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Review article

USING GEL POULTICES IN SOME ARCHAEOLOGICAL FIELDS: A REVIEW

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Abstract:
The study aims to explore the use of poultices in the field of heritage preservation, particularly in conservation, as an effective method for treating delicate surfaces of archaeological materials. Selecting the components of the poultice is crucial for ensuring treatment efficiency. It depends on the nature of the surface being treated, such as wood, stone, bone, wall paintings, paper, or others, as well as the required restoration conditions, such as cleaning, acidity treatment, or biological treatment. The materials used in preparing poultices vary and include clay substances, cellulose fibers, and gels, which can be combined with organic or aqueous solvents to suit the physical and chemical composition of the treated surface. This approach ensures effective and indirect treatment while preserving the physical and chemical integrity of the original surfaces without penetration, residue, or damage.

1. Introduction

Poultices are used as an effective restoration method for removing water-soluble contaminants from historic and archaeological surfaces [1]. Their effectiveness is based on two main components: Water and the base material of the poultice. The mechanism of their function is based on their ability to absorb and draw contaminants from the targeted surface and transfer them back into the poultice through the capillary action of water [2,3]. Various materials are used in preparing poultices, including clay-based substances, soft fibrous materials, such as cellulose, and gel-based substances (gel poultices) [3]. Traditional poultice mixtures, such as talc, chalk, and occasionally flour, have also been used [1]. The selection of poultice materials depends on the nature and characteristics of the surface to be treated, as well as the treatment conditions and objectives. It is a critical factor in achieving effective and controlled results. Poultice materials can be combined with cleaning agents, whether aqueous or organic solvents, or with other additives necessary for treatment. These mixtures are carefully selected to be compatible with the physical and chemical properties of the object to ensure efficient contaminant removal while avoiding any adverse effects on the original material [1-3]. Poultices can be applied precisely to affected areas, allowing for localized treatment. Additionally, the fast evaporation rate of solvents and the control over drying speed make poultices a versatile and efficient solution in various conservation fields [3].

1.1. *Gel-based substances*

Distinct category known as gel poultices are made of a non-liquid colloidal network composed of interconnected polymer chains [4,5]. As introduced by Richard Wolbers in the early 1990s, they can be considered biphasic systems [6], consisting of at least two components: A polymer phase that forms a crystalline structure, acting as a thickener, and a liquid phase distributed within the polymer in large quantities, making it the dominant phase [7]. As a result, the final material can be soft, solid, or semi-solid. These cross-linked systems can retain liquids within the polymer, reducing evaporation and allowing controlled release through interactions between the liquid and polymer [6]. Figure (1) illustrates the interaction between the hydrogel and the surface of a contaminated material, demonstrating how the porous structure of the hydrogel traps and retains pollutants within its pores. The higher the porosity of the hydrogel, the greater its ability to capture unwanted substances [8]. In the field of conservation, gel poultices have emerged as valuable tools due to their beneficial properties, particularly in the conservation of wall paintings, wooden artifacts, and historic stone buildings [6]. However, the most significant advancement in gel poultices is their use in treating objects that are sensitive to water or organic solvents. These poultices can carry effective cleaning liquids within the polymer, allowing them to contact the surface to be treated efficiently while minimizing the impact of solvent evaporation or direct contact with the object's surface [9].

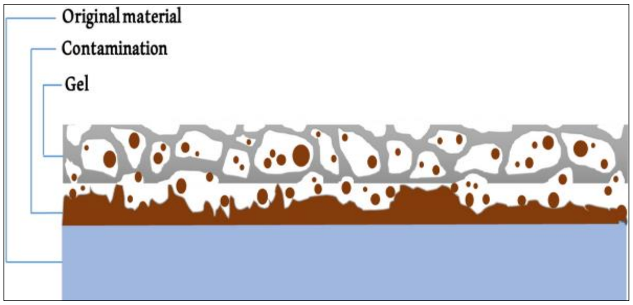

Figure (1) the cleaning mechanisms of gels poultice, which are entrapping the contaminants in the porous structure of the gel [8]

1.2. *Structure*

Based on the chemical nature of the internal bonds, gel poultices can be classified into two main types:

1.2.1. Physical gel poultices

Physical gel poultices are composed of polymer networks in which the chains are held together with secondary bonds by non-covalent interactions, such as hydrophobic forces, electrostatic interactions, van der Waals forces, and hydrogen bonds, fig. (2) [8]. In the field of conservation, they are often referred to as "smooth" gel poultices due to their tendency to leave residues on treated surfaces. These residues can be difficult to remove and may require solvent-based cleaning for complete elimination [10]. Physical gel poultices used in artifact conservation can be categorized into two subtypes: *) Strong physical gel poultices: these gel poultices are characterized by a double-helical molecular structure, allowing them to form semi-rigid films that can be peeled off after application. *) Weak physical gel poultices: in this type, the three-dimensional polymer network is stabilized by weak bonds, such as hydrogen bonds. As a result, the gel poultice forms more like a viscous paste, [11] which can be reversed or broken down by relatively weak van der Waals interactions [6].

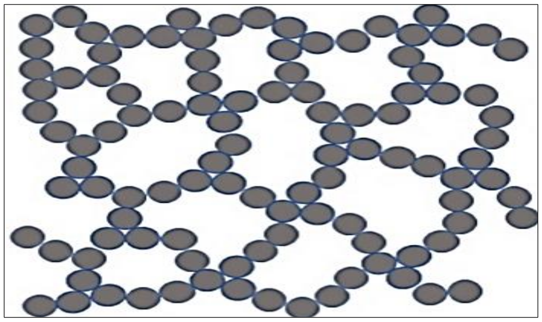

Figure (2) the physical interactions involved in the gel poultice formation, there is non-covalent bonds [8]

1.2.2. Chemical gel poultices

They are composed of polymer networks in which the chains are covalently bonded, fig. (3) [8]. These gel poultices are characterized by their strong mechanical and chemical stability [11,12]. Unlike physical gel poultices, which rely on aqueous systems, chemical gel poultices are typically loaded with organic solvents as their confined liquid phase. This feature allows them to be loaded with a wide range of cleaning agents, acting as a complementary alternative to aqueous-based gel systems used in conservation treatments [9]. Due to their mechanical properties, chemical gel poultices are classified as rigid gel poultices. They can be applied to surfaces and subsequently removed with ease and without leaving residues, due to the covalent bonding within their networks, which also renders them less polar than hydrogel-based poultices. These gel poultices are especially effective in softening and removing varnish layers, as well as eliminating both natural and synthetic adhesives [10].

