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Antibacterial Effect of Eco-Friendly Silver Nanoparticles and Traditional Techniques on Aged Heritage Textile, Investigated by Dark-Field Microscopy

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Abstract: An improper indoor microclimate has adverse effects on the state of preservation of historical textiles arranged in them, favoring the development of bacteriological microflora. The current study aims to combine traditional and innovative methods for cleaning and preserving a 100-year-old traditional blouse from Bihor, Romania. The material of the blouse was impregnated with 30 and 70 ppm silver nanosuspensions and washed with a substance obtained from boiling natural wood ash (lye). The research goals were to determine the antimicrobial action of lye washing and silver nanoparticles applied to the analyzed textile material and identify the way in which the environmental factors (light) act upon the conservation degree of textile objects impregnated with silver nanoparticles. All these procedures are eco-friendly and do not cause any damage to the constituent material of the fabrics. The use of the hyperspectral imaging technique proved the permeation of both 30 and 70 ppm silver nanosuspensions into the textile, producing changes in the textile's reflectance spectrum after being treated with them. The results showed anti-bactericidal/fungal properties of both silver nanoparticles and lye. Microbiological analyses revealed that bacterial colonies were reduced to more than 95% in both cases. The antibacterial effect of silver nanoparticles on the textile material of the blouse was maintained throughout the duration of the study, and under normal environmental conditions, the effects would remain active for a long period.

Keywords: hyperspectral images; textiles heritage; silver nanoparticles; traditional washing; antimicrobial treatments; eco-friendly

1. Introduction

The spaces in museums where rare, valuable objects are kept face feature conservation problems related to microclimatic conditions. The indoor microclimate is influenced by the architectural features of the building and construction techniques, materials, outdoor climate, etc. Furthermore, the level of biological contamination can determine the biodegradation of artifacts as it is directly influenced by the type of fabrics and furnishing materials, chemical composition, quality of the materials, aging process, internal mechanical stress, and the presence and activity of people (staff and visitors) [1,2]. All these aspects can cause

museum exhibits to deteriorate over time with special emphasis on very old items or those made of easily degradable materials, such as textiles, paper or wood [3–7].

The desired preservation of exhibits can be achieved by using both traditional methods and the latest-generation methods. Most of the time, using both as complementary methods is a viable solution because it takes into account both the need to examine and preserve them and the financial aspect; moreover, many museums have limited funds for conservation–restoration interventions, which makes traditional methods useful [8]. Most of the important progress achieved in recent years in conservation and restoration work consists of using modern tools such as X-ray, infrared and Raman spectroscopy, integrated microscopy such as Atomic Force Microscopy (AFM), Scanning Electron microscopy (SEM), or dark-field microscopy, infrared and UV techniques, and 3D and laser scanning techniques [9–11], as well as the use of different classical methods, such as photogrammetry [12,13] or the application of different natural solutions [3,14–16]. All of these are appropriate proactive and reactive strategies for studying the characteristics of materials that ethnographic textiles are made of, their deterioration and degradation mechanisms, and their behavior in response to the actions of unconventional conservation treatments.

Applying nanotechnology in preserving heritage objects, especially those made of cotton, can constitute a base for the development of alternative techniques in order to complete and boost conventional disinfection, treatment, and conservation methods, providing durability and protection [17,18]. The benefits provided in the conservation of heritage textile objects by applying nanotechnology consist of increasing antibacterial protection and improving antistatic and hydrophobic features [19–23].

The increasing interest in the utilization of metal and mineral nanomaterials is mainly due to two specific properties. The first property is the high specific surface area of nanomaterials, substantially increasing their effectiveness. The second is related to the recent environmental and health concerns in recent decades. Recent developments in nanotechnology have provided the opportunity to utilize materials that are non-toxic to both humans and wildlife, making them quite suitable for a wide variety of indoor and outdoor applications [24–27].

Recently, special emphasis has been placed on the use of metallic nanoparticles in different sectors of activity. The mode of action of these metallic nanoparticles depends on a number of factors related to both the type of metal and the method of obtaining them (chemical, physical, or biological). The most frequently used nanoparticles are silver (AgNP), gold (AuNP), zinc oxide, titanium oxide (TiO₂), silica, and iron oxide (FeO). Gold and silver nanoparticles are frequently used due to their unique physical properties, being less reactive and more stable in air and possessing a large contact surface and a high level of conductivity.

Among these, in the field analyzed in this study, silver nanoparticles have the highest degree of use. This metal is chemically inactive, stable in water, and does not oxidize in air. The optical, thermal, and catalytic properties of silver nanoparticles depend on the size, shape, distance between them, and the environment that surrounds them. Due to their high surface-to-volume ratio, silver nanoparticles show remarkable antimicrobial activity, even at a low concentration. AgNPs have unique properties in terms of toxicity, surface plasmon resonance, and electrical resistance. They also have low costs, low cytotoxicity, and immunological response. It is noted that the smaller the size of the nanoparticles, the more pronounced the antibacterial activity.

