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Multi-Technique Characterization and Conservation of an Ancient Egyptian Fabric from King Khufu First Solar Ship

Eman Nabil[1], Tawfik Khattab[2], Samir Kamel[3*]

[1]Restoration laboratory, Royal Chariots Museum, Cairo, Egypt
[2]Dyeing, Printing and Auxiliaries Department, National Research Centre, Cairo, Egypt
[3]Cellulose and Paper Department, National Research Centre, Cairo, Egypt
Email: *samirki@yahoo.com

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Abstract

Textiles are among the most fragile artefacts in the world. They are difficult to preserve even in the best circumstances. Herein, we studied an artefacts fabric of a special nature in terms of usage. Despite the multiple applications of textiles, the piece understudy is one of the unique pieces that the ancient Egyptian used as fenders for King Khufu's first solar boat, the second-largest discovery in Egypt history. The boat was discovered inside a limestone pit. It was disassembled and arranged in several layers. Four pillows of wrapped fabric were found in the first layer, which was used as boat fenders. This use is a great discovery of the role of textiles in the manufacture of ancient boats. Thus, we conducted tests and analytical studies of those fenders using scanning electron microscopy (SEM) and an optical microscope to identify the type and nature of fibers, spinning method, and aspects of damage. Both energy-dispersive X-ray (EDX) analysis and infrared analysis (FT-IR) were employed to explore the sample's elemental content and study the functional groups of the fabric. These analytical processes were useful in carrying out the restoration and preservation work necessary for the artefact under study.

Keywords

King Khufu, Solar Ship, Linen Fender, Analytical Methods, Conservation

1. Introduction

Textile research has been of growing interest within the field of archeology because of its potential to offer relevant information concerning the technical advancements, socio-economic and religious functions of textiles in ancient civilizations [1] [2]. Textile archaeology searches the dating of the archaeological samples using different techniques. It is a significant branch of cultural studies because textiles are a major characteristic of craft manifestation which is associated with cultures of nations [3] [4]. Ancient and prehistoric objects have introduced remarkable proof correlated to textile items as presented in paints and sculptures. Linen fabrics are the oldest textile products employed for dating purposes back thousands of years BCE. Ancient Egyptian clothing was mainly made of linen which in turn was made of the well-known strong and long flax fibers [5] [6] [7]. Textiles suffer from natural aging, such as thermal, chemical, and photochemical degradation as well as microbial attack [8] [9]. Heating cellulose leads to cross-linking amid two hydroxyl substituents on two cellulosic polymer chains forming stiffer fibers [10]. Furthermore, cellulosic polymer chains may also be exposed to the cleavage process due to the free-radical thermo-oxidative process. In the presence of acidic conditions, bonds cleavage is increased [11]. Thus, aqueous conservation procedures usually include the removal process of acidity with caution because high alkalinity can lead to a higher degradation rate during the aging course [12]. The rate of thermal decay can also be increased by moisture and other catalysts, such as transition metals which have been suggested as catalysts for the oxidative decay of cellulose [13] [14] [15] [16].

Textiles have had a glorious past in Egypt since ancient times, and they reflect the pattern of change in every country of civilization. It has multiple uses for various purposes of life and has played a large role in many industries. Especially the manufacture of boats that were developed extensively in the era of Egypt Old Kingdom as a result of developing the needs of the Egyptian religious or secular society. Egyptians became in urgent need of huge large boats that made long trips [17] [18]. Examples of these boats are the first solar boat of King Khufu, which is the largest wooden boat found in the whole world. It was confirmed that the craft of making boats is an organized craft. It is based on many materials, including basic materials, such as Arundo, papyrus, and wood; and auxiliary materials, such as ropes, mats, and linen [19] [20] [21]. The auxiliary materials in the Khufu boat played a large role in the boat construction technique as the ropes were used to connect and assemble the boat parts. The mats were also used to cover and protect the boat during the burial period. Interestingly, the ancient Egyptian used textile pillows as fenders that were fixed on wooden plates or rafters at the four ends of the boat with a rope to absorb shocks when the boat collides with the shore (**Figure 1**).

