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Antifungal and consolidation properties of linen textiles treated with silver nanoparticles loaded on hydroxypropyl cellulose polymer

Mahmoud Abo-Elmaaref^{1*}, Mohamed Marouf¹, W. S. Mohamed² and Walaa A. Abdel Wahab³

Abstract

Microorganisms are considered one of the most dangerous deterioration factors to cellulosic textiles, especially textiles made of linen fibers. Many of the traditional methods of resistance to microorganisms that infect textiles were used in the past, but they were of low effectiveness and high toxicity for those who applied these methods. The study used silver nanoparticles (AgNPs) prepared by the chemical reduction of silver nitrate (AgNO₃) in the presence of a polyvinylpyrrolidone (PVP) polymer as a stabilizing agent in inhibiting fungal strains *Aspergillus flavus*, *Trichoderma* sp. and *Penicillium duclauxii* that were isolated from the ancient linen piece No. 1345 preserved in the Sohag National Museum. The properties of the silver nanoparticles prepared and loaded on hydroxypropyl cellulose (Klucel G 1%) polymer were studied by many of examination and analysis methods such as TEM, XRD and FTIR. Evaluating the effectiveness of AgNPs/Klucel G by using well-cut diffusion technique revealed that the best concentration of AgNPs in inhibiting fungal strains is 3%. The results of treating raw and dyed linen textiles using AgNPs/Klucel G also indicated an improvement in the mechanical and chemical properties of the treated textiles. One of the most important results of the study is obtaining raw and dyed linen textiles with resistant properties to isolated fungal strains up to 3 months of treatment.

Keywords Polyvinylpyrrolidone, Silver nitrate, Silver nanoparticles, Stabilizing agent, Inhibition zone

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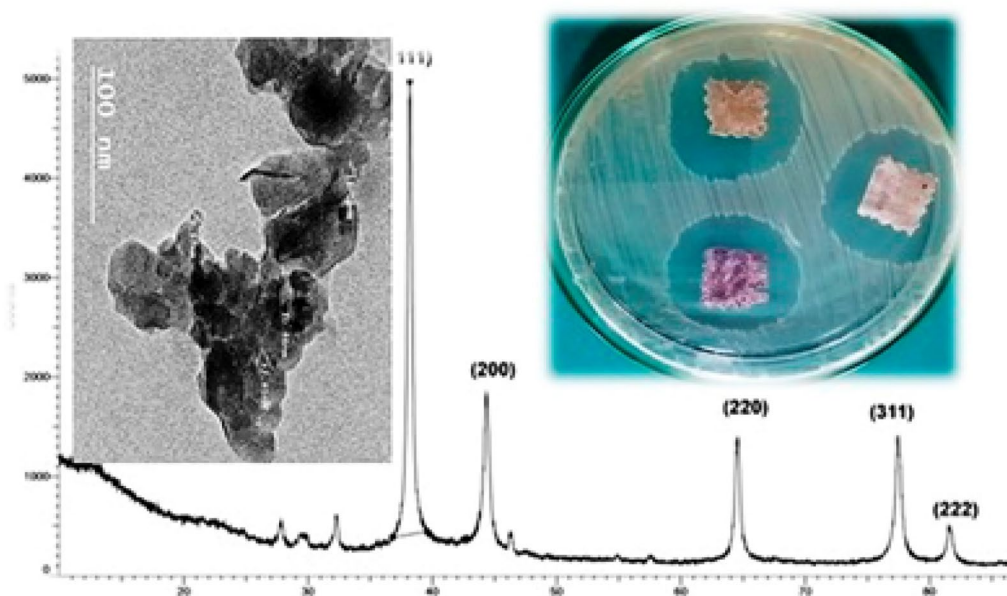
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Graphical Abstract



Introduction

Cultural heritage studies ultimately aim to provide, improve and evaluate practical solutions that can control microbial proliferation and thus biological degradation [1]. Archaeological textiles are considered to be an important part of the cultural heritage of civilizations, and the most vulnerable museum collections to damage caused by microorganisms (fungi, bacteria) [2–5]. The damage caused by microorganisms on archaeological textiles can be seen in the occurrence of a loss in the strength of the textiles, as well as the occurrence of color changes in the infected textiles [6, 7]. This research aims to evaluate silver nanoparticles prepared by the chemical reduction of silver nitrate in the presence of a stabilizing agent as an antifungal for fungal strains isolated from an archaeological piece of linen textile preserved in the Sohag National Museum, Egypt. Nanoparticles are a group of atoms whose size ranges between 1–100 nm, which show new properties depending on the size and distribution of those atoms, which gives them preference in application over atoms of materials in the bulk form [8]. Among those nanoparticles are silver nanoparticles (AgNPs), whose use in many applications has shown distinctive properties against a wide range of microorganisms. There are many methods to prepare AgNPs, some of which are prepared chemically, and some are prepared biologically (green synthesis) [9]. However, the most famous and simplest method for preparing AgNPs,

which was done by reducing the silver ion Ag^+ in an aqueous medium, to result in particles of colloidal silver whose grain size ranges from several nanometers [10]. Silver particles have been recognized for a long time as an antimicrobial agent, characterized by their low toxicity towards humans as well as their various applications within the laboratory [11]. The antimicrobial activities of AgNPs against microorganisms have been monitored, such as the inactivation of Thiol groups for some types of enzymes secreted by microorganisms [12]. The proliferation of the DNA of the microbial cell [13], the modification of the structure of the microbial cell membrane and the creation of electron dense granules in addition to stop microbial cell growth [14]. Ag and AgNPs have been used in many consumer products that humans use, such as the textile industry, in order to give them antimicrobial and odor-resistant functions. The growth of microbes on textiles can be controlled through processing processes by adding antimicrobials or by incorporating bio pesticides during fiber processing operations used in the manufacture of these textiles [15]. It is possible to modify the properties of textiles and give them new properties by adding nanometer materials to them. These materials work to improve the properties of these textiles and give them new properties such as friction resistance, antimicrobial resistance, and protection from ultraviolet radiation, as well as giving them water-repellent properties [16]. There are two basic ways to introduce AgNPs into

materials; the first method is by impregnating materials with colloidal solutions of pre-formed nanomaterials, the second method is by impregnating materials with a solution of silver nitrate AgNO₃ in the presence of other treatments with reducing agents to convert Ag⁺ into materials Nanometer NPs. In both cases, there must be a reducing agent, whether in the solution or on the material [17]. The activity of AgNPs in killing such microbes depends on the association of Ag⁺ particles with vital molecules present in the microbial cell, as it is assumed that AgNPs produce types of reactive oxygen and free radicals that cause the death of microbial cells, and given that AgNPs are smaller in size than living organisms, this helps to spread them inside the microbial cell and tear the microbial cell walls [18]. It is preferable to use AgNPs on textiles as antimicrobial agents better than using traditional antibiotics such as mineral salts and quaternary ammonium compounds because of the stability, resistance and environmental friendliness of these nanoparticles. Also, AgNPs are better than Ag⁺ because they don't lead to staining of fabrics. This keeps the textiles ventilated and handled [19].

