighted the presence of water in micropores, helping explain potential mechanical stresses and interactions with soluble salts. These characterization techniques primarily established the relationship between microclimatic conditions, the behavior of the porous material, and the degradation processes of the frescoes, and verified the effectiveness of conservation interventions. Thus, the study underlines the need for microclimatic monitoring and material characterization as a preliminary and ongoing stage of preventive conservation of mural paintings.

Giustetto et al. [125] conducted a multi-analytical archaeometric investigation of the mural painting “The Divine Adoration of King St. Louis IX” in the church of San Francesco dei Cappuccini in Racconigi, which was affected by progressive darkening, particularly in the red and pink areas. Material characterization relied primarily on X-ray powder diffraction (XRPD), micro-Raman spectroscopy, and FT-IR spectroscopy, complemented by microscopic examination (Table 3).

Table 3. Analytical techniques used by Giustetto et al. [125] for the archaeometric characterization of the wall painting.

Technique	Investigated	Role / Information obtained
XRD / XRPD	Crystalline phases in samples	Identification of mineral phases and alteration products, including hematite, magnetite, calcite, and gypsum
Micro-Raman spectroscopy	Pigments and degradation products at the microscopic scale	Identification of pigment phases and iron compounds; evidence of the hematite → magnetite transformation
FT-IR spectroscopy	Molecular composition of materials	Identification of characteristic carbonate and sulfate groups, particularly calcite and gypsum; evidence of sulfation
Optical microscopy	Surface appearance and material distribution	Observation of surface particles and pigment-bearing areas; complementary information for spectroscopic interpretation
Restoration-stage examination	Deposits, efflorescences and painted surface	Correlation of analytical results with the actual conservation condition and assessment/removal of surface deposits

Analyses identified hematite (Fe_2O_3) as the red pigment and revealed its partial transformation into magnetite (Fe_3O_4), which caused the blackening of the red-pigmented areas. Concurrently, the sulfation of the calcareous substrate (resulting in gypsum formation) was observed; this process was attributed to exposure to sulfur compounds (SO_2 and SO_3) generated by the burning of oil, candles, and incense in the immediate vicinity of the painting. Soot and combustion-derived dust deposits further contributed to the darkening of the surface. Correlating the mineralogical and spectroscopic data made it possible to distinguish between chemical pigment degradation and deposit-related surface alteration, and the results provided the basis for the restoration intervention.

Stamboliyska et al. [126] employed a multi-technique analytical approach to characterize the pictorial materials and degradation processes affecting the exterior mural paintings of the main church of Rila Monastery. The identification of pigments and alteration products was performed using ATR-FTIR spectroscopy, micro-Raman spectroscopy, SEM-EDS, and X-ray diffraction (XRD), providing complementary information on the molecular, elemental, and mineralogical composition of the samples (Figs. 5-7, Table 4). The enzyme-linked immunosorbent assay (ELISA) identified the organic binder, with results indicating a post-Byzantine egg-tempera technique. Correlation of the analytical data enabled identification of both traditional and synthetic pigments, as well as characterization of the chemical transformations of minium and copper–arsenic green pigments under environmental exposure. Gypsum and calcium oxalates were identified as important degradation products.

Table 4. Summary of characterization techniques according to Stamboliyska et al. [126].

Technique	Investigated / Identified	Role in the study
ATR-FTIR	Mineral pigments, degradation compounds and secondary products	Identification of inorganic phases and complementary information to Raman/XRD; particularly useful for carbonates, sulfates, oxalates and specific pigments
Micro-Raman spectroscopy	Pigments and alteration products	Mineralogical/molecular identification of pigments; differentiation of green pigments and identification of transformation products
SEM-EDS	Particle morphology and elemental composition	Detection of characteristic elements such as Pb, Cu, As, Fe, Si, Al, Ca, etc.; important for associating elemental composition with specific pigments
XRD	Crystalline phases	Confirmation of mineralogical identification and degradation products; identification of phases resulting from pigment transformation
ELISA	Organic binder	Identification of specific proteins and attribution of the painting technique to an egg-tempera technique, characteristic of the post-Byzantine tradition
Microscopic examination / micro-sampling	Stratigraphy and material appearance	Selection of representative samples and correlation of spectroscopic, elemental and mineralogical results

The study of the mural paintings at the Church of the Nativity of the Mother of God in Rila Monastery (Bulgaria) revealed the use of similar pigments in both the exterior gallery and the church interior. This includes yellow ochre and ultramarine blue (Fig. 5), lead white (Fig. 6), and green earth (Fig. 7). However, degradation was far more visible on the exterior paintings, which were exposed to rain, air pollution, and microbiological contamination.

A major concern is the red paint layer, where an inappropriate minimum was used, leading to severe discoloration, including its transformation into black plattnerite (PbO_2) and white lead carbonate (PbCO_3). In contrast, the vermilion in the original painting did not undergo significant changes, likely due to its application in mixture with hematite. Additionally, replacing unstable smalt with more stable ultramarine helped preserve the blue areas.