In this connection, the bactericidal and fungicidal effects of silver nanoparticles are efficiently increased due to the relatively large specific surface area and their reactivity to proteins and increased action capacity, even when longer periods of time have elapsed since washing them. Silver nanoparticles' action mechanism is based on their electrostatic affinity towards the bacterial membrane, destabilizing its integrity, reducing cellular metabolism, and inhibiting microorganisms' growth cells (approximately 99% reduction in bacterial growth within 1 h of contact), even in the case of small quantities of silver nanoparticles. The silver ions' antimicrobial mechanism is based on membrane protein deterioration, the

discrepancy with the electron transport system, and inhibition of respiratory enzymes in order to increase the production of Reactive Oxygen Species (ROSs) [28,29].

For a detailed examination, imaging technology started to generate better and better results, from multispectral information to hyperspectral information and non-invasive microscopy techniques with fast scanning to the nano-metric scale, which targets the topography of a non-conductive sample, providing 2D and 3D images. The applicative perspectives are of high quality and precision regarding the evaluation of heritage objects' conservation state and monitoring the degradation/deterioration processes on and within the fibers [30], as well as characterizing and mapping the multi-material and polychromatic surfaces [31–36].

The Hyperspectral Imaging Technique (HSI), together with other techniques such as AFM or SEM, is useful in characterizing surfaces on a nanometric scale, evaluating them in real-time, and monitoring the efficacy of applied treatments (cleaning, antifungal, antistatic, etc.). It emphasizes the eventual presence of residues (qualitatively and quantitatively—measuring the roughness of the profile surface and section by using specific software). Characterizing the surface on multiple scales makes an important contribution to the restoration of cultural heritage objects, with the conclusions easily extrapolated to a larger scale. Furthermore, the interaction between metallic nanoparticles and different molecules was observed using hyperspectral imaging by evaluating the change in nanoparticles' plasmonic resonance as a result of surface plasmons' decoherence when interacting with various molecules or ions [37].

The current study aims to identify a combined and non-invasive cleaning and conservation methodology of a heritage textile object in a museum (a 100-year-old traditional blouse from Bihor area, Romania). The work methodology aims to combine traditional (washing with lye) and latest-generation (application of silver nanoparticles in concentrations of 30 and 70 ppm) interventions. The analyzed portions were monitored using hyperspectral images, both before and after the application of the treatments, in order to identify the inhibitory effects on the microorganisms present on the fabric, as well as to prevent recontamination of the material.

2. Literature Review

Over the past two decades, metal and mineral nanoparticles and nanostrands have been used to mitigate the susceptibility of biological materials to different bacteria and fungi [38–41]. Specifically, silver, copper, and zinc nanometals have been clearly reported to significantly improve the biological durability against different fungi [42,43]. As mineral nanomaterials, nanowollastonite and nano-clay also successfully prohibited the growth of different fungi on wood, wood-based composite panels, paper, textiles, and other biomaterials composed of cellulose [41,44–47].

From the perspective of AgNPs' antibacterial action, higher sensitivity of Gram-negative bacterial strains compared to Gram-positive strains was noted. Recent studies focused on the effects of AgNPs on the sensitiveness of two Gram-positive bacterial species proved that AgNPs act differently; thus, they are more efficient on *Staphylococcus cells* and less efficient on *Bacillus cereus*. Comparisons between AgNPs' degree of activity on two Gram-negative species indicated higher sensitivity in the case of *Pseudomonas aeruginosa* than *Escherichia coli*. There were also correlations made [18–20,23,48–55] between the size and shape of AgNPs and the antibacterial and bacterial-static activity, unpleasant smell prevention, decrease in pathogenic germ level, etc.

A comparative analysis of the sensitivity of two Gram-positive bacterial species proved that AgNPs acted efficiently (the inhibition area diameter was between 12.8 mm and 11.4 mm) on *Staphylococcus cells* in the case of all tested samples (after several washes), while in the case of *Bacillus cereus*, antimicrobial activity was present but diminished (the inhibition area diameter was between 11.3 mm and 10.3 mm) for one sample and disappeared in the case of treated and washed samples. Regarding Gram-negative bacterial species, *Pseudomonas aeruginosa* showed higher sensitiveness to AgNPs with its inhibition area diameter between 12.6 mm and 12.3 mm, while in the case of *Escherichia coli*, it was between 11.3 mm and 10.3 mm, even after 20 washing cycles [56,57].

There are numerous studies (we mention, in this respect, Monteiro et al. [57]) that confirm AgNPs' antifungicide effect against *Candida* spp., alone or in combination with classical antifungicides, such as nystatin. The destruction of *Cryptosporidium parvum*, *Bacillus subtilis*, and *Pseudomonas aeruginosa* viability has also been proven [18,58–61], and that of *Fusarium oxysporum* and respective nanoparticles in concentrations of 10 and 20 ppm were deposited on cotton fabric in order to analyze their bactericidal effect upon *Staphylococcus aureus* [62]. The synthesized AgNP-coated fabrics (8–20 nm in size) provided pronounced antibacterial (*Aspergillus terreus*) activity and excellent laundering durability [63]. The destructive action of AgNPs was also noted in *Bacillus subtilis*, *Klebsiella mobilis*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Streptococcus pyogenes*, and *Salmonella typhi* [29]. At the same time, they had antifungicide actions against *Candida albicans*, *Penicillium citrium*, and *Aspergillus niger* [57].