Materials and methods

Materials

- Silver nitrate (AgNO₃) as precursor agent, produced by Sigma-Aldrich.
- Hydroxypropyl cellulose (Klucel[®] G) produced by C.T.S Italia.
- Polyvinyl pyrrolidone (PVP) as a stabilizing agent produced by Sigma-Aldrich.
- Potato dextrose agar (PDA) produced by (HIMEDIA REF) company used as the nutritional medium of the fungi.
- Linen textile produced by The Egyptian Textile Industries Company (Dintex) in Cairo. The number of threads per square centimeter of the linen fabric was 33 threads in the warp direction, and 30 threads in the weft direction.
- Turmeric dye *Curcuma longa* L. and Madder roots *Rubia tinctorum* was purchased from the Egyptian local market.

Methods

Chemical preparation of silver nanoparticles

Using an aqueous solution of polyvinyl pyrrolidone (PVP) as a stabilizing agent, the silver nitrate AgNO₃ precursor is added, to about 150 ml of deionized water containing 5 g of PVP for the formation of the silver colloid in a concentration of 500 mg/dm, adding drop wise to the silver nitrate solution and stirring for 1 h.

Thus, one of the first syntheses consisted in the photo reduction of AgNO₃ in the presence of PVP as a stabilizing agent using 400 watts ultrasonic irradiation. With this method, silver nanoparticles between 15 and 22 nm can be obtained depending on the molar ratio between AgNO₃ and (PVP) [20, 21]. The (poly vinyl pyrrolidone) polymer (PVP) is one of the most widely used stabilizing agents for metallic nanoparticles [22, 23]. As for the process of loading silver nanoparticles prepared on hydroxypropyl cellulose polymer, (0.01, 0.02, 0.03 g) of AgNPs granules were added separately to 100 ml of ethyl alcohol and this solution was stirred for 10 min, after that 1 g of Klucel G powder was added and vigorously shaken using the Sonication process to obtain concentrations of 1, 2 and 3% of AgNPs/Klucel G.

Linen samples processing and dyeing

Raw linen textiles were prepared and washed with hot soapy water, in order to get rid of impurities and sizing materials on the surface of the fibers. Then the turmeric and madder roots were ground well into a powder form, soaked in water for 24 h, and then heated to boiling point for 2 h. The extract was left to cool and then filtered well until a clear and transparent color of dye was obtained [24–26]. For dyeing process in the beginning, the linen fibers are moistened with water, then a certain amount of the previously filtered dyeing solution (50 ml per 1 g of dry fabric volume) is taken. The dyeing bath is heated to the boiling point, except for the madder, which is heated at a temperature of 60 °C. The dyeing bath is left at the same temperature. After that, the dyed linen textiles is washed using soapy water, then rinsed with distilled water and left to dry at room temperature for 24 h [27].

Isolation and identification of fungal strains

Three microbial swabs were taken from the ancient linen piece No. 1345 preserved in the Sohag National Museum, by scraping the infected places using sterile swipes [28]. Sterilized Petri dishes containing sterile (PDA) media were inoculated using these swabs. The inoculated dishes were placed in an incubator and maintained at a temperature of 28–30 °C for 1–7 days. The resulting colonies were then purified by repeatedly transferring them onto new PDA Petri dishes to create separate colonies. The resulting microorganisms were subsequently identified. The identification process was carried out using a microscope of type Olympus BX51 compound microscope equipped with Toup Tek XCAM1080PHA (Toup Tek, Zhejiang, China) digital imaging system at Fungi Laboratory, Faculty of Science, Sohag University.

Microbiological study of AgNPs

The antifungal activity of silver nanoparticles against isolated fungal strains was assessed using the agar well diffusion assay technique according to (Walaa A. Abdel Wahab et al.) with some modifications [29]. This method involves injecting PDA media with each isolated fungal strain separately, then pouring it into sterile Petri dishes. Using a drill, 50 μl of nanoparticles are then placed in this hole, and the plates are then placed in the incubator at a temperature of 28 ± 2 °C for 24–48 h. The diameter of the apparent inhibition zone around the hole is then measured in cm, and the greater the diameter of the inhibition zone, the higher the antifungal efficacy of the nanoparticle [30].

Examination and analysis procedures

Morphological study The morphological analyses of the prepared AgNPs/Klucel G nanocomposites were investigated by transmission electronic microscopy (TEM), where the TEM images were obtained by a JEM-1230 electron microscope operated at 60 kV (JEOL Ltd., Tokyo, Japan). Before taking a TEM image, the sample was diluted at least 10 times by water. A drop of well-dispersed diluted sample was placed onto a copper grid (200-mesh and covered with a carbon membrane) and dried at ambient temperature [31–34]. A scanning electron microscope (Quanta FEG250 NRC) was used for the investigation of the surface morphology of the untreated and treated linen and fine gold coater was used [35, 36].

Mechanical properties Tensile strengths and elongation of raw and dyed linen samples treated with AgNPs/Klucel G were measured using a US Tinius Olsen device with strength of 5 kN. Test conditions were under 25 °C and 65% relative humidity, the distance between the jaws of the device was 5 cm, and the dimensions of the samples were 3×15 cm. The measurement was done according to international standards (ASTM D503506 (2008) standard test method for breaking force and elongation of textile fabrics (strip method) [3, 25, 26].

Colorimetric measurements Portable colorimeter type (PCE-CSM7 S/N 330242 made in UK), used to measure the different colors of linen sample by CIE Lab colour system before and after treatments to identify any probable color changes might be resulted after AgNPs/Klucel G treatments [37]. Total color change (ΔE^*) of linen samples treated with AgNPs/Klucel G was calculated according to the following equation $\Delta E^* = \{(\Delta L^*)^2 + (\Delta b^*)^2 + (\Delta a^*)^2\}^{1/2}$ [38–41], where ΔL^* , Δa^* and Δb^* are the changes of the color coordinates L^* , a^* and b^* for the treated samples, compared to untreated sample [42].