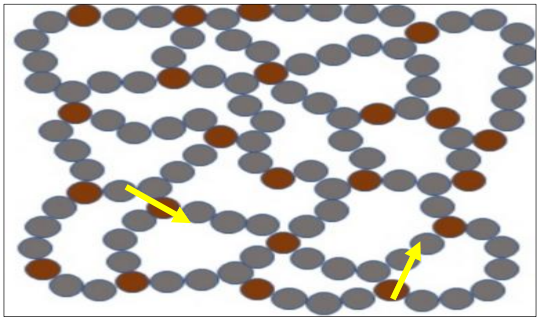

Figure (3) the chemical interactions involved in the gel poultice formation; the arrows indicate the covalent bonds [8]

2. Gel Poultices

2.1. *Types of gel poultices*

2.1.1. Natural gel poultices

Natural gel-based poultices, derived from polysaccharides such as gellan gum, xanthan, and levan, as well as marine sources like red algae and seaweed—including agar and chitosan—play a significant role in the conservation and maintenance of cultural heritage objects. They offer a non-invasive method for cleaning and stabilizing artifacts. They can selectively remove corrosion and surface dirt without compromising the original surfaces. This makes them particularly suitable for treating various historical materials, including stone, plaster, paper, and paintings. Additionally, their low toxicity, wide availability, low production cost, and ease of chemical modification further enhance their value in heritage conservation practices, this type of gel poultices include:

2.1.1.1. *Agar gel*

Agar is a rigid gel derived from Gelidium red algae. It is composed of two main polysaccharides: Agarose and agaropectin. The high gel strength of agar is primarily attributed to the presence of agarose, which has a strong gelling capacity. Agar demonstrates remarkable stability under both highly acidic and highly alkaline conditions. Prior to the incorporation of any cleaning agents, it is regarded as a non-toxic, naturally occurring gel material [13].

2.1.1.2. *Gellan gum*

Gellan gum gel poultices were first introduced to the field of conservation in North America by the Italian conservators, Iannuccelli and Sotgiu, affiliated with the Laboratory for the Conservation of library materials at the Central Institute for the Restoration and Conservation of Archival and Library Patrimony (ICPAL) in Rome [14]. It is a polysaccharide polymer obtained through the fermentation of the microorganism Sphingomonas elodea [15]. This material forms a rigid gel poultice, with the best performance achieved when applied in a warm state. It is particularly valued for its strong adhesion to treated surfaces, ease of removal, and transparency, which enables visual monitoring in cleaning [6].

2.1.1.3. *Chitosan*

It is a natural biopolymer derived from animal sources, including shellfish [16], as well as from the cell walls of certain fungi [6]. It is a linear polysaccharide with broad application across various fields due to its abundance, biodegradability, non-toxicity, and compatibility with both acidic and basic environments. In conservation, chitosan is particularly valued for its capacity to carry active treatment agents, ease of application and removal, and transparency, which allows observing surface changes during treatment [17]. It is also significant for its ability to gradually release water molecules while simultaneously absorbing soluble degradation products [14].

2.1.1.4. *Xanthan gum*

Xanthan gum is a heteropolysaccharide polymer produced by the bacterium *Xanthomonas campestris* through the fermentation of glucose or sucrose [6]. It is widely used in industry, including pharmaceuticals and cosmetics, and is recognized as one of the safest gel poultices -forming agents for conservators and the environment. Although xanthan gum is compatible with aqueous solutions of varying pH levels, it is not stable in strongly basic conditions. Its high viscosity makes it difficult to remove from treated surfaces. However, its rheological properties can be modified by blending with other polysaccharides or proteins, enabling the development of tailored formulations for specific conservation needs [18].

2.1.1.5. *Levan*

Levan is a naturally occurring polysaccharide that belongs to the fructan family and is classified as a homopolysaccharide composed of β-D-fructofuranose units linked by β-(2→6) glycosidic bonds. It features strong adhesive properties. In addition to its exceptionally low viscosity and high biocompatibility, levan offers a unique advantage despite its sensitivity to moisture: it can be rehydrated and reused as an adhesive. This reactivation capability after drying is particularly beneficial in the conservation and restoration of cultural heritage materials [13].

2.1.2. Synthetic gel poultices

Synthetic gel poultices are gel-based poultices derived from synthetic products, such as polyvinyl alcohol (PVA), polymethyl methacrylate (PMMA), polyvinylpyrrolidone, and polyacrylamide. They are formed through interlinked covalent bonds between polymer chains, resulting in materials with enhanced mechanical properties and greater chemical stability. They exhibit strong structural integrity, high water absorption capacity, thermal stability, and irreversibility. Furthermore, they are safe for application on archaeological surfaces because they do not leave residues or cause unacceptable alterations to the original material. These characteristics make them a suitable option for use in cultural heritage conservation. [8, 20], this type of gel poultices include:

2.1.2.1. *Poly (2-hydroxyethyl methacrylate) and poly (vinylpyrrolidone) (pHEMA/PVP)* [21,22]

Semi-interpenetrating polymer network (semi-IPN) hydrogels, in which multiple polymers are physically entangled without forming covalent bonds, are composed of poly (2-hydroxyethyl methacrylate) (pHEMA) and poly(vinylpyrrolidone) (PVP). They have been proposed for cleaning water-sensitive artworks and for use with organic solvents, fig. (4) [23]. The system combines the mechanical strength of pHEMA with the hydrophilic nature of PVP, resulting in a gel poultices system capable of confining both aqueous cleaning agents and polar solvents, such as ethanol, methanol, isopropanol, and benzene [13,21]. This gel poultice's structure enables a controlled release of the cleaning fluids onto water-sensitive surfaces, enabling the safe removal of adhesives or harmful residues. However, due to its non-elastic nature, it is less effective on rough or unevenly dimensioned surfaces. It is better suited for application on flat, smooth substrates [10].

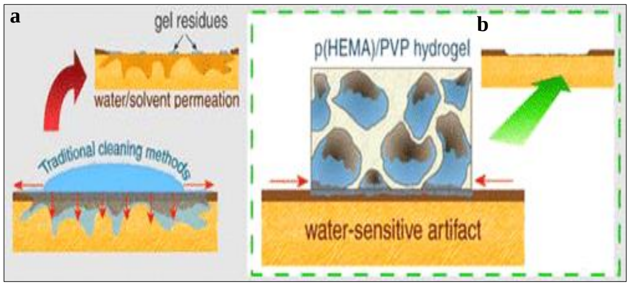

Figure (4) demonstrates the difference between; **a.** traditional methods, **b.** the use of pHEMA/PVP hydrogel poultice for removing contaminants from water-sensitive surfaces [23]

2.1.2.2. *Poly (vinyl alcohol) (PVA).*

Poly (vinyl alcohol) (PVA)-based hydrogels with physically crosslinked networks feature high flexibility and viscosity, as well as biocompatibility and non-toxicity. They exhibit high porosity and adaptability to rough surfaces, which can be enhanced by combining two types of PVA within a single network (a double-network structure). This is achieved by interpenetrating a network of high molecular weight PVA (H-PVA) with low molecular weight PVA (L-PVA), which imparts the hydrogel with efficient residue-free cleaning capabilities compared to networks made from pure PVA. Additionally, it offers rapid cleaning performance and a strong capacity for dirt entrapment, minimizing risks for the integrity of artworks. Consequently, it enables safe restoration processes for highly valuable artworks that were previously difficult to treat using conventional methods [22].

2.1.2.3. *Poly (vinyl alcohol)-borate*

Poly (vinyl alcohol)-borate hydrogels have been utilized in aqueous and co-solvent systems, with particular focus on their rheological properties and solubility, which can be significantly tuned by the addition of certain solvents, such as propanol, propylene carbonate, pentanol, and cyclohexanone. Studies have demonstrated their effectiveness in removing dirt and aged varnish layers without damaging the original paint layers when loaded with propanol [24,25].