Research on AgNP application on biomedical fabrics emphasized their destructive activity in *Escherichia coli* (Gram-negative) and *Staphylococcus aureus* (Gram-positive) bacteria, even after 20 washing cycles [55,58], as well as the viability of *Cryptosporidium parvum*, *Bacillus subtilis*, and *Pseudomonas aeruginosa* [18,59–62]. Kim et al. [62] stated that 10 and 20 ppm concentrations of silver nanoparticles act upon *Fusarium oxysporum*. Synthesized AgNP-coated fabrics (8–20 nm in size) displayed pronounced antibacterial (*Aspergillus terreus*) activity and excellent laundering durability [63].

The modern methodologies for studying the structure and physico-chemical properties of stable silver nanoparticles in solutions applied to cotton sample fabrics are UV-VIS spectroscopy, AFM (Atomic Force Microscopy), and TEM (Transmission Electron Microscopy) [55]. The interaction between bacteria *Escherichia coli* and citrate-reduced silver nanoparticles (AgNPs) (size 25 nm ± 8.5 nm) was studied by the team led by Vishnupriya [64] using Raman Spectroscopy (RS) in conjunction with hyperspectral images obtained through plasmon resonance. The fact that AgNPs can be fixed and well dispersed on the cotton fabric's surface was demonstrated through a series of analyses: Fourier Transform Infrared Spectroscopy (FTIS), Ultraviolet-Visible spectroscopy (UV), X-ray diffraction, X-ray photoelectron spectroscopy, Scanning Electron Microscopy (SEM), and Energy-Dispersive X-ray Spectroscopy (Table 1) [56].

Most of the articles presented in Table 1 classify nanoparticles as non-destructive, versatile, and cheap solutions for cleaning materials, with their efficiency remaining high even after several washes in the case of textiles. Limitations are constituted by the lack of studies comparing the different available techniques, the ability of nanoparticles to remain incorporated without losing their efficiency, and their long-term effects on human health and the integrity of materials.

Some scientific research has also emphasized the fact that the antistatic features of the fabrics can be improved (especially regarding synthetic fibers) by using nanotechnology, e.g., dioxide, zinc oxide whiskers, nanoantimonydoped tin oxide (ATO), silanenanol, etc. [20,23].

Table 1. The working methodology used in the reference bibliography for nanoparticle impregnation and material analysis.

Article		Methodology														
Dark Field Microscopy	Year	SEM	SM	EDFM	EDS	DLS	ESI	NIOSH Method 7400/CDC-NIOSH	NPs	TOF-SIMS	TEM	AFM	UVS	X-ray	FTIR	HI
Roth et al. [65]	2015			✓					✓							✓
Neu-Baker et al. [66]	2019			✓					✓							✓
Shi et al. [67]	2022			✓				✓								✓
Badireddy et al. [68]	2012			✓					✓							✓
Vishnupriya et al. [64]	2013								✓							✓
AgNPs Cotton fibers																
Duran et al. [59]	2007	✓			✓		✓		✓		✓		✓			
Liu et al. [49]	2014	✓							✓	✓				✓		
Hebeish et al. [69]	2011	✓							✓							
Khe et al. [54]	2019								✓		✓	✓	✓			
Rojas-Lema et al. [60]	2017	✓							✓		✓					
Perkas et al. [53]	2018	✓	✓						✓		✓					
Balakumaran et al. [63]	2016	✓							✓		✓		✓	✓		
Saad and Hafez [70]	2014	✓							✓							
Wool fibers																
Memon et al. [71]	2018	✓							✓							✓
Gokarneshan and Velumani [51]	2017	✓							✓							
Shahverdi et al. [72]	2007				✓				✓		✓		✓			
Montes-Hernandez et al. [61]	2021	✓							✓							✓
Polyester fibers																
Ribeiro et al. [73]	2022	✓				✓			✓						✓	
Medical fibres																
Selvakumar et al. [74]	2013	✓							✓				✓			

SEM—Scanning Electron Microscope, EDS—Energy-Dispersive Spectroscopy, NPs—Nanoparticles, SM—Sonochemical Method, DLS—Dynamic Light Scattering, TOF-SIMS—Time-of-Flight Secondary Ion Mass Spectrometry, EDFM—Enhanced Darkfield Microscope, ESI—Elemental Spectroscopy Imaging, TEM—Transmission Electron Microscope, FTIR—Fourier-Transform Infrared Spectroscopy, HI—Hiperspectral Imaging.

3. Materials and Methods

In order to emphasize AgNPs' effects on 100-year-old homemade cotton fabric textiles and the conservation conditions of the heritage object, the working methodology was divided into three stages, as shown in Figure 1.