Chemical properties

- **ATR-FTIR spectroscopy**
FTIR analysis was used to determine the distinctive functional groups of AgNPs/Klucel G, as well as to determine the effect of the treatment process using AgNPs/Klucel G on the functional groups of linen fibers [40]. FTIR measurements were carried out using ATR-FTIR Spectrometer (Bruker Alpha) at the Microchemical Analysis Unit, Faculty of Science—Sohag University—Egypt. The instrument was configured with ATR sample cell including a diamond crystal with a scanning depth up to 2 μm . The spectrum was recorded in absorbance mode over the spectral range $4000\text{--}400$ cm^{-1} with a resolution of 4 cm^{-1} [43].
- **X-ray diffraction**
XRD was used to determine the rate of crystallization of cellulose polymer, the main component of linen fibers, and to determine characterization of prepared AgNPs. The measurement were carried out at the (XRD) unit, Faculty of Science, Sohag University, using a Bruker D8 Advance device at room temperature, and the scanning range of the 2θ angle was $10\text{--}30$ [44].

Evaluation of the antifungal properties of linen treated with AgNPs/Klucel G The disk diffusion method according to Lo'pez-Oviedo et al. was used, with some modifications, to evaluate the antifungal properties of linen fibers treated with AgNPs/Klucel G [45]. Where raw and dyed linen samples treated with AgNPs/Klucel G were cut in 3×3 dimensions, then using a sterilization cabinet and PDA culture medium inoculated with fungal strains. The culture medium inoculated with fungal spores was poured into Petri dishes, then, after the medium hardens, the linen samples that were previously cut are placed, then the medium containing the fungus spores and the treated linen samples are incubated at temperature 28 ± 2 °C for 24–48 h. Then the diameter of the apparent inhibition zone around the linen sample is measured in cm this test was done on treated linen samples after a period of 1 and 3 months.

Results and discussion

Identification of isolated fungal strains

Through microscopic examination, it was found that the isolates belong to the fungal genera *Aspergillus* sp., *Trichoderma* sp. and *Penicillium* sp. [25]. Were Fig. 1 shows the morphology of the spores of the isolated fungal, and through previous studies, the presence of these fungal strains has been proven in many Egyptian

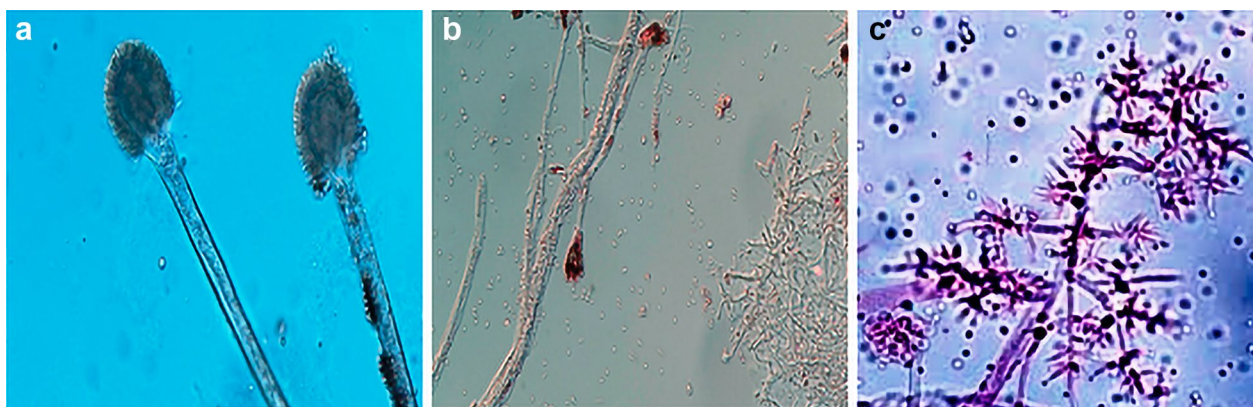


Fig. 1 The morphology of the fungal strains isolated from the archaeological linen, where **a** *Aspergillus flavus*, **b** *Penicillium duclauxii*, and **c** *Trichoderma* sp.

museums such as the Egyptian Museum and the Coptic Museum [46, 47].

Characterizations of AgNPs prepared by the chemical reduction of AgNO₃

Through the X-ray diffraction pattern in Fig. 2 of AgNPs prepared by the chemical reduction of AgNO₃ in the presence of PVP as a stabilizing agent, the pattern is attributed to the sharp values of the diffraction angle 2θ specified at 44.381, 64.573, 77.557, 81.715, and 38.185, corresponding to (111), (200), (220), (311), and (222) for a cubic diffraction pattern of AgNPs, and these results were according to the induction card of AgNPs (JCPDS File No. 04-0783) [48].

The FTIR pattern in Fig. 3 for the prepared silver nanoparticles showed the appearance of some spectral bands such as 3421 cm⁻¹, which is a band compatible with the

extension of the amine group (N-H), 2922 cm⁻¹, which corresponds to the extension of the alkenes group (C-H), 1383 cm⁻¹, which is a characteristic band for vibration in (NO₃) group. The vibration at the spectral range 1113 cm⁻¹ is a distinctive range for the PVP polymer used in the AgNO₃ reduction processes for the preparation of silver nanoparticles. The presence of the spectral range 1622 cm⁻¹ indicates the expansion of the carbonyl group (C=O) in the PVP polymer used in the preparation of AgNPs [48]. The appearance of the spectral band 1057 cm⁻¹ is due to the expansion of the primary bond (C-OH) [49].

Particles size of AgNPs prepared by the chemical reduction of AgNO₃ in the presence of PVP polymer as a stabilizing agent were studied using TEM, where the size of the granules before loading on hydroxypropyl cellulose