2.1.2.4. *Poly (vinyl alcohol) (PVA/PVP)-based hydrogels*

The results demonstrate that blending polyvinyl alcohol (PVA) with polyvinylpyrrolidone (PVP)—a component of semi-interpenetrating polymer network (semi-IPN) hydrogels used in cultural heritage cleaning—improves the mechanical and functional properties of the hydrogel. This combination enhances flexibility and adaptability to irregular surfaces, in addition to its capacity for water retention due to the hydrophilic nature of the polymer. Furthermore, it exhibits a low likelihood of leaving residues after application on treated surfaces. The composite hydrogel poultice shows promising performance in cleaning and removing dust from an experimental model of a textured painting surface, designed to replicate the techniques of abstract expressionist artists, such as Jackson Pollock and Willem de Kooning [26].

2.1.2.5. *pNIPA (N-isopropylacrylamide)-LAP (Laponite XLS synthetic hectorite nanoclay)*

This nanocomposite organo-gel is based on the polymer p(N-isopropylacrylamide), crosslinked with an inorganic nanostructure of Laponite XLS. The resulting gel poultice exhibits a high capacity for retaining solvent mixtures, along with excellent flexibility, cohesion, and mechanical strength. These properties prevent the degradation of the gel poultice during use or reuse. Owing to its mechanical durability and flexibility, it can be applied easily without leaving any residue. Additionally, it can be reused several times without losing its cleaning efficiency. It is safer for use on artworks and poses less risk to human health [27].

2.1.2.6. *PHB-GVL-TEC*

It is a bio-based hydrogel composed of poly(3-hydroxybutyrate) (PHB) as the gelling matrix. PHB belongs to the polyhydroxyalkanoates (PHAs), a promising class of biopolymers derived from renewable sources. It is known for its biocompatibility and complete biodegradability into harmless organic waste. γ-Valerolactone (GVL) is used as a green solvent in this system. It is a versatile compound derived from lignocellulosic biomass, characterized by low toxicity, minimal environmental impact, and thermal stability, which helps reduce the emission of volatile organic compounds (VOCs). Triethyl citrate (TEC) serves as a plasticizer, enhancing the gel's handling properties and environmental sustainability. TEC is a non-toxic, bio-based, and biodegradable additive. Owing to their low toxicity, renewability, and rapid biodegradability of all three components, these gel poultices are easy to use and environmentally friendly. Thus, the PHB-GVL-TEC system offers an effective green tool that helps develop sustainable and safe restoration protocols in cultural heritage conservation [28].

2.1.3. Hybrid gel poultices

Hybrid gel poultices are formulated by combining physical compresses derived from natural sources with chemical compresses based on synthetic materials. This integration yields a hybrid gel with enhanced properties that combines the physical benefits of natural gels with the chemical advantages of synthetic ones. Such hybrid systems offer improved mechanical performance and effectively address the limitations associated with each type. Notably, they exhibit high structural integrity and a strong ability to recover their original form after deformation, making them particularly advantageous for conservation applications [20,29].

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2.1.3.1. *Poly(acrylamide-co-(3-methacryloxypropyl) trimethyl ammonium chloride) (poly (AAm-co-MAPTAC)) network with a chitosan polymer*:

Despite numerous studies addressing semi-interpenetrating polymer network (semi-IPN) hydrogel poultices using chitosan as a linear polymer, no research has focused on semi-IPN hydrogel poultices formed by integrating the network of poly(acrylamide-co-(3-methacryloylpropyl) trimethylammonium chloride) (poly (AAm-co-MAPTAC)) with chitosan. In this context, semi-IPN hydrogel poultices based on poly (acrylamide-co-3-methacryloylpropyl trimethylammonium chloride)-chitosan were prepared via free radical polymerization of acrylamide (AAm) and the cationic comonomer 3-methacryloylpropyl trimethylammonium chloride (MAPTAC), using N, N'-methylenebisacrylamide (BAAm) as a crosslinker. Polymerization is carried out in the presence of chitosan, a natural cationic polymer, which may enhance the mechanical stability of the hydrogel poultices without the need to increase the crosslinker content [30].

2.1.3.2. *Polymeric PVA/CMC/PSD hydrogel*

A hydrogel poultice compress is synthesized through free-radical polymerization combined with a freeze-thaw technique, in which sulfobetaine methacrylate (SBMA) is covalently copolymerized with methacryloyloxyethyl trimethyl ammonium chloride (DMC) to form a zwitterionic copolymer known as PSD. This copolymer is incorporated into a hydrogel poultice network composed of polyvinyl alcohol (PVA) and carboxymethyl chitosan (CMC), enhancing the electrostatic interactions within the gel poultice and modifying its porous structure and water absorption capacity. The resulting hydrogel poultice exhibits high efficiency in absorbing dyes, such as rhodamine B and Congo red, as well as metal ions like copper and potassium. It has proven effective in cleaning wall painting mock-ups contaminated with dust, pigments, and salts, removing them without leaving visible or harmful residues. Thanks to its strong adhesion to rough surfaces, this hydrogel poultice represents a safe and efficient method for cleaning sensitive surfaces in artworks and heritage objects, marking a significant step forward in the development of smart and specialized cleaning materials for cultural heritage conservation [31].

2.1.3.3. *Agarose/polyacrylamide hybrid double-network gel*

This method uses a self-forming microemulsion gel poultice, prepared by emulsifying oil-loving solvents within a gel poultice matrix that exhibits strong adhesion to rough surfaces during cleaning processes. The hydrogel poultice confines solvent action to the targeted area, thereby enhancing treatment efficiency and minimizing undesired side effects. It can also be easily removed from the treated surface without leaving any noticeable residues, thanks to the mechanical reinforcement of its structure through the in-situ formation of a double polymeric network. The self-assembly behavior of the gel poultice significantly improves its effectiveness in removing unwanted layers, such as discolored coatings of Paraloid B72—a commonly used material in the consolidation and restoration of heritage objects. The gel poultice enables the efficient removal of such altered layers, making this strategy a promising approach for the precise and safe cleaning of rough archaeological and artistic surfaces using microemulsion-based gel poultices [32].

2.1.3.4. *Polyvinyl alcohol-borax/agarose (PVA-B/AG) double network hydrogel*

Agarose (AG) and polyvinyl alcohol cross-linked with borax (PVA-B) gel poultices have been widely used by conservation specialists as effective cleaning tools. However, incorporating agarose into PVA-B systems has led to the development of new hydrogel poultices with enhanced properties compared to conventional PVA-B gel poultices. These improved gel poultices overcome many of the limitations associated with traditional PVA-B gel poultices by enhancing the hydrogel's liquid retention capacity, increasing shape stability, and improving the mechanical strength of the mixture. Additionally, agarose helps reduce the problem of syneresis that occurs when PVA-B systems are loaded with low-polarity solvents or chelating agents. This makes agarose a novel and effective tool that can be added to the conservation specialist's toolkit for the preservation and maintenance of artworks. This system is particularly suitable for cleaning procedures involving rough and uneven surfaces, vertical surfaces, as well as applications requiring prolonged working times [33].