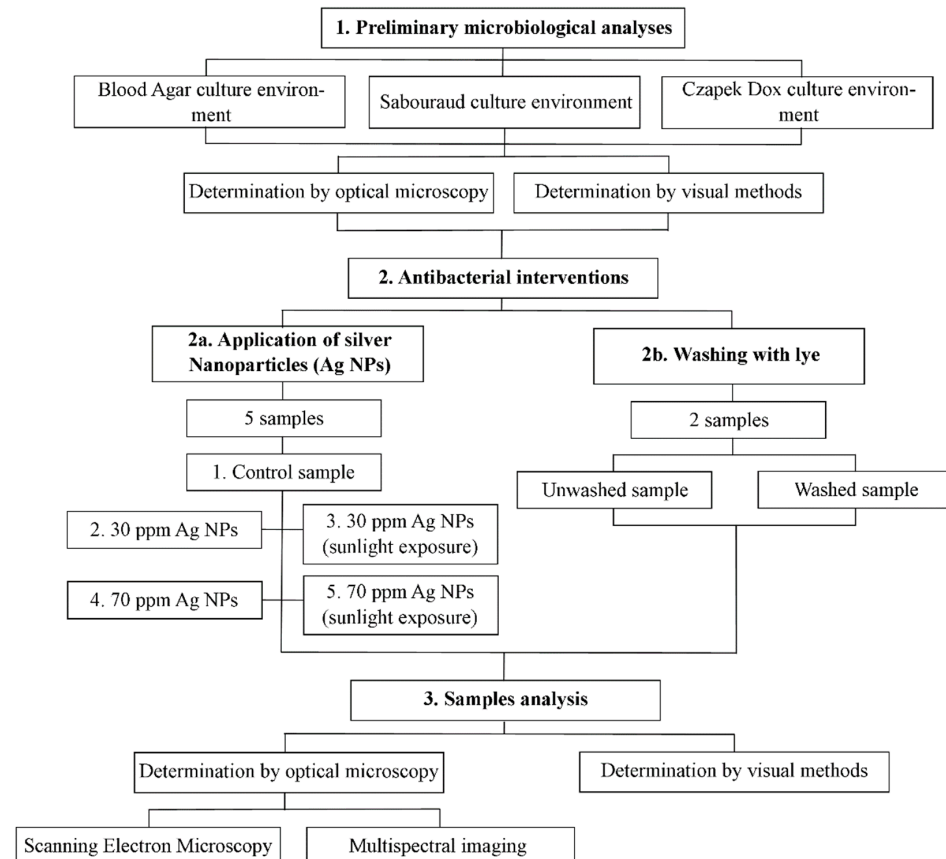


Figure 1. Schematic diagram of the main methodological stages of the study.

3.1. Preliminary Microbiological Analyses

The first stage was represented by the microbiological analyses undertaken on the material from which the heritage textile piece is made. In this sense, the collection of microbiological samples, their cultivation on Petri dishes, and the identification of their degree of microbiological contamination were considered.

With the help of sterile swabs, microbiological samples were collected from five distinct areas within the object, with these being delimited as the work surfaces. After preservation, each swab was unloaded in three culture environments, as follows: The Blood Agar (bioMérieux-CRAPONNE-France), Sabouraud with Chloramphenicol and Gentamicin (Mikrobiologie labor-technik, Arad, Romania), and the Czapek Dox environments (Biolab, Budapest, Hungary). The Czapek Dox environment is usually used to cultivate fungi such as *Candida*, *Aspergillus*, *Penicillium*, and *Actinomicete* and to form *Chlamydo孢子* by *C. albicans*. The Sabouraud Agar Chloramphenicol Gentamicin environment is another culture environment recommended for the isolation of filamentous fungus species from biological samples. Gentamicin and chloramphenicol inhibit bacteria development, such as *Enterobacteriaceae*, *Pseudomonas*, and *Staphylococci*. Blood agar is an environment used to cultivate saprophytes and pathogenic bacteria.

The culture media were incubated at a temperature of 28 °C for 10 days in order for the colonies to develop. Starting with the fourth day, the colonies began to be visible, and the isolation and identification of the fungi and bacteria developed on the culture media were carried out. Plates were evaluated daily by observing their evolution in terms of

changes in the appearance of the colonies in question, with the assessment undertaken sequentially, following the order of shape, texture, consistency, diameter, color, and outline.

3.2. Antibacterial Interventions

The cleaning and preservation interventions of the textile material constituted a combination of traditional and latest-generation methods. This was performed in order to analyze the antibacterial results offered by two completely different methods in terms of the materials used and the method of application, as well as to draw up a work methodology for the preservation–disinfection of historical textiles that face a high degree of fragility. Therefore, the traditional method consisted of washing the material with lye (an ecological substance obtained from ash) while the innovative method involved the use of AgNPs. The samples used were examined with the help of the Hyperspectral Microscope System produced by CytoViva (Auburn, AL, USA), both before and after applying the treatments. This system allows the analysis and spectral mapping of the samples at the nanometric scale. It also allows non-invasive measurements based on the resulting hyperspectral images within the compatible CytoViva ENVI software.

Washing with Lye

Lye is an ecological substance obtained from boiling wood ash in fresh spring or river water. This is traditionally used in different parts of Romania to wash and disinfect textile materials. When properly prepared it is recognized as having high antifungal effects while also being non-invasive regarding the material from which the fabric is made [55]. Its eco-friendly properties are provided by the fact that it is entirely of natural origin and not chemically treated, existing as a mixture of minerals. In addition to its antifungal properties when washing different types of natural fabrics, it is also used for application on the hair and skin in order to treat various ailments.