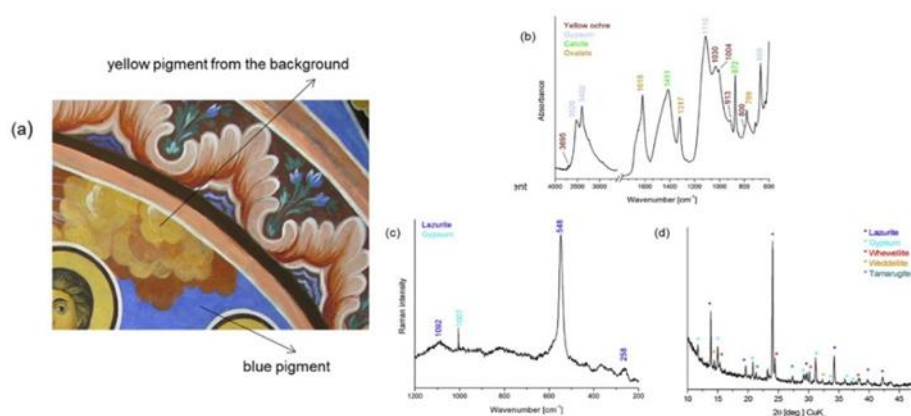


Figure 5. (a) Yellow and blue pigments from the image of Saint Sophia and her daughters; (b) ATR-FTIR spectrum of the yellow pigment; (c) μ Raman spectrum of the blue pigment; (d) XRD pattern of the blue pigment [126].

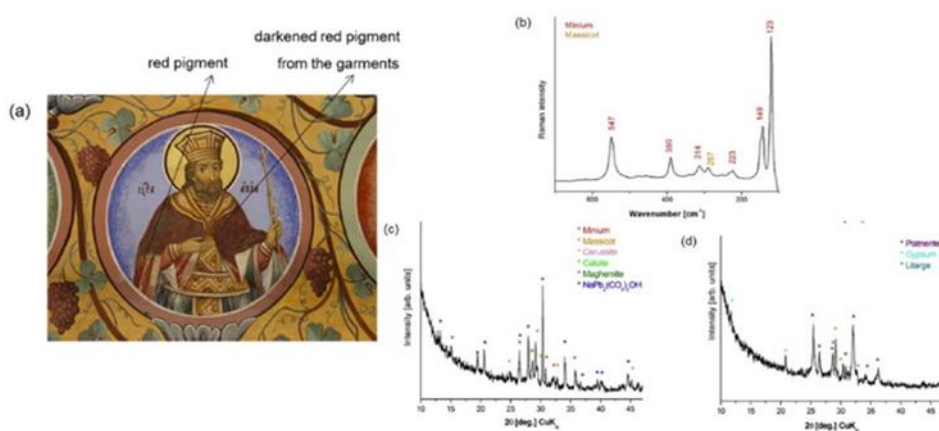


Figure 6. Red lead minium pigment from the image of King Abijah – (a) image detail; (b) μ Raman spectrum; (c) XRD pattern of the red sample; (d) XRD pattern of the dark red sample [126].

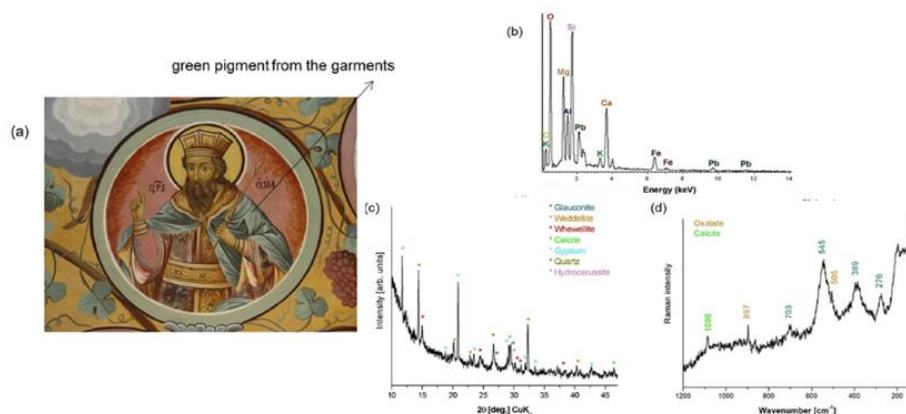


Figure 7. (a) Green pigment from the image of King Uzziah; (b) SEM-EDS spectrum; (c) XRD pattern; (d) μ Raman spectrum [126].

A combined analysis suggests that the murals were created using the post-Byzantine tempera technique with egg as a binder, but the binder suffered severe degradation over time. Modern air pollution, especially the fixation of acidic gases (mainly SO₂), has been identified as a primary degradation factor. A comparison of the pictorial materials found at Rila Monastery with those in other Byzantine and post-Byzantine monuments in the Balkans and Turkey suggests that the decoration of the main church of Rila Monastery followed post-

Byzantine techniques but incorporated new materials due to industrial developments in the 19th century [126].