2.1.3.5. *Gellan gum combined with calcium compounds or titanium dioxide nanoparticles*

Incorporating gellan gum—a hydrogel poultice commonly employed in cleaning applications for cultural heritage materials, particularly paper—with either calcium-based deacidifying agents or titanium dioxide nanoparticles provides a dual-action effect. This integration enables surface cleaning and effective removal of discoloration caused by Aspergillus versicolor in a single treatment step. Additionally, the incorporation of titanium dioxide nanoparticles exhibits strong antimicrobial properties, suggesting its potential as a promising tool for the sustainable protection of cultural heritage objects. The use of these hybrid hydrogel poultices is further characterized by their ease of application and cost-effectiveness [34].

2.1.3.6. *OBC hydrogel (ozone-activated bacterial cellulose)*

The bacterial cellulose hydrogel (BC) is obtained from kombucha fermentation, sourced from a local Italian producer in Meda. It is subsequently treated with ozone to produce ozone-activated bacterial cellulose (OBC), a hydrogel poultice endowed with antimicrobial properties and suitable mechanical performance. This material demonstrates its potential as an effective, eco-friendly, and safe solution for combating the biodeterioration of stone materials. It shows complete elimination of bacterial and fungal microorganisms and a significant reduction in overall microbial activity. The innovative OBC hydrogel poultice represents a biodegradable, sustainable solution that addresses the drawbacks associated with traditional biocides and synthetic polymers. Its effectiveness and safety make it a practical and eco-friendly option for the cleaning and conservation of heritage stone materials, allowing sustainable practices in cultural heritage preservation [35].

3. Some Uses of Gel Poultices in the Archaeological Field

3.1. *Cleaning*

According to Fontaine et al. [36] 3% agar gel poultice was used as a medium for electrolyte transfer, loaded with a 1% potassium nitrate solution serving as the electrolyte agent, to remove localized chlorine from ferrous or copper-based alloys in metallic archaeological artifacts. The gel poultice was applied to the targeted surface for 30 minutes to prevent drying during treatment. In most cases, the procedure had to be repeated several times to ensure the complete removal of chlorides, And the results demonstrated the gel poultice's effectiveness in extracting chlorides efficiently, making it a promising option for stabilizing composite artifacts or for precise, localized treatment of copper-based objects. Accordingly, localized electrochemical treatment using agar gel poultice could be an innovative and effective solution in cultural heritage conservation. Agar gel poultice was employed by Diamond et al. [37] as an aqueous delivery system, loaded with Aquazol 50 and dry pigments, for the treatment of water-based stains on the surfaces of acrylic paintings. The gel functions as a protective medium, minimizing potential risks to the original materials of the artwork during treatment, And the results illustrated that this aqueous system offered an effective and safe cleaning method for delicate surfaces, without compromising the original paint layers on acrylic artworks. They also proved suitable for use on textiles and paper-based artworks. This approach demonstrated promising outcomes in terms of safety and efficacy, making it a viable option for precision conservation treatments on sensitive surfaces. According to Sáenz-Martínez et al. [38] a comparative evaluation was conducted to assess the effectiveness of various cleaning methods on archaeological ceramics using three chemical agents: A weak acid (acetic acid), a strong acid (nitric acid), and a chelating agent (EDTA). These agents were applied through different techniques, including direct application, immersion, cellulose-based poultices (Arbocel JRS), and a rigid gel poultice (Vanzan NF-C, CTS). The primary goal was to remove insoluble salt deposits from archaeological ceramic surfaces, Also, the result revealed apparent differences in cleaning performance depending on the chemical agent and the application technique. Immersion and cellulose pulp poultices yielded the most effective results, while the rigid gel poultice showed comparatively lower performance, regardless of the chemical agent used. Al-Emam et al. [39] mentioned that a double-network hydrogel poultice composed of polyvinyl alcohol–borax and agarose (PVA-B/AG) was selected and loaded with a cleaning mixture containing 5% ammonia, 0.3% ammonium carbonate, and 0.3% EDTA as a chelating agent. It was applied to remove thick crusts of soot deposits accumulated on the ceiling surfaces of the temple of Seti I in Abydos, Egypt, and the results proved the high effectiveness of this hydrogel poultice in eliminating the dense soot layers without causing any damage to the original surface materials following treatment, fig. (5).

Figure (5) removing thick crusts of soot deposits accumulated on the ceiling surfaces of the temple of Seti I in Abydos, Egypt, a before treatment, b after treatment [39]

Al-Emam et al. [40] reported that a polyvinyl alcohol–borax/agarose (PVA–B/AG) hydrogel poultice was used and loaded with a selection of organic solvents, including ethyl acetate (EA), propylene carbonate (PC), EA/PC mixtures, methyl ethyl ketone (MEK), and MEK blended with 1-propanol (1-PeOH), to identify the most effective formulation for removing and cleaning an aged varnish layer from the 19th- century neo-Gothic wall painting *The Last Judgment*, located in the chapel of Sint-Jan Berchmanscollege in Antwerp, Belgium, And the results demonstrated that the hydrogel poultice loaded with 10% propylene carbonate (PC) was the most effective and safest option for varnish removal. It enabled the successful restoration of the wall painting's original colors and textures without causing alterations to the paint layer, fig. (6).

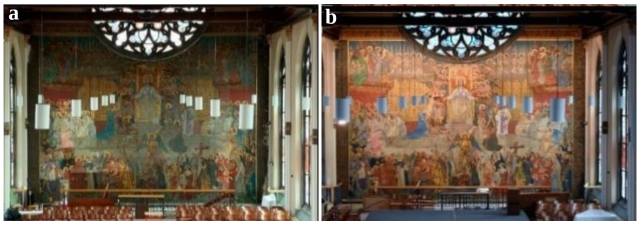

Figure (6) cleaning an aged varnish layer from the 19th -century neo-gothic wall painting, the last judgment in the chapel of Sint-Jan Berchmanscollege; **a.** The wall painting during the dark varnish removal. **b.** final results of the wall painting after removing the dark varnish layer