For the present study, the substance was prepared from the very fine ash of *Fagus Sylvatica*, resulting from the natural burning of the wood. Thus, one liter of fresh ash was mixed with 10 L of water, boiled for 30 min, and then left to soak for 48 h. After this period, the entire composition was filtered several times through different sieves with a small diameter to remove all impurities. The surfaces of the analyzed object were soaked in the resulting solution for one hour and rinsed with clean water afterward.

3.3. Application of Silver Nanoparticles (AgNPs)

For the application of silver nanoparticles, the sampling of five material samples from the analyzed object was considered. The sample preparation was performed in aseptic conditions in a bacteriological hood with laminar flow to avoid further sample contamination, which could distort the results (Figure 2).



Figure 2. Preparation of cotton fabric samples for AgNP impregnation.

The experiment focused on impregnation of the above-mentioned textile with two concentrations of 30 ppm and 70 ppm silver nanosuspensions. Since application in the form of functional coatings plays a protective role for textile materials, we opted for this method in this study. Two types of silver nanoparticle solutions with sizes of 30 nm and 70 nm from Pure Life Group SRL, Bucharest, Romania were used. Because the samples had the same sizes, impregnation with 30 ppm and 70 ppm concentrations of the AgNP solution

was performed manually by adding the same volume of solution for each type of nanoparticle (1 mL). To emphasize the influence that silver nanoparticles have on the analyzed fabrics, we used a hyperspectral microscope with improved dark-field technology, which allowed us to obtain morphological and structural information on the molecular level based on spreading the light on the sample components. In order to emphasize the antibacterial property of the silver nanoparticles after a period of time following application and under circumstances of sunlight exposure, we determined the antimicrobial activity of AgNPs-treated samples (both 30 and 70 ppm) exposed to sunlight for 10 days (Samples 4 and 5).

3.4. Samples Analysis

The samples were analyzed both before and after the interventions with the help of electron microscopy and hyperspectral imaging. The microscope allows non-destructive spectral measurements of the samples and the detection of metallic nanoparticles and metallic oxides in textile fabrics. The hyperspectral data were recorded at a spectral resolution of between 400 and 1000 nm of approximately 2 nm. For each pixel from the image, a reflectance spectrum was acquired. Compared to multispectral and ultraspectral imaging, this type of imaging (hyperspectral) is superior due to the improved spectral resolution and the fact that each pixel in the image has a complete spectrum.

The CytoViva microscope allows the observation and spectral characterization of a large variety of nanomaterials while they interact with biological environments or other complex matrices. The basic principle that hyperspectral imaging relies on is the fact that any material, because of its physical structure and chemical composition, interacts with electromagnetic radiation in a unique manner (its spectral signature and spectral print). Among the nanomaterials that can be visualized and characterized from a spectral perspective are noble metals, polymers, lipids, bacteria, and viruses. For each sample, a thread was collected, which was placed on a microscope slide to obtain images and hyperspectral data in the dark field. The sample was focalized using a 40× (N.A.0.60) lens. After the acquisition, the region of interest was selected from each sample, and the average reflectance spectrum was calculated for it.

4. Results and Discussions

4.1. Preliminary Microbiological Analyses

The identification of fungi and bacteria was performed after evaluating the macroscopical and microscopical characters. On the 10th day, the cultures were examined. On the blood agar culture, the results were negative (no culture developed) (Figure 3a). On the Sabouraud and Czapek Dox cultures, with samples from batches 2 and 3, *Penicillium* spp. developed with colonies that developed rapidly and were green, blue-green, grey-green (2), and yellow (3) in color. The colony surface was more powdered. The presence of *Penicillium* spp. was microscopically confirmed (Figures 3b and 4).

4.2. Antibacterial Interventions

After the samples were treated with 30 ppm and 70 ppm AgNPs, specimens were taken again with sterile swabs and seeded again in the same culture environments: Blood Agar, Sabouraud with Chloramphenicol and Gentamicyn, and Czapek Dox, with incubation at 28 °C temperature and observation for 7 days (Figure 5).

For the best possible accuracy of the results, the samples were tested for microbiological content twice, and then their arithmetic mean was calculated. For the textiles treated with silver nanoparticles, small pieces of fabric were analyzed. For each fabric sample, the mean reflectance spectrum was calculated. For fabrics treated with the 70 ppm nanosuspension, the nanoparticles were incorporated into the fabric since there are noticeable areas where there is a spectrum specific to the silver nanoparticles' extinction spectrum. The dark-field images with the delimitation of one silver nanoparticle and the specific extinction spectrum are presented in Figure 6. For the fabric treated with 30 ppm nanoparticles, on the spectra from the brighter areas, the incorporation of nanoparticles into the fabric cannot

be evaluated using hyperspectral imaging because of the detector's limitation to under 400 nm. The resonance of silver nanoparticles' surface plasmons does not have similar shapes to the spectra specific to silver nanoparticles.



Figure 3. Plates seeded with primary samples (before interventions) on the 10th day of incubation ((a) dishes with Blood Agar culture environment, samples 1–5; (b) dishes with Sabouraud culture environment (top) and Czapek Dox (bottom) culture environments, samples 1–3).

