# A review on deterioration of textile cultural heritage objects and sustainable solutions to mitigate the degradation

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ABSTRACT – REZUMAT

**A review on deterioration of textile cultural heritage objects and sustainable solutions to mitigate the degradation**

*Heritage textiles are important evidence of human history. Folk costumes, quilts, tapestries, rugs, hangings, etc. constitute a rich collection of products that are particularly valuable but also extremely fragile. This paper presents the main causes of the deterioration of heritage textiles, followed by a summary of the main bio-treatments that are effective in their case. Essential oils and plant extracts have a strong antibacterial, antifungal and insecticidal effect and are therefore recommended to be used as sustainable alternatives to conventional treatments. At present, bio-treatments used to prevent and reduce the deterioration of heritage textiles are carried out in two ways. One of them targets bioaerosols in museum spaces and the second one targets microbial agents on the surface or in the structure of textiles. The application of bio-treatments on heritage textiles should be done taking into account the specific features given by their fibrous composition, the structure of the materials, their age, the environmental conditions in which they are, etc. At present, these treatments are not yet commonly used for heritage textiles or the spaces in which they are stored or exhibited, even though there are studies that have proven the effectiveness and safety of their use.*

***Keywords:*** *heritage textile, essential oils, plant extracts, antibacterial, antifungal, antimicrobial*

**O analiză a cauzelor deteriorării produselor textile din patrimoniul cultural și soluții durabile pentru atenuarea degradării acestora**

*Textilele de patrimoniu constituie dovezi importante ale istoriei omenești. Costumele populare, cuverturile, tapițeriile, covoarele, ștergarele etc. constituie o colecție bogată de produse care sunt deosebit de prețioase, dar în aceeași măsură și extrem de fragile. În acest articol, sunt prezentate principalele cauze ale deteriorării textilelor de patrimoniu și o sinteza a principalelor bio-tratamente care s-au dovedit a fi eficiente în cazul acestora. Uleiurile esențiale și extractele de plante au un puternic efect antibacterian, antifungic, insecticid și de aceea ele sunt recomandate a fi utilizate ca alternative sustenabile la tratamentele convenționale. La ora actuală, bio-tratamentele folosite în scopul prevenirii și diminuării deteriorării textilelor de patrimoniu sunt realizate pe două direcții. Una dintre ele vizează bioaerosolii din spațiile muzeale și cea de-a doua vizează agenții microbieni aflați pe suprafața sau în structura materialelor textile. Aplicarea bio-tratamentelor pe textilele de patrimoniu trebuie realizată ținând cont de particularitățile specifice date de compoziția fibroasă a acestora, structura materialelor, vechimea lor, condițiile de mediu în care sunt depozitate etc. La ora actuală, aceste tratamente nu sunt încă utilizate în mod uzual în cazul textilelor de patrimoniu sau a spațiilor în care acestea sunt depozitate sau expuse, chiar dacă există studii care au dovedit eficiența și siguranța utilizării acestora.*

***Cuvinte cheie:*** *textile de patrimoniu, uleiuri esențiale, extracte de plante, antibacterial, antifungic, antimicrobian*

## INTRODUCTION

Textiles are an important part of cultural heritage values, which must be preserved and passed on to future generations. Textiles are testimonies of technology, fashion, aesthetics and social life of a certain period, providing information on unpublished aspects of daily life in the past. Most heritage textiles have become part of the collections of museums or various exhibitions, having previously been worn, more or less, by different categories of wearers, on the occasion of different events or even daily. The main factors that may have left their mark on these textiles are environmental conditions (temperature, humidity, exposure to light, microbial contamination, etc.). These factors can also affect them after they have become part of the heritage of a museum, exhibition, etc. In addition to these natural factors, heritage textiles can also be affected by the interventions of restorers. Heritage textiles can undergo ageing, deterioration and decay processes that profoundly affect their beauty and their economic and ethnological value. Analysis of the causes of degradation is of paramount importance to protect heritage items and prevent their deterioration. It is also particularly important that the methods used to prevent the deterioration of heritage textiles are not only effective but also sustainable.

**This paper aims** to show that essential oils and plant extracts can be successfully applied to heritage textiles due to their antimicrobial effects, thus complementing the fields in which they are more commonly used, namely: everyday clothing, protective clothing, and medical textiles.