Moreover, no infiltration of the varnish into the preparatory layers was observed, and the treatment left no gel poultice residue on the cleaned surfaces. Poultices composed of sepiolite clay and silica fume (an ultrafine silica powder, a by-product of pure silicon or silicon alloy production proposed for use in heritage conservation, such as cleaning stone surfaces) were prepared by Gallo et al. [41] with benzalkonium chloride (BAC), a derivative of quaternary ammonium salt. BAC is widely used as a long-lasting disinfectant for surfaces, particularly stone, due to its potent antimicrobial activity and high chemical stability, and the results indicated that silica-based poultices were the most effective in the rapid release of ammonium salts, making them particularly suitable for surface disinfection applications on stone materials. The use of gel poultices made from calcium alginate (CA), a polysaccharide derived from brown algae, and borate-crosslinked konjac glucomannan (KGB), extracted from the tubers of *Amorphophallus konjac*, was proposed by Lee et al. [42] as a potential alternative to traditional agar gel poultices. These biopolymer gel poultices were loaded with an eco-friendly surfactant and applied for the removal of soiling and sweat residues from both smooth and rough wooden heritage surfaces, fig. (6) and the results demonstrated the effectiveness of these gel poultices in the conservation of wooden artefacts, offering efficient cleaning performance with mechanical properties superior to those of conventional agar gel poultice, particularly due to their reduced brittleness and rigidity. This performance was achieved with fewer cleaning applications, highlighting the practical advantages of CA and KGB gel poultices in heritage conservation. De France et al. [43] reported that a composite hydrogel poultice dressing was developed, featuring dual physical and chemical crosslinking, based on regenerated cellulose and cinnamoyl-modified gelatin. Regenerated cellulose was obtained by dissolution using specific solvents followed by regeneration in water, while the cinnamoyl groups introduced into the gelatin matrix facilitated chemical crosslinking. The hydrogel poultice was fabricated using a straightforward method involving the co-dissolution of cellulose and gelatin in an ionic liquid, followed by casting and regeneration in water. This approach is aimed at enhancing water retention capacity and providing an effective cleaning method for painting surfaces highly sensitive to water and solvents, and the resulting hydrogel poultice films demonstrated the ability to undergo photodimerization (chemical crosslinking) due to the uniform distribution of cinnamoyl groups throughout the matrix. Moreover, the dual crosslinked hydrogel poultice dressings exhibited superior mechanical strength and improved water-holding capacity when compared to physically crosslinked hydrogels alone. Zidan et al. [44] mentioned that the effectiveness of carbogel poultices was evaluated through the preparation of three distinct formulations by mixing carbogel poultice with distilled water, a water–ethanol mixture, and a water–acetone mixture. Each formulation was applied to samples of pine wood—a commonly used softwood in historical artifacts—for durations of 5, 10, and 15 minutes. The study aimed to assess their cleaning performance on softwood-based artifacts and to investigate the long-term effects of these treatments on the wooden substrate, and the results showed that all three formulations provided efficient and precise cleaning, without causing significant damage to the structural integrity of the wood or noticeable color changes. These results suggest that carbogel poultice is a promising and safe material for cleaning softwood elements in the conservation and restoration of wooden cultural heritage objects. Ali et al. [45] investigated the use of agarose gel poultice in cleaning the surface of albumen prints by preparing three types of poultices with different concentrations of agarose gel poultice (2%, 3%, and 4%). The first poultice combined agarose gel poultice with distilled water, the second with ethanol, and the third with toluene, and the results demonstrated that the poultices containing agarose gel poultice with distilled water and ethanol were effective in removing surface dirt, particularly at a 4% concentration. The combination of agarose gel poultice with toluene showed notable efficiency in eliminating adhesive residues. In all cases, these treatments were followed by simple mechanical cleaning using cotton swabs to remove any residues. Spile et al. [46] reported that a poultice composed of synthetic magnesium silicate clay (Laponite® RD) mixed with cellulose fibers (Arbocel® BC1000) was used to enhance the porosity, absorption capacity, and water retention of the mixture. In addition, a proportion of sodium carboxymethyl cellulose (CMC) was added to improve the rheological and mechanical properties of the poultice. The components were combined with water in a ratio of 10:10:1:86. This poultice was then loaded with a solution containing 0.1 M cysteine (Cys) and 0.1 M sodium dithionite (SD) to remove rust stains from naturally stained Greenlandic marble. The method was also applied in situ on a large rust-affected surface at the Marble Church in Copenhagen, Denmark, where rust staining occurred due to pyrite oxidation, and the results demonstrated the effectiveness of this poultice in eliminating rust stains from marble surfaces, fig. (7).

Figure (7) cleaning of naturally stained marble shows a cleaned and an uncleaned area, the piece at the right shows the poultice after removal.