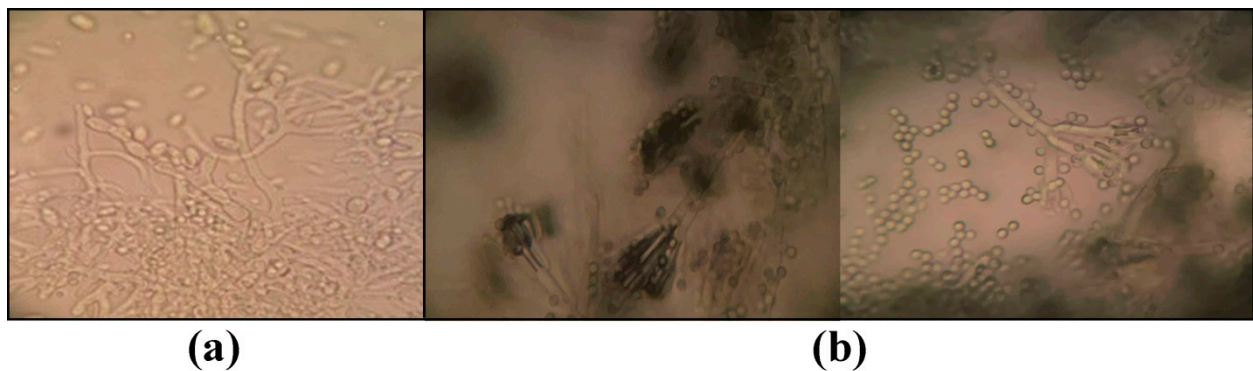


Figure 4. Microscopical aspects sample ((a) *Cladosporium* spp.; (b) *Penicillium* spp.).

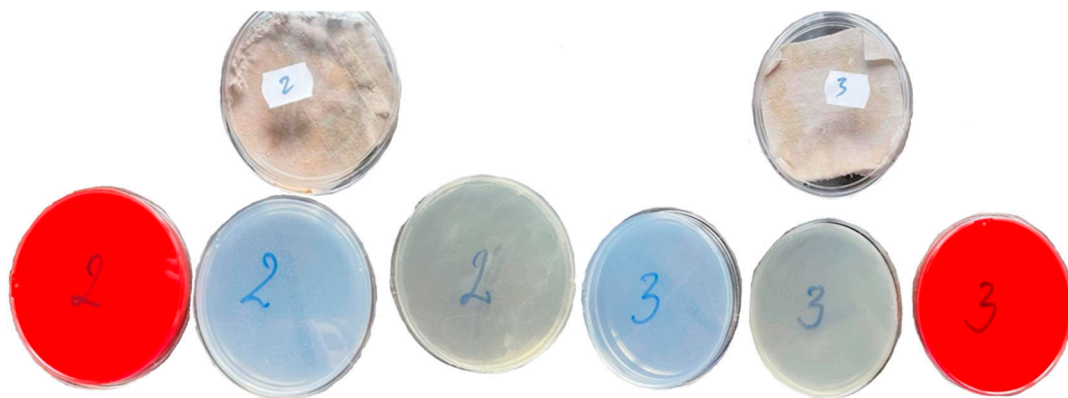


Figure 5. Culture plates after NNPSAg treatment of samples 2 and 3.