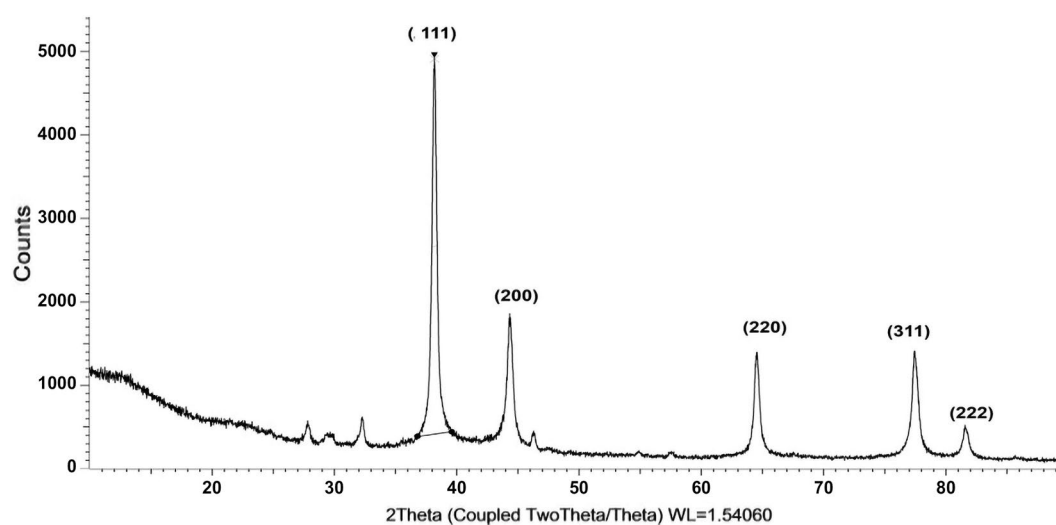


Fig. 2 (XRD) pattern of AgNPs prepared by using PVP as a stabilizing agent

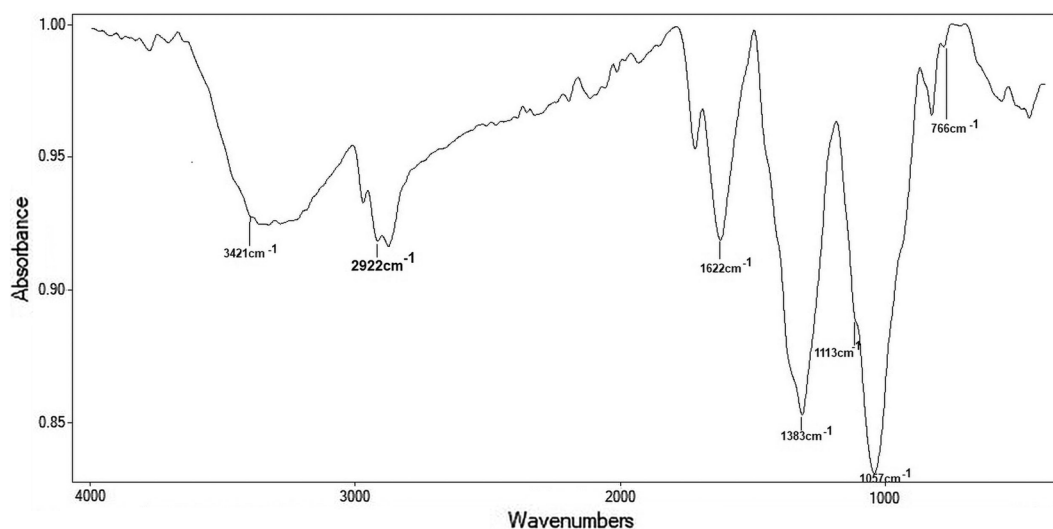


Fig. 3 FTIR-ATR of AgNPs prepared by the chemical reduction of AgNO_3 in the presence of PVP polymer as a stabilizing agent

polymer ranged from 2–3 nm and after loading 9–13 nm as shown in Fig. 4.

Antifungal properties of AgNPs/Klucel G

The inhibition zone diameter of AgNPs/Klucel G against fungal strains *Aspergillus flavus*, *Trichoderma* sp, and *Penicillium duclauxii* was measured using the well-cut diffusion technique. The diameter of the inhibition zone of the AgNPs/Klucel G + H_2O_2 clearly shows that the

best concentration to inhibit fungal strains with high efficiency is 3%, as shown in Fig. 5 and Table 1. Moreover, the diameter of the inhibition zone, which reached at a concentration of 3% to 5 cm, also clearly demonstrates that the AgNPs/ Klucel G + H_2O_2 were more effective in inhibiting the fungal strain *Trichoderma* sp.

It is also clear that the AgNPs/ Klucel G were more effective in inhibiting the fungal strain *Trichoderma* sp., as is evident from the diameter of the inhibition

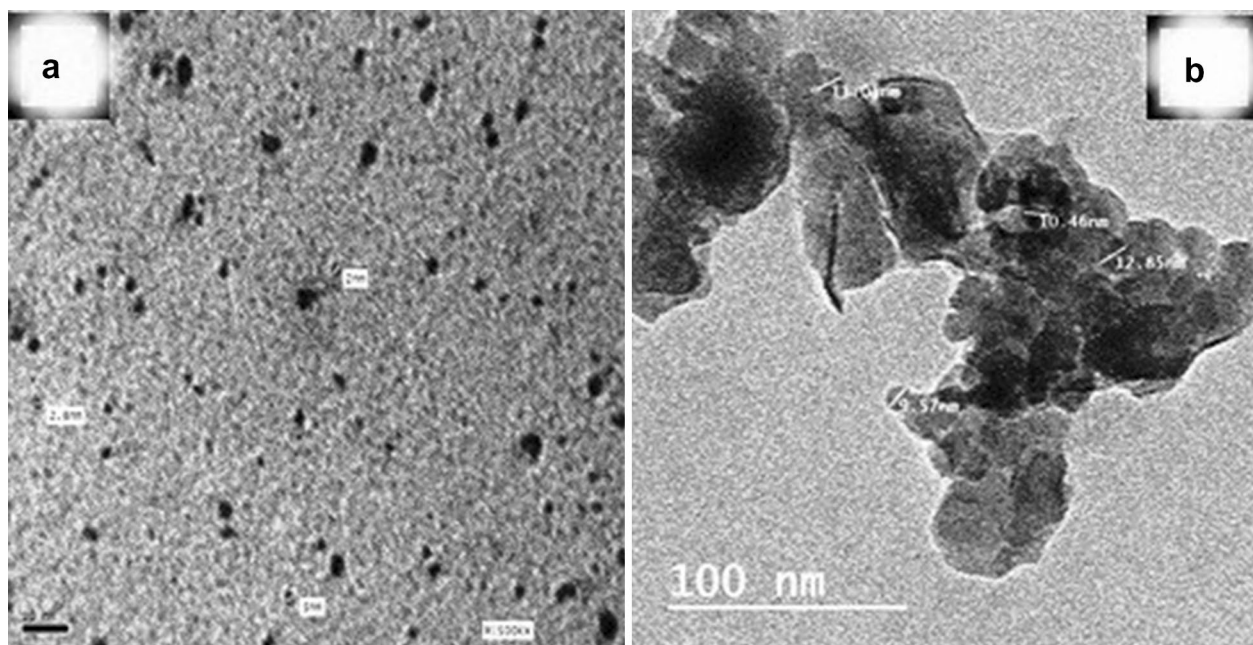


Fig. 4 The size of the AgNPs where **a** size particles before loading on Klucel G polymer, **b** size of the particles after loading