**Methods of scientific research** that have been used in the paper are data collection, analysis and interpretation, and summarizing of literature. The first part of the paper there are presents and analyses the most common causes of the deterioration of heritage textiles and the second part there are presents the bio-treatments used to prevent and reduce the deterioration of heritage textiles in the two ways in which they can be applied.

## FACTORS OF DETERIORATION OF TEXTILE CULTURAL HERITAGE OBJECTS

The deterioration processes of heritage textiles are caused by: the action of physical-chemical factors, microbial degradation and deterioration and mistakes in human treatment.

### Physical and chemical factors contributing to the deterioration of heritage textiles

The main causes of degradation of heritage textiles are considered to be light, heat and oxygen. Light, which is so necessary for the enhancement of exhibits, can cause their degradation. This includes both natural and artificial light, the latter being less harmful because it is relatively constant in intensity and because it can be controlled and dosed in intensity, type, time and distance.

The visible effects of light on coloured textiles are fading of colour or spots, and the less visible effects are decreases in tear and tensile strength of the materials [1].

These effects depend on the raw material from which the textiles are made. For example, light exposure to wool products causes yellowing or bleaching. The critical factors that influence the yellowing of wool by light are the light's wavelength distribution (UV radiation), humidity and the type of pre-bleach applied to the wool. The photobleaching of yellow pigments is encouraged by visible blue light (maximal effect 420–540 nm) exposure of wool, therefore promoting unwanted colour changes, especially in the case of wool products that have been dyed to pastel colours [2].

Exposure of wool to UV radiation at wavelengths between 380–475 nm causes not only a change in colour but also a decrease in fibre strength [3]. Treigiené and Musnickas have shown that the tensile strength of wool fibres decreases by between 8 and 20% when exposed to UV radiation for between 40 and 120 hours [4]. Cotton fibres are sensitive to UV radiation between 200 and 300 nm. The most common photochemical damage to cotton occurs through photo-oxidation. As a result of this process cotton fibres change colour and mechanical properties – they become stiffer, more brittle and have a much lower tensile strength. Cotton fibres subjected to radiation show lower strength than wool and silk fibres [5]. Another fibre that has a long and important place in the history of textile production is silk fibres. They are strongly affected by radiation of wavelengths between 220–370 nm, radiation that causes photodegradation. "Irreversible" changes in colour and affect physical properties of fabric, such as strength and elasticity, are all causes of silk photodegradation [6].

In the case of linen fabrics, UV rays cause their colour to change and their tensile strength to decrease [7].

In the case of synthetic fibres, light sensitivity manifests itself differently, depending on chemical composition and stabilization. The most resistant are polyester fibres, followed by polyacrylonitrile and polyamide [8]. For these types of fibres, exposure to light causes different degrees of yellowing, a decrease in mechanical strength and a decrease in the degree of polymerization [1].

Temperature is another microclimate factor involved in the deterioration of heritage goods, influencing chemical reactions (oxidation reactions, hydrolysis reactions, etc.) through energy transfer, causing accelerated molecular agitation. Its variations can be determined either by the exchange of heat with the external environment or by variations in the humidity of the internal environment. Temperature is also one of the factors that can contribute to the growth of different types of microorganisms [8].

### Microbial degradation and deterioration of heritage textiles

Heritage textiles serve as a substrate for microbial growth, which is frequently undetectable unless the biofilm over-agglomerates and discolours or damages the fabric's physical integrity [9].

Depending on the species of organism attacking the material and its properties, biodegradation of textiles results in various sorts of damage. The growth of micro-organisms on cultural heritage textiles often causes serious aesthetic damage due to the formation of colonies and fungal pigments. Vornicu and Bibire [10] classify the factors favouring biodeterioration into 3 groups, namely: meteo-climatic, physico-chemical and mechanical and biotic and show that the rate of deterioration and the type of degradation depends on these factors but also the simultaneity of their action. Humidity and relatively high temperatures, associated with lack of light and air, favour the growth of microorganisms. The optimum temperature for the growth of most micro-organisms is in the range 20–35°C. At low temperatures, in winter, fungal spores are very resistant due to their shape and cell envelope and their ability to remain dormant. Raising or lowering the temperature above or below the optimal value for the development of microbiodeteriogens prevents their multiplication. Oxygen also plays an essential role because most micro-organisms that grow on art objects are aerobic [10]. Microorganisms use the components of textile materials (carbon, nitrogen, sulphur, phosphorus) to grow and multiply [11].