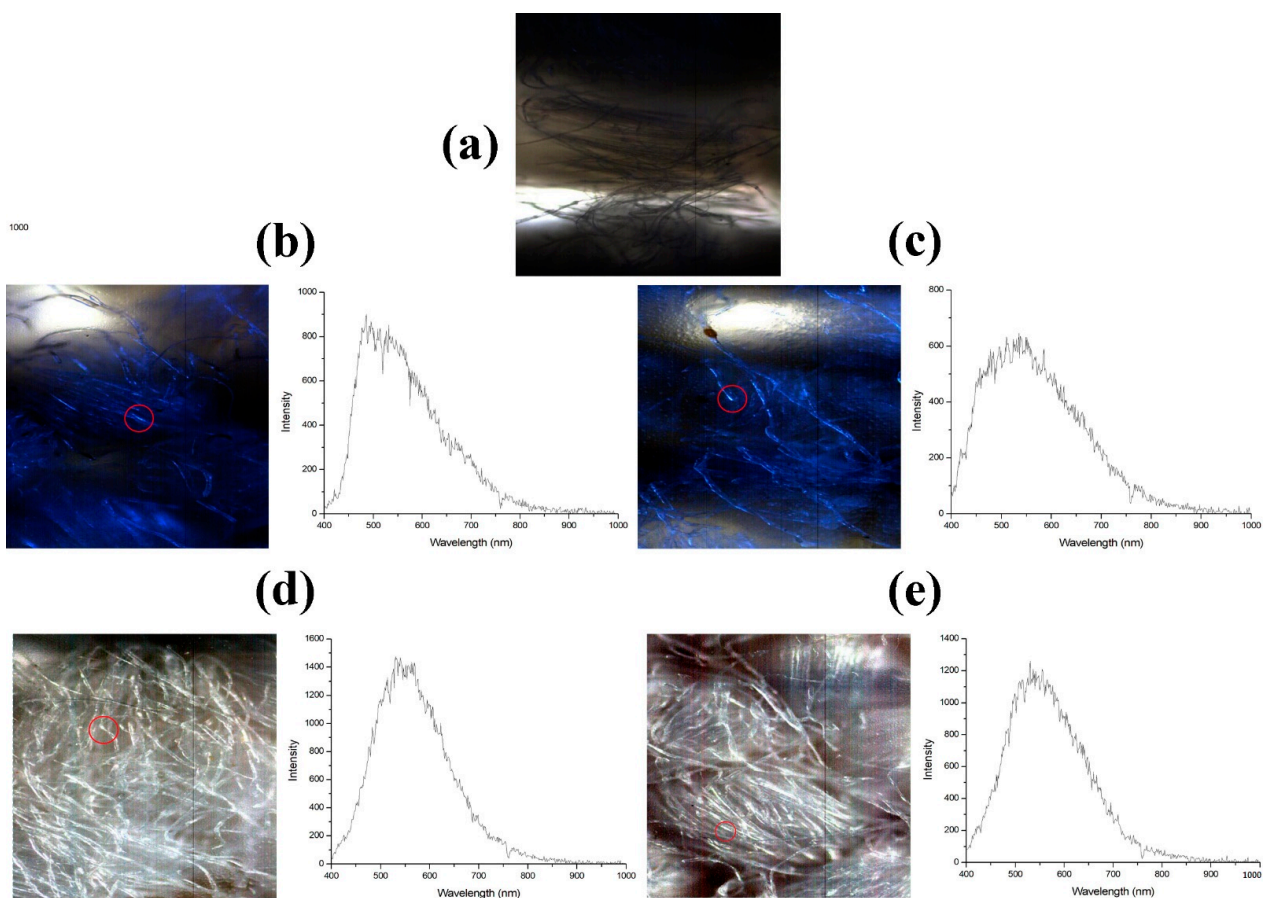


Figure 6. Dark field images for fabrics treated with silver nanoparticles and the scattering spectra of AgNPs in the fabrics acquired in the marked regions. (a) Control fabric, untreated (b) Fabric treated with AgNPs 30 nm (c) Fabric treated with AgNPs 30 nm and exposed to light (d) Fabric treated with AgNPs 70 nm (e) Fabric treated with AgNPs 70 nm and exposed to light.

For each fabric, the spectra specific to the points are indicated, which represent the AgNPs present. For each fabric, the mean spectrum was calculated on an area delimited around the nanoparticle (Figure 7). We noted a slight shift toward smaller wavelengths in the case of the mean reflectance spectrum of the control fabric compared to that of the fabrics treated with silver nanoparticles.

Figure 7 shows the reflectance spectrum of fabrics treated with AgNPs compared to the control fabric. For each fabric, the average spectrum was calculated on a region delimited around the nanoparticle. A shift towards smaller wavelengths can be noted, irrespective of AgNPs' dimensions and light exposure. No significant difference was observed between the reflectance spectra of fabrics impregnated with either 30 ppm or 70 ppm nanosuspensions. However, exposure to light led to a significant decrease in the intensity of the reflectance spectra and a slight shift towards larger wavelengths.

Regarding the treatment of the material through traditional method, sample threads from the washed sample and the unwashed sample were measured using the hyperspectral imaging technique. After applying the treatment (Figure 8a), aesthetic changes could be observed in the threads that make up the material, with these being much cleaner than the initial ones (Figure 8b). This can be explained by the reduction in the volume of dust within the fibers and their microbiological load.

We acquired hyperspectral images for the two threads taken from the fabric before and after washing. For comparison, the reflectance spectra for the two samples are shown in Figure 9.

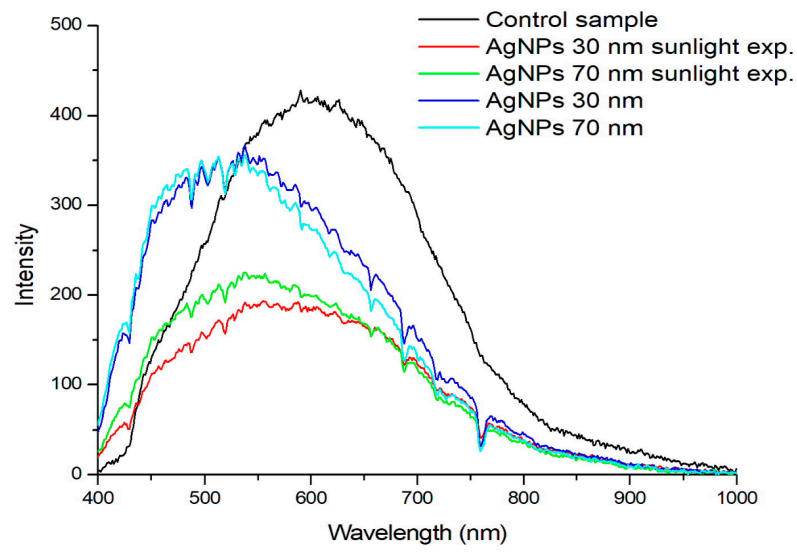


Figure 7. Mean reflectance spectrum of fabrics.