The study of materials and environmental conditions should be based on an integrated investigation programme combining complementary characterization techniques with the systematic assessment and monitoring of environmental factors. Correlating information on the composition, structure, and state of degradation of the materials with data on environmental conditions enables a scientifically sound diagnosis and identifies the mechanisms responsible for deterioration. The results provide a scientific basis for defining appropriate conservation conditions, selecting suitable restoration materials and technologies, and establishing compatible and effective treatment strategies aimed at ensuring the long-term stability and durability of fresco paintings.

8. CONCLUSIONS

The study on the degradation of the pictorial layers of fresco painting was based on an analysis of 126 bibliographic references: 18% were publications issued before 2000, 52% were published between 2000 and 2020, and 30% were recent publications from 2020–2025. The distribution of the references reflects both the importance of established research and the integration of recent findings and approaches concerning the investigation and conservation of mural paintings.

The analysis of the scientific literature highlighted the main factors responsible for the degradation of fresco paintings, considering both their individual effects and their combined and cumulative action. Among these factors, moisture is one of the major agents of deterioration, its effects being amplified by temperature fluctuations, unfavorable microclimatic conditions, and biological factors such as microorganisms, fungi, and algae. The combined action of these factors may lead to complex deterioration processes, manifested by the formation of salt efflorescences, cracking and detachment of the pictorial layers, changes in the properties of the constituent materials, and irreversible color alterations.

An important aspect identified in the literature concerns the influence of air pollution and the accumulation of deposits and foreign materials on the painting surface. Local temperature fluctuations associated with natural or artificial lighting, as well as the introduction of heating systems, may also modify the microclimatic conditions and contribute to the acceleration of deterioration processes. These observations emphasize the need to assess mural paintings not only in terms of their constituent materials but also in relation to the environmental conditions in which they are preserved.

The synthesis of the techniques and methods used for material characterization and condition assessment demonstrated the need for a multidisciplinary approach and complementary diagnostic techniques. In most cases, no single analytical technique can provide all the information required for a comprehensive characterization of the materials and deterioration processes. Correlating results from complementary methods enables a more accurate assessment of the composition, structure, and conservation condition of the materials and, in particular, a better understanding of pigment alteration processes.

The case studies highlight the importance of integrated experimental programs and the need to correlate and interpret results interdisciplinarily. Integrated data analysis allows relationships to be established between material composition and structure, environmental factors, and observed deterioration phenomena, thereby improving understanding of the mechanisms responsible for fresco alteration.

The literature review identified several major requirements and research directions: (i) Strengthening interdisciplinary collaboration among specialists in material characterization, conservation-restoration, chemistry, physics, microbiology, and art history is essential for establishing comprehensive diagnoses and developing conservation and restoration treatments adapted to each individual case. (ii) The investigation of materials and environmental conditions should be conducted through an integrated research program, combining complementary characterization techniques with systematic assessment and monitoring of environmental parameters. Correlating information on the composition, structure, and deterioration state of the materials with data on microclimatic conditions enables a scientifically grounded diagnosis and the identification of the mechanisms responsible for deterioration. (iii) There is a clear need for the development and harmonization of investigation protocols for cultural heritage materials, with particular emphasis on the standardization of procedures for monitoring and assessing salts in fresco paintings. Such standardization would enable more rigorous comparisons across studies and support long-term monitoring of deterioration processes. (iv) Case studies provide valuable information for understanding the behavior of materials under specific environmental conditions and may serve as important methodological references for future research. Their value increases when researchers systematically document and correlate investigation methodologies, experimental conditions, and results. (v) The integration of modern technologies and non-destructive methods offers significant opportunities for the investigation and conservation of mural paintings. In this context, the use of biocompounds for controlling microorganisms represents a promising approach. Further investigation of biocompounds as more sustainable alternatives, with potentially lower impacts on heritage materials than conventional biocides, may represent an important future research direction.

Overall, the analysis shows that fresco deterioration results from complex interactions between the properties of the constituent materials and environmental factors. Consequently, assessing them requires an integrated approach based on interdisciplinary investigation, environmental monitoring, and correlation of analytical data.

The results of this literature-based research and the synthesis of the available information should provide a scientific basis for defining appropriate conservation conditions and selecting suitable conservation and restoration treatments. They may also help establish scientifically supported criteria for the compatibility, effectiveness, and long-term durability of restoration materials and technologies.

Therefore, an integrated understanding of the materials, deterioration factors, and environmental conditions is essential for developing effective conservation strategies and ensuring the stability, compatibility, and long-term durability of fresco paintings.

ABBREVIATIONS LIST

Abbreviation	Full Term/Meaning
AFM	Atomic Force Microscopy
CL	Cathodoluminescence Microscopy
EDS	Energy Dispersive Spectroscopy
ELISA	Enzyme-Linked Immunosorbent Assay
FTIR	Fourier-transform Infrared Spectroscopy
IR	Infrared Microscopy
Macroscopy	Macroscopic examination
OM	Optical Microscopy
Raman	Raman Spectroscopy
RH	Relative Humidity
SEM	Scanning Electron Microscopy
SEM/EDS	Scanning Electron Microscopy/Energy Dispersive X-Ray Spectroscopy
Ta	Ambient Temperature

Abbreviation	Full Term/Meaning
UV-Vis	Ultraviolet-Visible
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

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