Studies have shown that the microbial flora grown on fabrics made from plant fibres is different from that grown on fabrics made from animal fibres. The most frequent biodeteriogens of cellulosic textiles are microfungi (*Alternaria, Aspergillus, Cladosporium, Fusarium, Memnoniella, Myrothecium, Neurospora, Paecilomyces, Penicillium, Scopulariopsis, Stachybotrys, Stemphylium, Trichoderma, Trichothecium, Verticillium*) and bacteria (*Arthrobacter, Bacillus, Cellvibrio, Cellfalcicula, Cellulomonas, Clostridium, Microspora, Sporocytophagamyxococcoide*) [10, 12–15]. Textiles made from flax and cotton plant fibres are prone to deterioration because they are rich in hemicellulose and pectin which are easily degradable by microorganisms. In the case of these textile items, microbial growth leads to changes in appearance, such as discolouration, and loss of strength and elongation [14]. The non-cellulosic components of hemp and jute textiles, such as lignin, give the fabric a greater resistance to degradation because few microorganisms possess enzymes capable of degrading them [16].

Wool and silk textiles are more resistant than vegetable textiles due to the keratin in wool and the fibroin in silk. Microorganisms such as *Trichophyton* and *Trichoderma* attack the disulfide bonds that hold the keratin chains together and are thus the main factors in wool degradation [14]. Wool is also easily attacked by insects. Silk is very sensitive to light and this favours the modification of the fibroin structure by various bacteria (*Bacillus, Pseudomonas, Serratia* and *Streptomyces*) and fungi (*Aspergillus*). Synthetic fibres are resistant to the action of bacteria and fungi. Besides these microorganisms, heritage textiles can also be attacked by some insects such as moths, beetles and ants which act destructively on all types of fibres except synthetic ones. In addition to these microorganisms, heritage textiles can be attacked by some insects such as moths, beetles and ants which act destructively on all types of fibres except synthetic ones [8].

In addition to the above-mentioned factors, known in the literature as exogenous factors, there are endogenous/internal factors that influence the biodeterioration of heritage textiles. The most relevant of these are the nature and type of raw materials; the structure of the materials; the presence and nature of biological attack; the nature and treatments carried out for conservation; the physicochemical and mechanical treatments to which they have been subjected; and the age of the material. The structural characteristics of the surface of the textile material such as type of bonding, thickness, absorbency/hydrophobicity, etc. are essential for the adhesion of microorganisms, their colonization and spread [17].

### Incorrect human treatments in the conservation of heritage textiles

Heritage textiles can also be affected by the interventions of restorers [18]. Incorrect conservation can play a role in harming cultural heritage objects. In many cases, the consolidation of broken fabrics has been achieved by applying adhesives. These can be of animal origin – usually composed of collagen, obtained from bones, cartilages, tendons and skins of different mammals and fish, or vegetable origin – starch, derived from barley, corn, oat, rye, rice, potato and wheat [19, 20].

When using animal glue, factors such as temperature, light, and humidity can lead to the cross-linking of proteins and the oxidation of peptide bonds, while microbial flora invasion might encourage the appearance of undesired pigments.

When applying plant-based adhesives, it was found that the starch paste not only causes the yellowing of the material but also its strengthening/stiffening, constituting a habitat rich in nutrients for the development of bacteria and fungi, which favour the deterioration of textiles over time [20].

## BIO-TREATMENTS APPLIED TO HERITAGE TEXTILES

The bio-treatments used to prevent and reduce the deterioration of heritage textiles are carried out in two ways. One targets bioaerosols and insects in museum spaces and the second targets microbial agents on the surface or in the structure of textiles.

The presence of high levels of bioaerosols in the air inside museum spaces is associated with a higher risk of biodeterioration of art object surfaces. High levels of bioaerosols are also associated with poor indoor air quality, which can reduce visitor comfort and increase health risks for visitors and those working in these spaces [21–23]. The very large number of museum visitors of different nationalities make cultural heritage objects "*important bridge nodes in the global network of pathogen spread*" [24].