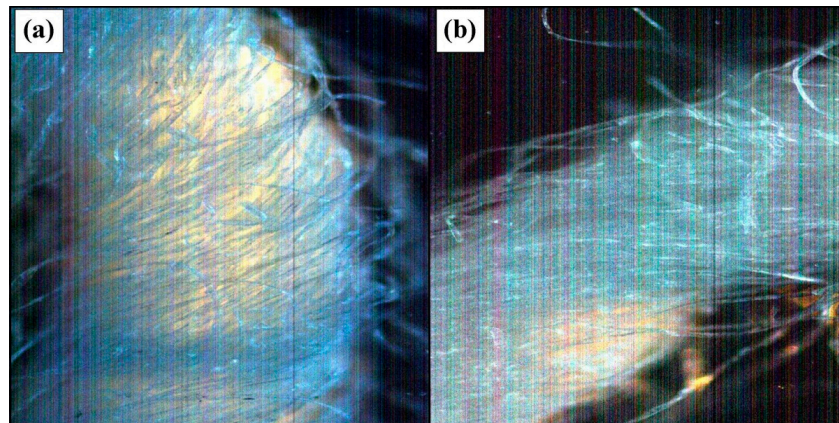


Figure 8. Dark-field image of a thread from the cotton fabric ((a) before washing; (b) after lye washing).

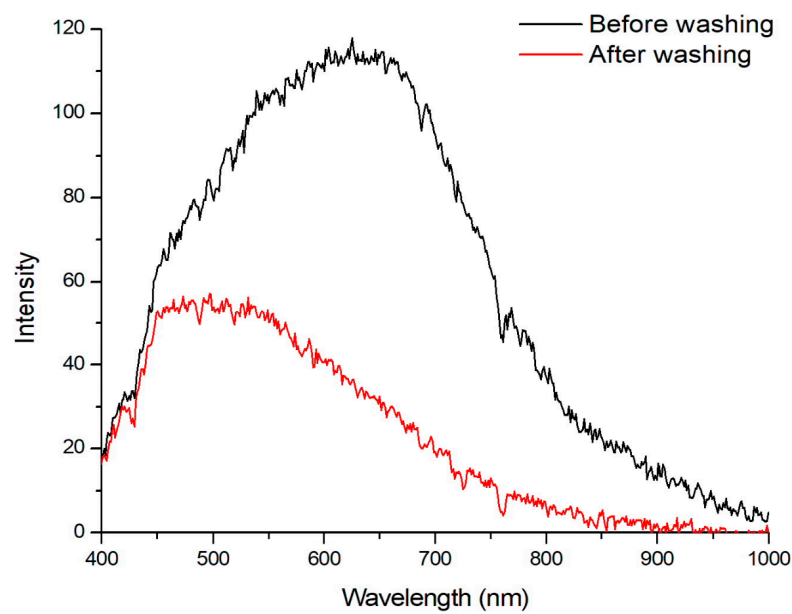


Figure 9. Mean spectra for the two cotton threads before washing and after lye washing.

We noticed a shift in the thread's mean spectrum toward smaller wavelengths after the fabric was washed (Figure 9). The reflectance spectrum shift may be the result of eliminating certain components through washing.

Microscopic images of the cotton fabric samples analyzed before and after lye washing were obtained using the CytoViva optical microscope and are presented in Figure 8.

5. Conclusions

Applying non-invasive techniques in the conservation process of heritage objects represents a vital goal for the future to improve the durability of priceless historical heritage. Moreover, it provides a properly protective environment for objects, museum areas, and visitors. Silver nanoparticles applied in 30 and 70 ppm concentrations and washing with lye both had antibacterial/antifungal properties, with microbiological analyses emphasizing the fact that bacterial colonies were diminished by over 95%, a property that was maintained during the time the study was conducted. Using HSI (hyperspectral imaging), analyses of the fabric's reflectance spectra after treatment with silver nanoparticles provided information regarding the permeation of AgNPs (both 30 and 70 ppm) into the fabric. Moreover, through imaging analysis, we did not notice major changes in the cotton thread as a result of lye washing. As silver is non-toxic and possesses antimicrobial properties, the use of AgNPs is encouraged as coatings on textile fabrics of different types, even on aged fabric.

6. Perspective

The information regarding fibers' adhesive and elastic properties, in addition to other details such as 2D height and 3D images of the fiber surface, surface roughness, and other parameters of the surface texture, was obtained with the help of AFM (Atomic Force Microscopy) and was used to compare various types of fibers and establish and monitor the damage caused by exposure to different environments and their effects over time on fabric fibers. The main research directions that we have in mind are focused on the synthesis of nanoparticles with properties controlled by the use of reaction/stabilization agents that are as environmentally friendly as possible, as follows:

- In the processes of obtaining silver nanoparticles, the use of certain plant extracts obtained from plants specific to areas from which the cult objects analyzed in this study come as reducer and stabilizing agents to stabilize the silver nanoparticles and follow the dynamics of the rate of increase of silver nanoparticles depending on the operating conditions.
- Expanding the research using gold nanoparticles obtained using the vegetable extracts mentioned in the previous paragraph and comparing their efficiency to those of nanosilver obtained under the same working conditions.
- Synthesis of nanomaterials with controlled properties, using environmentally friendly reagents.

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