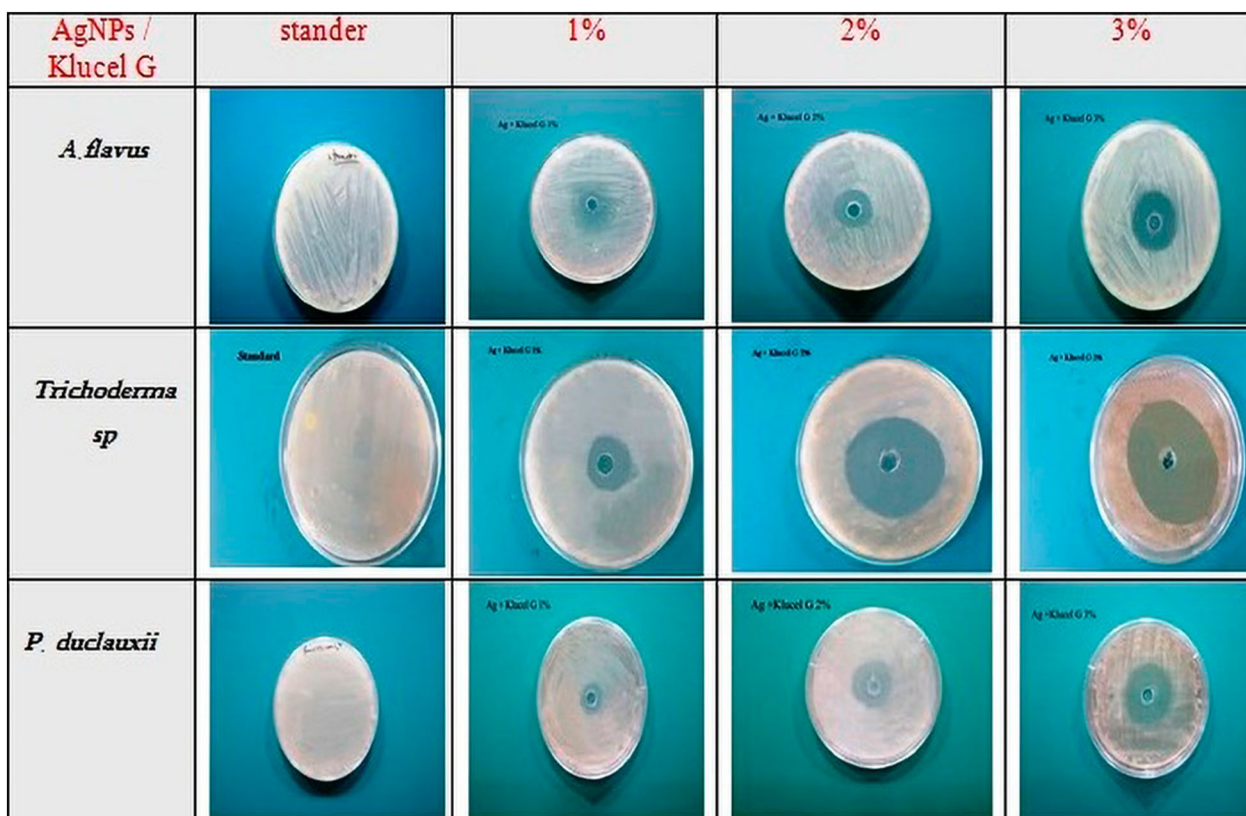


Fig. 5 The inhibition zone of AgNPs with a concentration of 1, 2 and 3% loaded on Klucel G polymer with a concentration of 1%

Table 1 Inhibition zone diameter in cm for AgNPs loaded on Klucel G polymer against fungal strains

Fungal strains	Inhibition zone diameter in cm		
	1%	2%	3%
<i>A. flavus</i>	0.5 cm	0.75 cm	2.2 cm
<i>Trichoderma</i> sp.	1 cm	4 cm	5 cm
<i>P. duclauxii</i>	0.3 cm	0.9 cm	2.3 cm

zone, which reached at a concentration 3% to 5 cm as shown in Table 1.

Surface morphology of linen fibers treated with AgNPs3%/Klucel G1%

Microscopic examination using SEM of linen fibers treated with AgNPs3%/Klucel G1% showed good coverage and packaging of the treated fibers, which appears in giving the fibers smooth surface compared to the untreated sample as shown in Fig. 6.

Mechanical properties of linen textiles treated with AgNPs/ Klucel G

Application of treatment with AgNPs 3%+Klucel G1%+H₂O₂ 3% forms a film on the surface of the linen textiles, in addition to the penetration of the treatment solution into the inner regions of the fibers. This resulted in an improvement in the mechanical (tensile strength and elongation) properties of treated linen textiles as shown in Table 2.

The effect of treatment with AgNPs3%/Klucel G1% on the colorimetric measurements of linen textiles

The color change properties of treated linen samples were studied. where it is noted that the samples increased in darkness as is evident in the value of L*, which refers to the rates of the dark of the samples or their brightness (black–white), as it expresses the lowest value on the dark of the samples, while the value from (0–100) on the brightness of the samples [50, 51]. Where the value of L* before treatment for the raw linen sample was 65.33, but after treatment, it is noted that this value decreased to 55.81, which confirms the increase in the rate of darkening of the sample after treatment, as well as the rest

of the dyed samples. It is also noted that the total color difference values ΔE^* for the raw and dyed linen samples after treatment increased significantly, as the value of ΔE^* for the raw linen sample after treatment reached 13.30, which is an unacceptable rate in the textile treatment process, as shown in Table 3.

Through the color change values in Table 3, it is clear that the treatment solution resulted in color changes that cannot be approved or applied to textiles, so a 3% hydrogen peroxide solution H_2O_2 was used as a bleaching agent

that helps transform the color of the treatment solution into a transparent color [52] as shown in Fig. 7.

Where a solution of H_2O_2 was used at the rate of 1 ml per 5 ml of the treatment solution. By applying a nanometer silver solution to which bleach is added, a significant improvement is observed in the color change values of raw and dyed linen samples. As the value of ΔE^* for the raw linen sample treated with AgNPs/Klucel G/ H_2O_2 was observed. ΔE^* 1.13, while the linen sample treated with a silver solution to which the H_2O_2 was not added was 13.30 as shown in Tables 3, 4.