Essential oils have a strong antibacterial, antifungal and insecticidal effect and are therefore recommended to be used for treating air in closed spaces [25,26]. Díaz-Alonso et al. evaluated the effectiveness of the *Melaleuca alternifolia* and *Thymus vulgaris* essential oils in reducing bacterial and fungal contamination of air in unventilated indoor spaces. The vaporization of tea tree essential oil showed the best results allowing a 77.3% reduction in air contamination for fungi and 95.0% for bacteria, respectively. They tested the efficacy of the *Melaleuca alternifolia* essential oil in the Camarín of Santos Juanes church of Valencia, Spain. The results showed improved air quality and no damage to artistic surfaces [27].

Ethanol 70%, deltamethrin (commercial pesticide, CP), *Pinus regida* essential oil (EO), and low oxygen microenvironment (LOM, 0.1%) were tested as fumigants individually and jointly by Abdelrahman et al. against *Alternaria alternata*, a fungal strain found in museums. The outcomes demonstrated the rate of mycelial growth suppression following each fumigation, the rise in the fungicidal activity of each chemical (CP or EO) when applied to LOM, and the progression of the EO's action from fungistatic to fungicidal upon combining with LOM [28].

Promising results were also obtained by WANG et al., who also tested by fumigation the efficacy of essential oils against 4 museum insect pests (*Lasioderma serricorne, Sitophilus zeamais, Tribolium confusum* and *Falsogastrallus sauteri)*. Out of the 13 essential oils studied, 4 *(muskmelon oil, geranium oil, spikenard oil* and *patchouli oil)* have demonstrated strong insecticidal effects against the four pests [29].

Faheem and Abdurraheem tested the efficacy of botanical fumigants with the essential oils of *Ferula asafoetida, Syzygium aromaticum,* and *Mentha piperita* against larvae of *Anthrenus verbasci*. They showed that the EO of *Mentha piperita* was the most effective, followed by *Syzygium aromaticum* and *Ferula asafoetida.* Their study also revealed that although there are numerous important biodeteriogens, museums do not take proper action to control and prevent the damage they cause. They recommend integrating natural and traditional methods in the museum's Integrated Pest Management (IPM) strategies, not only for the safety of the museums' valuable collections but also for the safety of their environment, their employees and visitors [30].

Even if the bio-treatments targeting the air inside museum spaces and the insects in these spaces are not yet widely applied, we are convinced that they will in the future complement preventive conservation measures for heritage textiles (adequate ventilation of the spaces, maintaining a relative air humidity around 55%, a temperature around 20°C, and maximum room illumination levels of 50 lx and 50,000 lx-hours per year, as recommended overall exposure limits) [31, 32].

The effectiveness of bio-treatments on different types of textiles has been proven by numerous studies. The antimicrobial effects of numerous plant extracts and essential oils, applied to different types of materials, made from different raw materials, have been studied (table 1).

The application of essential oils and plant extracts on heritage textiles should be done taking into account