The presence of sodium dithionite played a key role in accelerating cleaning by rapidly reducing ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}), which facilitated the removal of rust. The developed poultice proved to be a simple, fast, low-cost, and non-toxic method for manual application without the need for specialized equipment. Richard et al. [47] utilized agar gel poultice alone or a composite of agar and polyvinyl alcohol (PVA-B) loaded with high concentrations of solvents, such as methyl ethyl ketone (MEK) and ethyl acetate (EA), to remove aged rubber-based adhesive residues from the printed paper cover of a book. The treatment protocol incorporated the use of a silicone-based solvent, cyclomethicone D5, applied immediately prior to the application of the solvent-loaded gel poultice as a treatment aid, and the use of cyclomethicone D5 as a treatment aid achieved visually satisfactory results. Additionally, it demonstrated effectiveness in preventing the formation of stains and tidelines caused by color variation during localized gel poultice treatment. Voronina et al. [48] applied a poultice composed of a kaolin/sand/water mixture in a weight ratio of 1:5:0.2 to the surface of a porous fired-clay brick to extract soluble salts. The efficiency of salt extraction is highly dependent on the compatibility between the pore size distributions of both the brick and the poultice. For effective transport of salts, the poultice material must contain smaller pores than those of the underlying brick substrate, and the measurement results indicated that the accumulation of salts transferred from the brick to the poultice could enhance extraction efficiency due to the reduction in the effective pore size of the poultice material, which occurred due to osmotic pressure generated at the interface during drying. Li et al. [49] used two types of poultices in the electrokinetic desalination of the *Hamipterus* pterosaur fossils and the surrounding rock: A commercial paper pulp (Bioline®) and a composite material known as CKS121, composed of cellulose, kaolin, and sand in a 1:2:1 weight ratio, and the experimental results demonstrated that CKS121 exhibited slightly higher efficiency in salt removal compared to the Bioline® poultice. This difference could be partially due to variations in the physical properties of the poultice materials, particularly their pore size distribution. Additionally, the results indicated that both poultices were effective in reducing salt content, with approximately 70% removal on the surface of the fossils and 80% within the internal structure. These results underscored the effectiveness of direct current (DC) electrokinetic treatment in the desalination of fossil materials. Five types of poultices were tested by Lee et al. [3] for the removal of Paraloid B72, a resin used for fixing murals. The poultices included clay-based types (sepiolite and bentonite) and gel poultice types (laponite and sepiolite gel poultices), which were loaded with various solvents and solvent mixtures, such as acetone, ethanol, and methyl ethyl ketone (MEK), and the results indicated that most poultices achieved optimal removal efficiency when the solvents were used at a 50% concentration, while removal performance decreased at a 25% concentration. Among the solvents tested, MEK demonstrated the highest efficacy, whereas acetone and ethanol showed comparable but lower effectiveness. Additionally, clay-based poultices exhibited lower performance due to their faster drying rate, whereas gel-based poultices were more effective, benefiting from a longer solvent application time. Zhu et al. [50] used a hydrogel poultice composed of polyvinyl alcohol (PVA) through thermal treatment to effectively remove animal glue, commonly applied as a temporary protective layer on mural surfaces, without compromising the original layers of the artwork. By adjusting the concentration of PVA within the range of 8-11%, hydrogel poultices with appropriate hardness and flexibility were achieved, making them suitable for conservation applications. Upon heating, the hydrogel was applied to the surface treated with animal glue, causing partial dissolution, resulting in the controlled release of hot water enriched with PVA molecules. This hot water gradually softened and dissolved the animal glue, increasing its viscosity and promoting its adhesion to the undissolved portion of the hydrogel poultice. When the hydrogel poultice was removed, the dissolved glue was also lifted from the surface, leaving no residue or damage to the mural substrate, and this method offered a safe and efficient approach for the removal of animal glue from historical mural surfaces, reducing the risks associated with conventional techniques. Moreover, it provided a high degree of precision and control in the cleaning process, making it a suitable option for delicate conservation treatments for cultural heritage, while ensuring the integrity of the original material. To protect the pterosaur fossils excavated from the *Hamipterus*, Peng et al. [51] utilized four types of polysiloxane-based gel poultices, including a simple polysiloxane gel poultice derived from tetraethyl orthosilicate (TEOS), commonly used as a consolidant for stone materials, along with three hybrid polysiloxane gel poultices synthesized using TEOS combination with various organosilane monomers: ***)** *TEOS-BTME*: derived from bis(trimethoxysilyl)ethane, ***)** *TEOS-TMPE*: derived from γ-(2,3-epoxypropoxy) propyl-trimethoxysilane, and ***)** *TEOS-TMPM*: derived from 3-(trimethoxysilyl) propyl methacrylate. Furthermore, all hybrid gel poultices exhibited excellent permeability and good resistance to aging induced by light and heat exposure. However, their aging resistance was slightly lower than that of the pure TEOS-based gel poultice due to the presence of organic groups, which, in turn, imparted a degree of flexibility to the final solid network. These findings confirm that siloxane-based polymers are promising candidates for fossil conservation, though each formulation presents specific advantages and limitations. Among the tested materials, the TEOS-TPME hybrid gel poultice, incorporating epoxy functional groups, showed the most balanced and superior overall performance in terms of structural reinforcement, hardness, water resistance, and stability under environmental aging conditions. Smith et al. [52] applied a poultice composed of a methyl cellulose mixture and fumed silica powder, incorporating ammonium hydroxide to maintain a basic pH and propylene glycol to enhance the poultice's viscosity and flexibility. This formulation helped remove heavy coal dust and dirt from the surface of a small-scale marble replica of the Venus Italica statue, originally sculpted by the Italian artist Antonio Canova in 1812 and housed at the historic Culbertson Mansion in New Albany, and the results demonstrated that the poultice effectively removed thick layers of grime, especially in crevices and delicate areas of the statue, restoring the artwork with remarkable uniformity while preserving its fine details. Three different types of clay-based poultices, commonly used in the conservation of stone heritage sites, were employed according to Randazzo et al. [53]: ***)** A mixture of sepiolite and Arbocel in a 3:1 ratio; ***)** A combination of sepiolite, Arbocel, and sand in equal parts (6:6:6); ***)** Westox-Cocoon®, a commercial ready-to-use product composed of cellulose, absorbent siliceous earth, and distilled water. These poultices were applied to stone surfaces and mock-up wall sections designed to replicate the traditional mortar compositions historically used in the city of Palermo. The aim was to evaluate their effectiveness in extracting and removing water-soluble salts, and all treatments were generally effective in reducing salt concentrations, though apparent differences in performance were observed. Among the tested formulations, Westox-Cocoon® demonstrated the highest efficiency in terms of the amount of salt extracted. Vergès-Belmin et al. [54] mentioned that cellulose powder-based poultices, commercially known as Arbocel®, are widely employed in the conservation and restoration of stone buildings and mural paintings. These poultices are utilized primarily for the removal of soluble salts, as well as for surface consolidation and cleaning purposes, and the results indicated that the relatively uniform pore size distribution of Arbocel® poultices, approx. 10 micrometers, made them more suitable for substrates with medium to large pores (15 micrometers and above). However, their effectiveness decreased on substrates with fine pores (10 micrometers or smaller), where salt removal was less efficient. An organic gel poultice based on PMMA (polymethyl methacrylate) was utilized by Baglioni et al. [10], incorporating various solvents, for the removal of specific adhesive residues and other unwanted materials, including historical varnish layers from lined canvas samples and fine art canvas paintings. The type of solvent used in the preparation of the gel poultice could be modified to selectively target different types of coatings or other un-desirable surface layers, and the results demonstrated the effectiveness of the PMMA-based gel poultice in removing historical varnishes. One of its key advantages is its transparency, which allows continuous visual monitoring of the treated surface during application. This characteristic makes it a suitable chemical alternative to conventional physical gel poultices, particularly in terms of the ability to confine solvents efficiently and applicability in delicate cleaning operations Kaniewska et al. [27] reported that a gel poultice composed of pNIPA (N-isopropylacrylamide) – LAP (Laponite XLS synthetic hectorite nanoclay), loaded with a mixture of organic solvents (35% isopropanol, 45% isooctane, and 20% acetone), was employed to remove the lining adhesive—composed of beeswax and resin—from the reverse side of the 1878 painting *Battle of Grunewald* by Jan Matejko. The same cleaning method was also applied to two additional oil paintings: *Zinnias in a Blue Vase* (a privately-owned work by an unknown artist, dated to 1930) and *Empress Catherine* (from the collection of the National Museum in Warsaw, also by an unknown artist), and the experimental results demonstrated that the direct application of the pNIPA–LAP gel poultice onto the canvas for periods exceeding 20 minutes enabled the efficient removal of the wax-resin adhesive. The short contact time was a significant advantage, as it reduced solvent exposure to the original paint layers. Analytical testing confirmed that the gel poultice was effectively safe for the key components of the artworks, including cellulose and oxidized oils. Following cleaning, the paintings recovered their original gloss and color intensity, and their reverse sides were rendered ready for the application of new conservation layers without requiring further treatment, fig. (8)

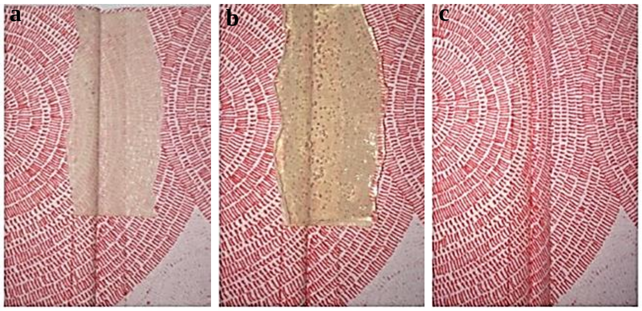

Figure (8) the "Zinnias in a Blue Vase" (a privately-owned work by an unknown artist, dated to 1930) and Empress Catherine (from the collection of the National Museum in Warsaw, also by an unknown artist), **a.** before treatment, **b.** during usage the poultice, **c.** after treatment [27]

Mirabile et al. [55] investigated the use of a hydrogel poultice composed of pHEMA/PVP loaded with a nanofluid derived from EAPC, which consisted of oil-in-water (O/W) emulsions prepared using ethyl acetate (EA) and propylene carbonate (PC) as the dispersed organic phase. Another hydrogel poultice composed of PEMA loaded with an organic solvent, diethyl carbonate (DEC), was utilized. The aim was to clean and remove pressure-sensitive tapes (PSTs) from the surfaces of paper-based artworks, and the results demonstrated the efficiency and effectiveness of both hydrogel poultices (pHEMA/PVP-EAPC and PEMA-DEC) in controlled solvent release and the permeation of the nanofluid, enabling the removal of various types of pressure-sensitive tapes (PSTs) without affecting the chemical, physical, or optical properties of the paper artworks. Additionally, no adhesive residues, color bleeding, or paper delamination were observed, fig. (9).