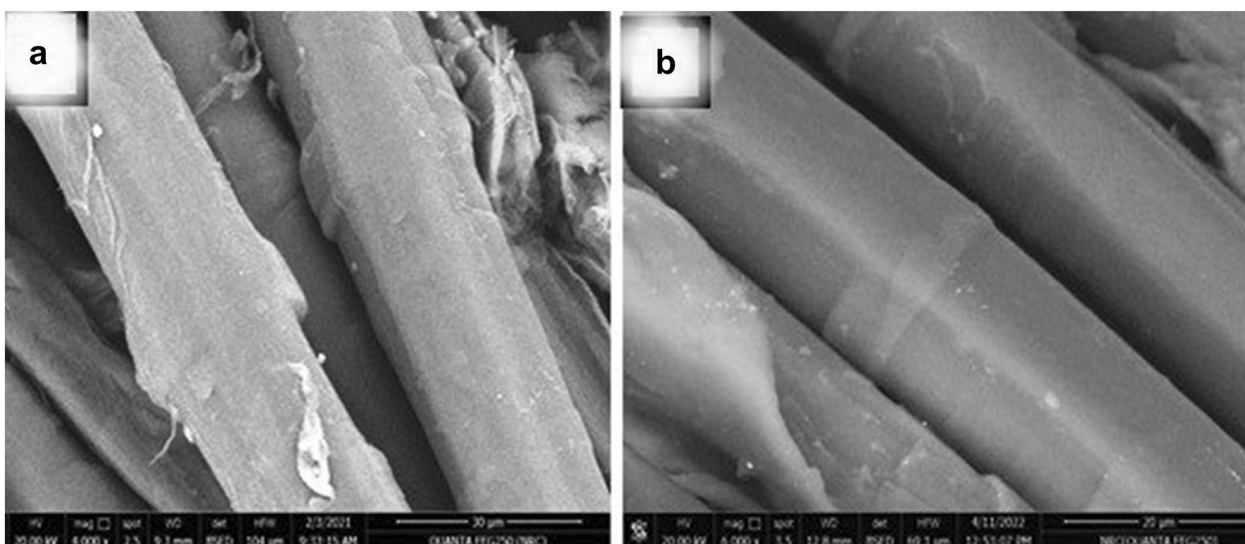


Fig. 6 Linen fibers treated with AgNPs3%/Klucel G1%. were **a** sample before treatment, while **b** sample after the treatment

Table 2 Tensile strength and elongation of linen samples before and after treatment with AgNPs/Klucel G

Sample	Tensile strength kg/f before treatment	Tensile strength kg/f after treatment	Elongation % before treatment	Elongation % after treatment	Change ratios after treatment (%)
Raw linen	54.1469	73.4196	10.23	33.23	35.6
Linen dyed with turmeric	60.0613	61.6928	6.17	9.34	2.8
Linen dyed with madder	47.6207	49.6432	5.69	9.42	4.2

Table 3 Color change values of raw and dyed linen samples treated with AgNPs/Klucel G

N	Sample	Before treatment			After treatment			Color difference			
		L*	a*	b*	L*	a*	b*	L*	Δa^*	Δb^*	ΔE^*
1	Raw linen	65.33	2.90	9.43	55.81	9.24	16.74	- 9.52	6.34	7.31	13.30
2	Linen dyed with turmeric	65.10	4.68	51.99	54.04	9.54	43.37	- 11.06	4.86	- 8.62	14.84
3	Linen dyed with madder	48.66	15.42	14.98	44.83	15.18	16.46	- 3.83	- 0.24	1.48	4.11

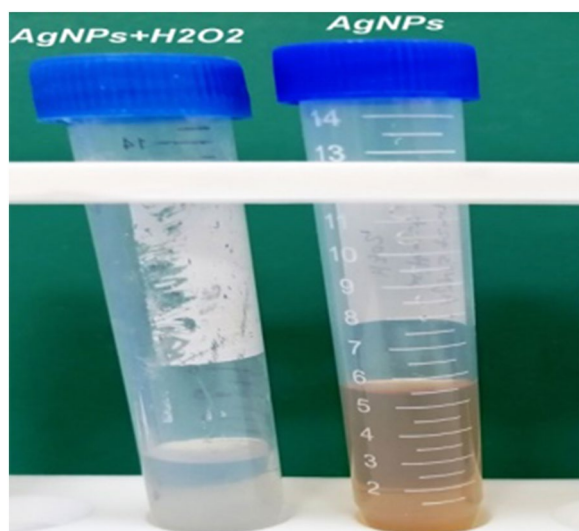


Fig. 7 AgNPs/Klucel G solution before and after adding H₂O₂ as a bleaching agent

Crystallinity index of linen textiles treated with AgNPs/ Klucel G/H₂O₂

Through XRD analysis, the effect of treating linen fibers with AgNPs/Klucel G was evaluated by measuring the crystallinity index of cellulose polymer, the main

component of linen fibers. The crystallinity index is calculated according to the Segal peak height method a maximum intensity value I₀₀₂ is found between the scattering angles of 2θ = 22° and 23°. The minimum value I_{am} is taken using a minimum in the data, typically between 2θ = 18° and 19 [53–55], then the crystallization index of fibers before and after the treatment was carried out using the following equation:

$$CI = \frac{IC - I_{am}}{IC} \times 100$$

where CI expresses the Crystalline Index, which is calculated according to the previous equation, IC represents the highest crystalline point in the sample and I_{am} represents the amorphous region in the sample [44]. And by measuring the crystalline and amorphous area of the linen samples before and after treatment, it is clear that there has been an improvement and increase in the polymerization index of cellulose, the main component of the fibers, Whereas, the crystallization index of the raw linen sample dyed with turmeric and madder before treatment with AgNPs/Klucel G reached 55.44, 80.2 and 75.3% respectively and it increased after treatment to become 58.56, 80.8 and 78.4% respectively as shown in Table 5.

Table 4 Color change values for linen samples treated with AgNPs/Klucel G/H₂O₂

N	sample	Before treatment			After treatment			Color difference			
		L*	a*	b*	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
1	Raw linen	64.28	3.23	9.54	64.07	3.38	8.43	-0.21	0.15	-1.11	1.13
2	Linen dyed with turmeric	62.91	7.05	52.24	62.76	6.13	51.28	-0.15	-0.92	-0.96	1.33
3	Linen dyed with madder	48.40	13.67	15.71	49.60	14.26	16.27	1.2	0.59	0.56	1.44

Table 5 Crystallinity index of linen samples before and after treatment with AgNPs/Klucel G

N	Sample	Crystalline area IC	Amorphous area I _{am}	Crystalline index CI (%)
1	Raw linen before treatment	2θ 22.922 Y23130	2θ 19.295 Y 10313	55.41
2	Raw linen after treatment	2θ 22.922 Y2601	2θ 19.295 Y10780	58.56
3	Linen dyed with turmeric before treatment	2θ 22.995 Y 13970	2θ 19.029 Y 2759	80.2
4	Linen dyed with turmeric after treatment	2θ 23.012 Y 13962	2θ 19.013 Y 2679	80.8
5	Linen dyed with madder before treatment	2θ 23.028 Y 9502	2θ 19.013 Y 2338	75.3
6	Linen dyed with madder after treatment	2θ 23.028 Y 13052	2θ 19.013 Y 2761	78.4