Table 1

ANTIMICROBIAL EFFECTS OF NUMEROUS PLANT EXTRACTS AND ESSENTIAL OILS APPLIED TO DIFFERENT TYPES OF MATERIALS

| Biotreatment applied | Material on which it was applied | Micro-organisms against which the applied treatments work | Reference |
|---|---|---|---|
| *Punica granatum L.*, (pomegranate) peel extract | Cotton fabric | – *Staphylococcus aureus* and *Aspergillus niger* | [33] |
| *Punica granatum* peel extracts | Hemp fabric | – *Staphylococcus aureus* and *Klebsiella pneumoniae*<br>Effectiveness rate of 99,99% | [34] |
| Pomegranate, neem and turmeric extracts | Cotton fabric, used for medical purposes | High effectiveness against gram-negative bacteria | [35] |
| Peony, pomegranate, clove, *Coptis chinenis* and gallnut extracts | Cotton, Silk, and Wool fabrics | – *Staphylococcus aureus* – reduction rate: 96,8–99,9%<br>– *Klebsiella pneumoniae* – reduction rate: 95,7–99,9% (exception: extraction from peony) | [36] |
| *Rosmarinus officinalis* (rosemary) EO | mix of cotton (56%) and polyester (44%) | – *Aspergillus niger* – reduction rate of maximum 22,12%<br>– *Candida albicans* – reduction rate of 100%<br>– *Trichoderma viride* – reduction rate of maximum 76,48%<br>– *Aspergillus flavus* – the maximum efficiency of the treatment was 18,3%<br>– *Epidermophyton floccosum dermatophyte* – reduction rate of maximum 56,99% | [37] |
| *Citrus sinensis* (orange) EO | mix of cotton (56%) and polyester (44%) | – *Aspergillus niger* – reduction rate of maximum 51,45%<br>– *Candida albicans* – reduction rate of 100%<br>– *Trichoderma viride* – reduction rate of 100%<br>– *Aspergillus flavus* – the maximum efficiency of the treatment was 60,57%<br>– *Epidermophyton floccosum dermatophyte* – maximum reduction rate: 92,48% | [37] |
| Thyme EO | Linen-cotton blended fabric (55% linen and 45% cotton) | *Corynebacterium xerosis, Bacillus licheniformis, Micrococcus luteus, Staphyloccocus haemolyticus, Staphyloccocus aureus, Escherichia coli, Klebsiella pneumoniae, Pseudomonas aeruginosa* | [38] |
| Aloe gel extract | Cotton fabric | – *Staphylococcus aureus* | [39, 40] |
| Extracted from neem plants | Cotton fabric | – *Staphylococcus aureus* | [40] |

Table 1 (continuation)

| Biotreatment applied | Material on which it was applied | Micro-organisms against which the applied treatments work | Reference |
|---|---|---|---|
| Hybrid combination of extracted from aloe vera and neem plants | Cotton fabric | – *Escherichia coli* and *Aspergillus niger* | [40] |
| *Moringa stenopetala* seed oil | Cotton fabric | – *Staphylococcus aureus* and *Escherichia coli* | [41] |
| Olive oil | Cotton fabric | – *Staphylococcus aureus* and *Escherichia coli* | [42] |
| Herbal extracts – chamomile, sage and green tea | Cotton fabric | – Gram negative bacteria – *Salmonella tyhimurium, Escherichia coli*<br>– Gram positive bacteria – *Bacillus subtilis, Bacillus cereus, Staphylococcus aureus*<br>– unicellular fungi – *Candida albicans, Candida tropical's, Candida pseudo tropical's* | [43] |
| Eucalyptus leaf extracts – *E.cinera* and *E.odorata* | Cotton fabric<br>Wool fabric | – *Staphylococcus aureus* and *Escherichia coli* (*E. odorata* extract)<br>– Higher efficiency in the case of wool textiles | [44] |
| *Murraya Koengii* (curry leave) and *Zingiber Officinale* (ginger) oil | Cotton fabric | – Gram positive bacteria – *S. aureus, B. subtilis, B. pumilus*<br>– Gram-negative bacteria – *Pseudo, Candida, E.coli* | [45] |
| Propolis, beeswax and chitosan | Cotton knitted fabric | – Gram-positive bacteria – *Staphylococcus aureus* and *Streptococcus β hemolitic*<br>– Gram negative bacteria – *Escherichia coli* and *Pseudomonas aeruginosa* | [46] |
| Extracts from *Galinsoga parviflora* plant leaves | Cotton fabric | 98,54 % and respectively 97,96% reduction rates of *Staphylococcus aureus* and respectively *Pseudomonas aeruginosa bacteria numbers* | [47] |
| Peppermint EO | Cotton Fabric | *S. aureus* and *E. coli* | [48] |
| *Melaleuca alternifolia* (tea tree) EO | Viscose fabric | *E. coli* and *S. aureus* | [49] |
| Lime EO | Cotton fabric | inhibited *E. coli, B. cereus, S. Typhimurium* and *S. aureus,* even after washing | [50] |
| Cinnamon; basil; lemongrass, and mint EOs | Polyethylene non-woven fabric | *Escherichia coli* and *Staphylococcus aureus* – the best oil is cinnamon, basil oil ranks the second, the next is the mint oil, and the lowest effective is the lemongrass oil | [51] |
| *Citrus aurantifolia* (lime) EO | Cotton fabric | *S. aureus, E. coli, K. pneumoniae,* and *S. epidermidis* | [52] |
| *Salvia officinalis L.* / *Salvia lavandulaefolia Vahl.* EOs | non-woven viscose | *E. faecalis* (33 %) / *S. saprophyticus* (31%) | [53] |