Figure (9) removing pressure-sensitive tapes (PSTs) from the surfaces of paper-based artworks **a.** detail of the PST, **b.** applying p(HEMA)/PVP EAPC gel poultice, on top of the PST, **c.** the same area after removing the PST and adhesive [55]

3.2. *Neutralizing acidity and improving mechanical properties*

The use of agar poultices was reported by Salim et al. [56] at concentrations of 3% and 6% to investigate their effectiveness in disinfection, deacidification, and other conservation treatments of paper manuscripts. Various barrier materials, i.e., rayon, pure linen, and Japanese gampi paper, were applied between the agar gel and the paper surface to minimize potentially harmful residues left by the poultice, and the results showed that a 3% agar-borax poultice achieved significant success in neutralizing acidity and improving the mechanical properties of the treated paper. Among the tested barriers, pure linen provided the most favorable results, as no visible residues were observed after treatment. This outcome highlighted the effectiveness of the agar-borax poultice, particularly when combined with a linen barrier, in preserving the integrity of cellulose fibers during conservation interventions. A 2% gellan gum hydrogel was mentioned by Botti et al. [57]. It was prepared and loaded with a ready-made deacidification agent, calcium propionate $Ca(C_2H_5COO)_2$, at a concentration of 3.5-5 g/L. This method was applied as an alternative approach for the cleaning and deacidification treatment of paper artworks dating back to the seventeenth century, and the results demonstrated that deacidification using the 2% gellan gum hydrogel poultice increased the pH values more than traditional immersion methods, while leaving a notable amount of alkaline reserve, fig. (10).

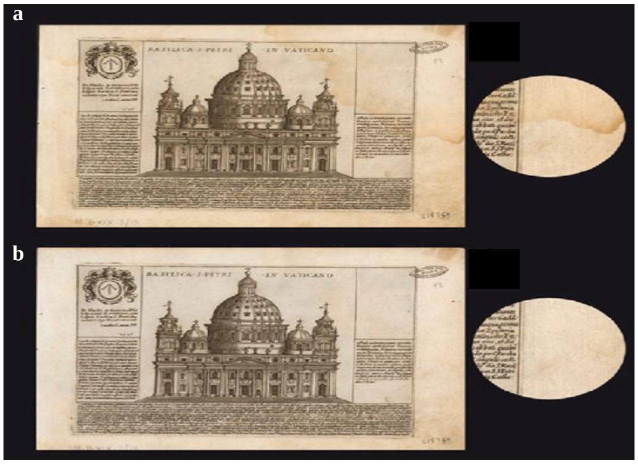

Figure (10) neutralizing the acidity of the burin engraving Basilica S. Petri in Vaticano (1626) by Giacomo Lauro, a before treatment, b after treatment with gellan gum poultice [57]

Additionally, mechanical testing and colorimetric analysis of the papers treated with the gellan gum hydrogel poultice showed a slight improvement in tensile strength, indicating the effectiveness and safety of the hydrogel poultice application. This finding contributes positively to the preservation of archival heritage. Two types of clay poultices were mentioned by Siddique et al. [58] to evaluate the efficiency of electrokinetic (EK) desalination in removing a mixture of water-soluble salts, namely sodium chloride, sodium sulfate, and sodium nitrate, from fired-clay brick. The first poultice consisted solely of kaolin clay, while the second was enhanced with pH-buffering agents, specifically calcium carbonate ($CaCO_3$) and acetic acid (CH_3COOH). The EK treatment was conducted by applying a constant direct electric field of 1 V/cm for 24 hours, and the Clay poultices enriched with pH-buffering agents were highly effective in minimizing pH fluctuations and enhancing the removal efficiency of salt ions from the mixed salt solution. Removal rates reached 66% for sodium, 80% for chloride, 79% for sulfate, and 72% for nitrate within the first 24 hours of treatment. These results suggested that most ion migration occurred within the initial 24-hour period, and extending the treatment duration beyond this point may yield diminishing returns. Additionally, the buffered poultice proved effective in mitigating acidic and alkaline conditions even after 48 hours of treatment when the bricks were contaminated with sodium chloride.

3.3. *Antioxidant treatment*

A rigid gel poultice composed of gellan gum at a concentration between 2% and 4%, combined with 3% benzotriazole (BTA) in 96% ethanol, was applied by Humenuck [59] for the stabilization and treatment of paper damaged by verdigris. The treatment was conducted on a historical artifact known as the "Languedoc Map," a mid-17th-century French map printed on handmade laid rag paper, and the results demonstrated the effectiveness of the gellan gum gel poultice, particularly when loaded with BTA, commonly used as a copper corrosion inhibitor. This formulation proved beneficial in treating paper-based artworks containing copper compounds. It successfully complexed free copper ions, potentially limiting further degradation of the paper. Rapti et al. [60] applied semi-rigid agarose hydrogel poultices, adjusted to pH levels of 6.5 and 8.6, and loaded with desferrioxamine B (DFO-B), a siderophore representing a new group of environmentally friendly chelating agents, which was explored in the conservation of paper and waterlogged wood. These agents feature a strong affinity for ferric ions, which allows them to inhibit the formation of harmful free radicals and reduce potential environmental risks. The study aimed to remove common iron corrosion products, such as akaganeite (β-FeOOH) and maghemite (γ-Fe_2O_3), found on archaeological wooden objects that incorporate metal components like handles, nails, keys, frames, and hinges. These metal elements are prone to corrosion in environments where relative humidity exceeds 65%, leading to the formation of iron oxides and hydroxy-oxides, and the most effective formulation of DFO-B was the alkaline hydrogel poultice (pH 8.6), followed by the acidic hydrogel poultice (pH 6.5). No alterations were observed in the chemical composition or color of the wood when either of these pH-adjusted hydrogels was applied. Furthermore, the ethanol-based gel poultice containing DFO-B proved to be a promising alternative to aqueous hydrogel poultices when treating water-sensitive wooden substrates. In addition, agarose residues were found to be minimal, indicating that the cleaning protocol employed was successful in mitigating one of the known limitations associated with gel poultices treatments. Tamburini et al. [61] reported that the hydrogel poultice composed of poly (2-hydroxyethyl methacrylate) and poly(vinylpyrrolidone) (pHEMA/PVP) loaded with maleic anhydride (MA), was developed for cleaning copper stains from artworks. It was tested using marble samples stained with brochantite ($CuSO_4 \cdot 3Cu(OH)_2$), a common compound found in corrosion layers on external bronze surfaces, serving as a typical simulation of heritage surfaces stained with copper, and the specific incorporation of maleic anhydride (MA) into the hydrogel poultice network achieved superior copper removal from marble surfaces. Figure (11) exhibiting a copper removal capacity four times greater than the original hydrogel poultice. This improvement could be attributed to MA's role as a metal chelating agent, which enhanced the removal of metal stains while remaining bound to the hydrogel poultice matrix without leaving any residues. It is significant because it is the first application of MA in cleaning formulations designed for cultural heritage, despite its previous use in pharmaceuticals and plastics. A hydrogel poultice based on agar mixed with 5% tetrasodium EDTA was applied by Guilminot [62] 5 minutes to an Armenian censer in the collection of the Musée de la Fondation Eugène Delacroix (Musée Dobré), composed of gilded copper and decorated using chasing, engraving, and openwork techniques. The aim was to remove a thick corrosion layer obscuring the gilding, as well as a heavily soiled varnish layer. Cleaning was continued by applying another agar hydrogel poultice, combined with 2.5% disodium EDTA for an additional 5 minutes. The surface was then rinsed using deionized water and a cotton swab.