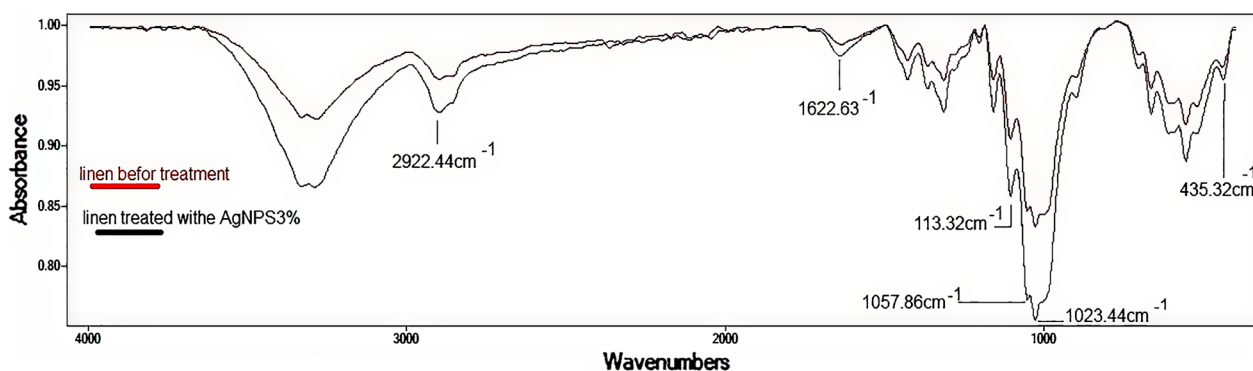


Fig. 8 ATR-FTIR spectrum of the treated and untreated linen textiles

The effect of treatment with AgNPs3%/Klucel G1% on the chemical structure of linen textiles

The results obtained from the ATR-FTIR spectrum Fig. 8 of the treated linen sample compared to untreated sample proved that, Increasing the intensity of vibration in the spectral range 435.32 cm^{-1} and the spectral range 1023.44 cm^{-1} , which are two distinct bands for the crystallization processes of cellulosic fibers. Increasing the intensity of vibration expresses an increase in the rate of crystallization of samples [56]. This result is consistent with the results of measuring the crystallization rates of samples by (XRD), which confirmed an increase in the crystallization rate of the sample after treatment compared to the untreated sample. The intensity of the band 1113.32 cm^{-1} reflects the PVP polymer used in the AgNO₃ reduction process used in the preparation of silver nanoparticles, and the spectral band 1622.63 cm^{-1}

appeared, which is characteristic of the expansion of the carbonyl group in the PVP polymer [48]. The appearance of the spectral band 2922.44 cm^{-1} is compatible with a C–H extension of the alkenes group [49].

Antifungal properties of raw and dyed linen samples

The disc diffusion method was used to evaluate the antifungal properties of linen samples treated with AgNPs/Klucel G + H₂O₂, which revealed the presence of a large diameter inhibition zone around the treated linen samples incubated with fungal strains isolated previously from the Sohag National Museum, demonstrating the high effectiveness of the treatment compound used to give linen fiber resistance to fungal strains, even after 3 months of treatment, as shown in Figs. 9, 10 and 11.

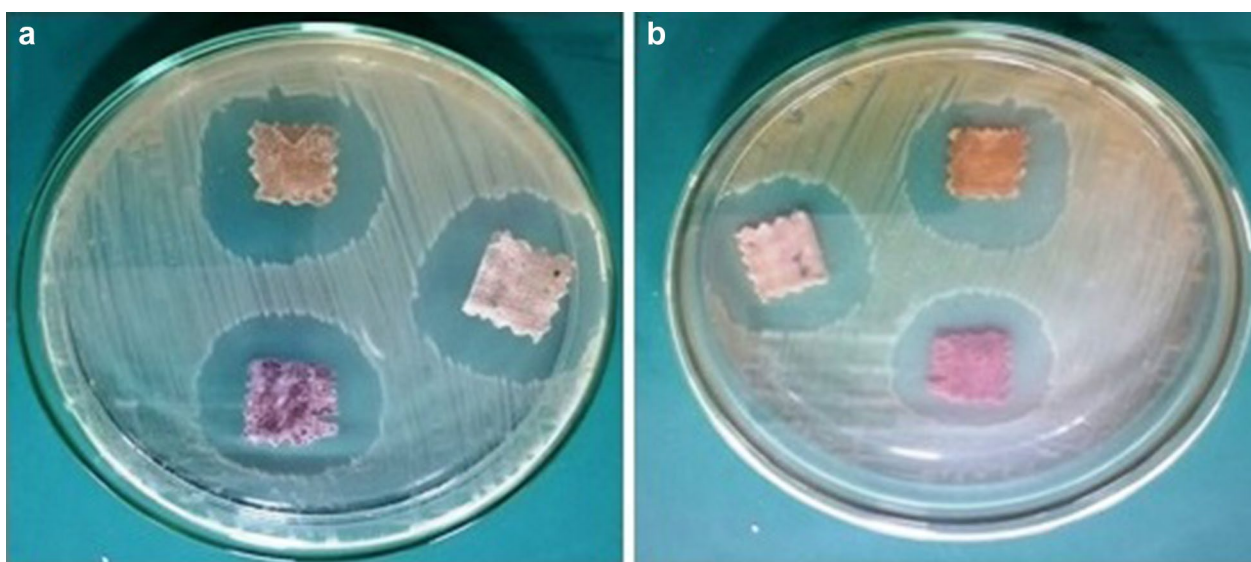


Fig. 9 Inhibition zone for linen samples treated with AgNPs/Klucel G incubated with *A. flavus*, where **a** inhibition zone after 1 month, **b** inhibition zone after 3 months