the specific features given by their fibrous composition, their age, the environmental conditions in which they are stored, etc. At present, essential oils are not yet commonly used for the treatment of heritage textiles, even though there are studies that have proven their effectiveness and safety as alternative methods of conservation of heritage textiles.

One such study was conducted by Matusiak et al. [54]. Their study focused on determining the antimicrobial efficacy of *Cinnamomum zeylanicum* essential oil (CEO) in the vapour phase to disinfect heritage textiles and its impact on the materials' mechanical, optical, and structural characteristics.

They showed that for the moulds *Aspergillus niger*, *Penicillium funiculosum* and *Trichoderma viride*, a minimum concentration of CEO in the vapour phase of 5.625 μg ml$^{-1}$ is required, and for the bacteria *Streptomyces rutgersensis*, *Bacillus megaterium* and *Pseudomonas fluorescens*, a minimum concentration of 22.5 μg ml$^{-1}$. After being disinfected with CEO, the amount of viable microorganisms on the tested fabrics was decreased by 2 to 7 logarithmic units. Since no significant changes in optical, mechanical and structural characteristics of textiles were observed after the CEO treatment, it can be considered that this method of disinfection of heritage textiles is effective, sustainable and safe.

Another study was conducted on short coats for young men, handmade from hemp and cotton yarns and lined with sheepskin from the Mara Valley, Maramures, Romania. After testing on different delimited surfaces of the garment, it was concluded that all EOs (*Citrus limon, Lavandula angustifolia, Marjoram, Melaleuca alternifolia, Mentha piperita, Origanum vulgare*) had a strong inhibitory effect on six fungal colonies (*Alternaria sp., Aspergillus sp.,* *Botrytis sp., Cladosporium sp., Mucor sp.* and *Penicillium sp.*) and a class of yeast (*Candida guilliermondii*). None of the treatments applied had visible adverse effects on the product's physical characteristics in the treated areas [55].

The effect of essential oils of lemon (*Citrus limon*), lavender (*Lavandula angustifolia*) and peppermint (*Mentha piperita*) was also tested by applying them to an "ie", a piece of clothing from the Romanian cultural heritage, stored in a museum of ethnography in Beiuş, Romania. The inhibitory effects of the three essential oils were demonstrated on *Botrytis sp., Cladosporium sp.*, respectively *Rhodotorula mucilaginosa* [56].

Fierascu et al. studied the effect of seed extracts of linden and basil (plants native to Romania), (*Allium ursinum* and *Ocimum basilicum*) on different cultural heritage artefacts. The extracts were made using the least toxic solvents possible (water, ethanol-water mixture, ethanol). The results obtained showed their efficiency in protecting the artefacts against biodeterioration, due to the antifungal effect these extracts have [57].

Other studies, carried out on different textiles from the Romanian cultural heritage, have highlighted the antimicrobial and antifungal effects of chitosan but also the fact that these treatments have contributed to the improvement of the shrinkage resistance of the materials, to the increase of the absorption degree of the dyes and the whiteness degree due to the cleaning of the stains existing on these products [58, 59].

The antifungal activity of chitosan was also tested by applying it to 3 old maps made of silk, cloth and paper. A chitosan solution (10 g/l) was used to treat the 3 types of maps and the electronic microscope was used to evaluate the results. The study highlighted the antimicrobial effect of chitosan regardless of the material on which it was applied [60].

In another study, the essential oils (EOs) from *Vitex agnus-castus* leaves and fruits, *Eriocephalus africanus* leaves, *Cymbopogon citratus* leaves, and *Rosmarinus officinalis* leaves were tested as antifungal agents against *Aspergillus flavus, Cladosporium cladosporioides*, and *Penicillium chrysogenum*. These pathogens were identified and collected from an ancient Egyptian child's mummy and then used to colonize different flax fibre samples, which were subsequently treated with the 5 types of essential oils. The highest efficacy was found to be in the case of *Vitex agnus-castus* leaf EO, which generated the most effective reduction in fungal mycelial development [61].