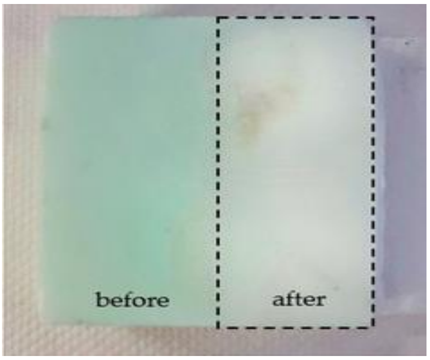

Figure (11) removing copper stained from marbel surfaces with developed hydrogel poultice composed of poly (2-hydroxyethyl methacrylate) and poly(vinylpyrrolidone) (pHEMA/PVP) loaded with maleic anhydride (MA), before and after contact for 60 min [61]

This agar gel poultice treatment yielded highly satisfactory results according to conservators, effectively removing corrosion products, dirt, and varnishing residues from the copper surface while preserving the decorative details and the original gilded layer, fig. (12). Zha et al. [63] mentioned that carboxymethyl chitosan (CMCS), a natural derivative of chitosan known for its biocompatibility, biodegradability, metal chelating ability, and amine and carboxyl functional groups, was employed as the base material. It was loaded with tannic acid (TA), a naturally occurring plant-derived compound rich in reactive phenolic groups, to remove a protective polyethylene glycol (PEG) layer and iron deposits from archaeological wooden components of the Nanhai I shipwreck. Nanhai I is a Southern Song Dynasty (1127-1279 AD) merchant vessel salvaged in 2007 and currently housed at the Maritime Silk Road Museum in Guangdong, China .The interaction between CMCS and TA formed a stable three-dimensional hydrogel poultice network upon drying. This gel poultice effectively removed iron residues and PEG deposits from the shipwreck's wooden structure while preserving the structural integrity of the archaeological wood. Thus, this hydrogel poultice system is proposed as a safe, efficient, and field-applicable solution for the cleaning of immovable heritage objects.

Figure (12) removing a thick corrosion layer obscuring the gilding, as well as a heavily soiled varnish layer from Armenian censer in the collection of the Musée de la Fondation Eugène Delacroix (Musée Dobré), composed of gilded copper and decorated using chasing, engraving, and openwork techniques [62].

3.4. *Biological treatment*

Filpo et al. [34] used gellan gum hydrogel poultices loaded with various substances, including calcium compounds (sulfate, hydroxide, chloride, and acetate), titanium dioxide nanoparticles, and calcium acetate, to deacidify, clean, and disinfect stains on the pages of an old book affected by *Aspergillus versicolor*, and these experimental results confirmed the effectiveness of the compresses and the active materials in stain removal. However, the highest cleaning efficiency was observed with hydrogel poultices containing either calcium acetate or titanium dioxide nanoparticles, fig. (13).

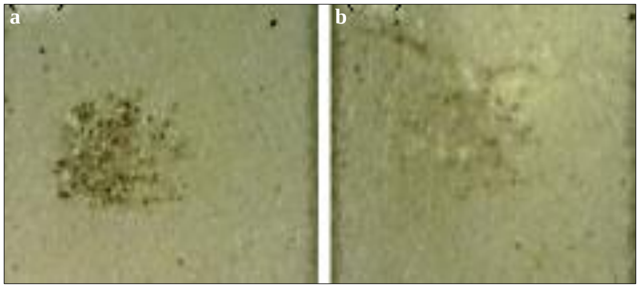

Figure (12) cleaning stains on the pages of an old book affected by Aspergillus versicolor, **a.** before treatment, **b.** after treatment [34]

Notably, these hydrogel poultices compresses did not cause any adverse effects on the inks used in the book's printing. Barrulas et al. [64] showed the effectiveness of agarose- and gellan gum-based hydrogel poultices in removing common fungal pigments from historic paper manuscripts. This aim was achieved by applying these hydrogel poultices onto paper samples impregnated with alizarin, a model compound that simulated fungal pigments of the poly-ketonic quinone type. The study also examined the influence of pH variations in the hydrogel poultices on cleaning efficiency and the absorption of polyphenolic compounds. The potential of agarose and gellan gum hydrogel poultices was demonstrated in removing fungal stains from historic paper. Moreover, pH adjustment of these hydrogel systems may serve as a valuable tool to regulate the interactions between the polymer matrix and alizarin-like compounds on the paper surface. Mansour et al. [65] tested three poultices composed of carboxymethyl cellulose (CMC) and plant-derived phytagel (PGP), each loaded with different volumes (1, 2, and 4 ml) of titanium dioxide nanoparticles (TiO_2NPs), to protect manuscripts from microbial contamination using safe and environment-friendly materials. The objective was to develop an effective and sustainable method for manuscript preservation, and the findings demonstrated that these poultices have promising antibacterial properties. Notably, the formulation containing 2 mL of TiO_2NPs exhibited the highest efficacy in inhibiting the growth of *Aspergillus sydowii* and *Nevskia terrae*. These results highlighted the potential of such poultices as eco-friendly alternatives for the conservation and protection of historical manuscripts.

4. Conclusion

Hydrogel poultices are promising functional materials for cultural heritage conservation. Their high-water content, ability to retain both organic and inorganic solvents, as well as their tunable mechanical and physical properties, make them particularly suitable for use on highly sensitive archaeological materials. These poultices offer unique characteristics that allow for indirect treatment methods, avoiding penetration of the artifact's surface or leaving residues. They demonstrated effectiveness in a wide range of conservation applications, including cleaning, treatment of waterlogged archaeological wood, and controlled, uniform delivery of stabilizing agents or pH regulators. Hydrogel poultices have been successfully applied to various archaeological materials, such as wood, stone, bone, wall paintings, and paper, while preserving the physical and chemical integrity of the original surfaces. They also enable precise and gentle removal of surface contaminants like soot, salts, and aged varnishes, minimizing the risk of chemical or mechanical damage to fragile surfaces. Additionally, they can be used to eliminate unwanted substances, such as acids or oxides, from or within artifact surfaces. Thanks to these advantages, hydrogel poultices represent a rapidly developing area with significant potential for broad application in cultural heritage conservation. Their use aligns with environmentally sustainable practices, especially when formulated from renewable, non-toxic natural polymers, such as chitosan, alginates, cellulose derivatives, and gelatin. They not only adhere to the principles of green chemistry but also exhibit good compatibility with the surfaces of valuable artifacts.

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