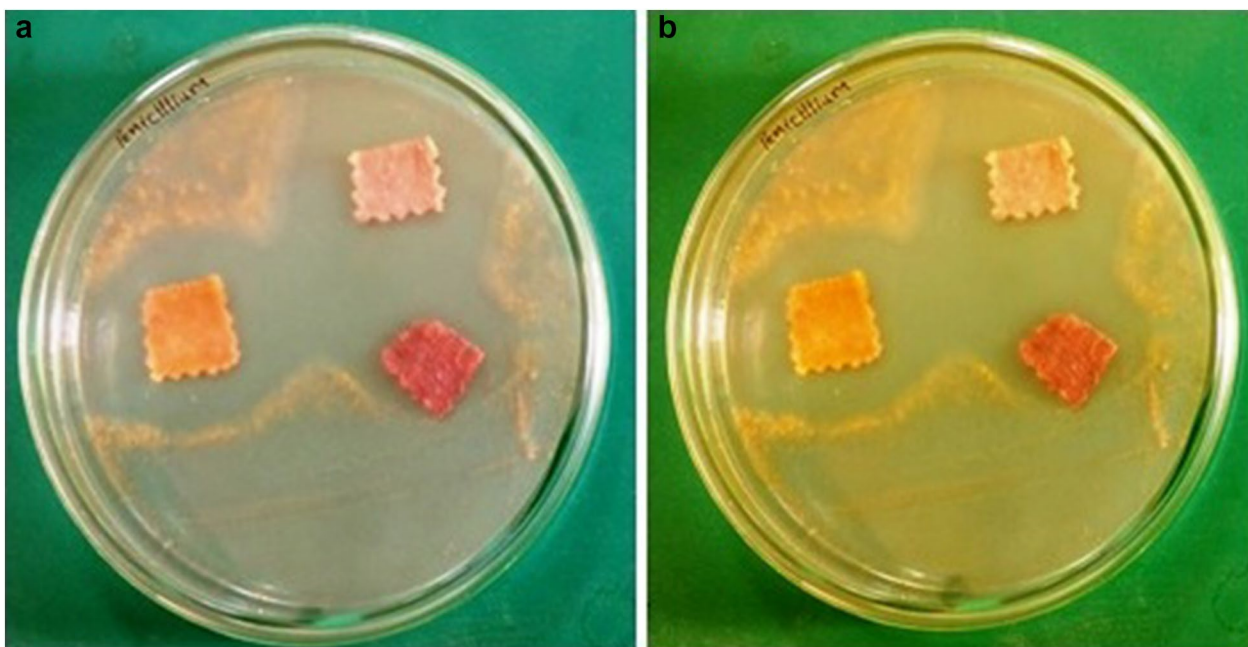


Fig. 10 Inhibition zone for linen samples treated with AgNPs/Klucel G incubated with *P. duclauxii*, where **a** inhibition zone after 1 month, **b** inhibition zone after 3 months

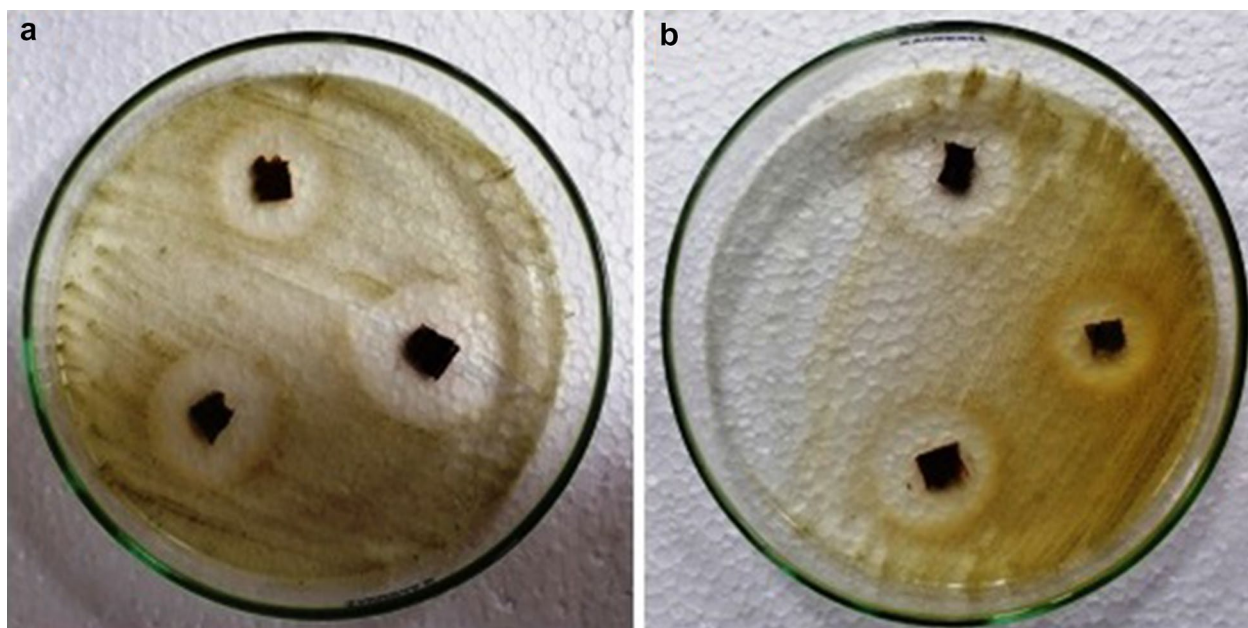


Fig. 11 Inhibition zone for linen samples treated with AgNPs/Klucel G incubated with *Trichoderma* sp., where **a** inhibition zone after 1 month, **b** inhibition zone after 3 months

Conclusion

The preventive conservation of archaeological textiles is one of the most important requirements for preserving the cultural heritage. The study used AgNPs prepared by

the chemical reduction of $AgNO_3$ in the presence of PVP polymer as a stabilizing agent, By studying the properties of the prepared AgNPs, it was found that the size of their granules by examination and imaging using TEM

ranged between 2–3 nm and 7–13 nm after loading those particles on Klucel G 1% polymer. The microbiological study using well-cut diffusion technique of AgNPs/Klucel G demonstrated the effectiveness of AgNPs at a concentration of 3% in inhibiting fungal strains *A. flavus*, *Trichoderma* sp. and *P. duclauxii* that were isolated from the ancient linen piece No. 1345 preserved in the Sohag National Museum in Egypt. The study also demonstrated the occurrence of color changes in raw and dyed linen textiles after applying AgNPs/Klucel G to them. The study was able to reduce these color changes by adding a bleaching solution of H₂O₂ at a concentration of 3% to a solution of AgNPs/Klucel G. And by applying AgNPs/Klucel G + H₂O₂ to raw and dyed textiles and evaluating the different properties of textiles before and after treatment, a significant improvement was found in the tensile strength and elongation of samples after treatment, as well as a significant improvement and increase in the crystallization index of cellulose polymer, the main component of linen fibers after treatment.

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Author contributions

MA contributed to the preparation and dyeing of the experimental samples, conducting some tests and analyzes in the study, and interpreting its results. MM contributed to the interpretation of some results of the analysis of linen textiles. WS prepared the AgNPs used in the study and loaded them on the Klucel G polymer, and studied the properties of the prepared silver nanoparticles. WAW also carried out the tests to study the anti-fungal properties of the prepared AgNPs. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article and its additional information files.

Declarations

Competing interests

The authors declare that they have no competing interests.

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