The use of essential oils in the conservation of heritage textiles has also been studied by a team of researchers from the University of Beira Interior in Portugal. They focused their research on the materials used to wrap heritage textiles when they are preserved. They developed a packaging material made of Polycaprolactone (PCL) which they also treated with *Lavandula luisieri* EO. The results of the study showed that both materials (PCL and PCL+EO) have good breaking strength and excellent whiteness index. They also showed that PCL+EO has a 99.33% reduction rate against *Staphylococcus aureus* bacteria and 99.29% against *Pseudomonas aeruginosa* bacteria, clearly superior to other protective materials commonly used in museums (Raw Cotton, Non-woven Polyester) [62].

Combining traditional and innovative methods of textile cleaning and preservation, Ilies et al. showed antibacterial/fungal properties of both substances obtained from boiling natural wood ash (lye) and silver nanoparticles. For this, they impregnated a very old traditional blouse from Bihor county, Romania, with 30 and 70 ppm silver nanosuspensions and washed it with lye. In both cases, the microbiological analyses showed that the reduction rate of bacterial colonies was 95%. The antibacterial effect of the silver nanoparticles present on the blouse's textile material (cotton fabric) was kept up throughout the entire study [63]. The efficiency of using silver nanoparticles for the conservation of heritage textiles and the multitude of methods that can be used for their deposition on textiles (layer-by-layer deposition, solution immersion, and sonochemical methods) are also highlighted by Lite et al. [64]. The effect of lye on heritage textiles was also analysed by Ilies et al. They showed that washing with lye a woman's blouse, made of cotton and having an age of 80–100 years, caused a decrease in the number of microorganism colonies and the amount of dust initially existing on the surface of that product [65].

Indrie et al. analysed the effects of Salvia and Thyme essential oils on the tensile strength of traditional hemp and cotton heritage textiles. They showed that the application of Salvia essential oil to cotton fabric increased tensile strength by 20% in the warp direction and 39% in the weft direction. On the other hand, the application of Thyme essential oil to the same cotton fabric resulted in a 29.9% reduction in tensile strength. The application of essential oils on the hemp fabrics determines the decrease in tensile strength in the warp direction, by up to 36% when applying Salvia essential oil and by 40% when applying Thyme oil. This study underscores the importance of consistency between the type of essential oil and the fabrics it is applied [66].

## CONCLUSIONS

Heritage textiles are objects of high cultural and social value. They constitute important evidence of human history and therefore need to be protected and preserved to prevent their deterioration. However, restoration strategies are sometimes unavoidable.

Metals, metal-based chemicals, quaternary ammonium salts, phenolic compounds and other antimicrobial agents are frequently used to treat textiles, although they are hazardous and have negative environmental effects. For this reason, it is particularly important to find sustainable and effective alternatives at the same time.

The antimicrobial effects of essential oils and plant extracts have been highlighted and demonstrated by numerous researchers. A multitude of studies have shown the effectiveness of their application on different types of textiles. The most common material used in these studies was cotton fabric, but studies have also been carried out on cotton knitwear, hemp fabrics, wool, silk, rabbit hair, etc. Materials treated with different types of essential oils, plant extracts, or mixtures thereof, in different proportions and concentrations, have in all cases developed antibacterial and/or antifungal properties. It should be noted that numerous studies have focused on indigenous plants and have shown their effectiveness. Another important aspect is that these treatments did not affect the physical properties of the textiles.

The diversity of areas in which these treatments have proven useful – from textiles found in various clothing products to medical textiles or those forming part of cultural heritage – will lead to these treatments being applied on a much wider scale in the future, both because of their sustainability and because of their much lower price compared to products used in traditional treatments.

At present, biotreatments are not yet commonly used in the conservation of heritage textiles, even though numerous studies have proven the effectiveness and safety of their use. Research in this field will certainly expand in the future as well, both in the treatment of the air inside museum spaces and in the application of biotreatments on heritage objects, and these new conservation methods will become common practices in all museums.

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