It is of high significance in cultural heritage research to use nondestructive techniques. Modern analytical nondestructive techniques are playing increasingly important roles in the field of textile archaeology [22] [23]. This paper describes the characterization and conservation processes of an Ancient Egyptian fabric employed as fenders in King Khufu first solar boat employing a number of scientific and nondestructive analytical techniques in order to present a

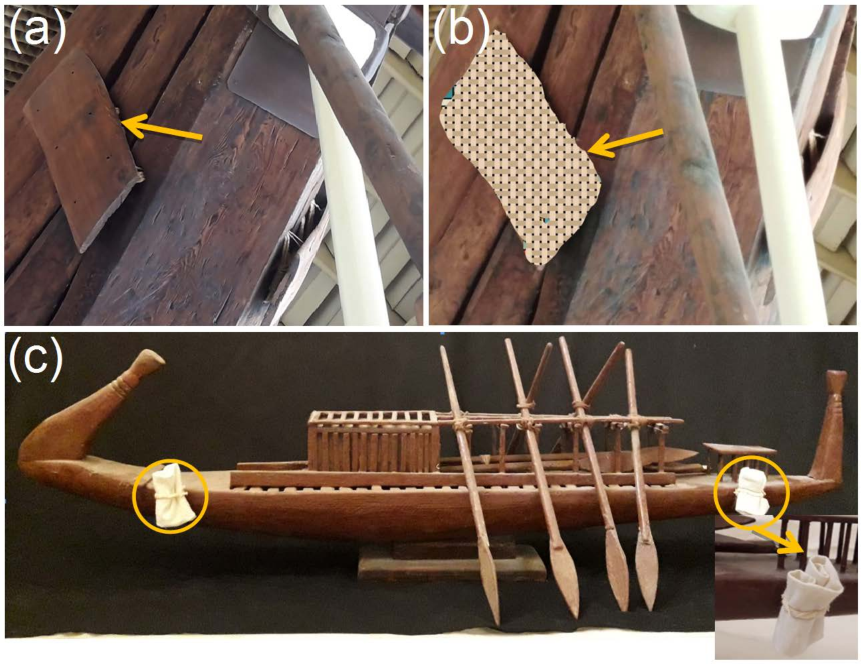

Figure 1. Positions of fixing fenders on rafters of Khufu's boat (a), diagrammatic representation of the locations for fenders, and wooden model of Khufu's boat demonstrating positions of fenders and fixing method.

deeper conclusion for the deterioration state, and a better realization of how was and/or will be preserved the artefact item. We analyzed an ancient Egyptian fabric from King Khufu's first solar ship and this will be helpful in carrying out the conservation work necessary for the current artefact.

2. Experimental

2.1. Materials

Ancient Egyptian artefact fabrics were obtained from the Giza Solar boat museum. The fabrics were used as fenders in King Khufu's first solar ship. Panels made from Cardboard (185/200 GSM) and foam (White Smooth Surface Archival Buffered Acid-Free Foam Board, Pkg of 10 Sheets Antique White 40' × 32 6 Thick), and equipped with cotton handles were designed to facilitate the handling of the artwork until the completion of the restoration work and complete transportation to the place designated for them either for museum display or storage. Stand with a drawer shape lined from the inside with two layers of polyethylene was employed for storage. This drawer method is an excellent method used to save small-sized artefacts. Japanese papers were used to cover the carrier drawer for artefacts that suffered from fragility. Cedar oil was obtained from the local Egyptian market; to be applied as a natural sterilizing substance against infectious fungi. Beva 371 was purchased from the local Egyptian market and was applied to strengthen the fabric. Beva 371 (Berger ethylene vinyl acetate) is a product based on ethylenevinyl acetate, paraffin, ketone resin, 40% solids content in aliphatic and aromatic solvents. Gustav Berger's O. F. 371, used in combination with the special Thinner 372, forms a reversible adhesive with good elasticity and chemical stability. Appearance: opalescent gel, solids content—40% melting point is 68˚C and flash point < 21˚C.

2.2. Apparatus

In this study, different analytical approaches such as scanning electron microscope (SEM) images, energy-dispersive X-ray (EDX) spectra, optical microscopy and Fourier transformed infrared (FT-IR) spectra were employed to elucidate the constituents, and original nature of an ancient Egyptian fabric from Khufu first solar ship at Giza solar boat museum as well as to better accomplish the conservation status of this artefact fabric.

2.2.1. Field-Emission Scanning Electron Microscopy

The morphology of the current artefact fabric was examined by field-emission scanning electron microscopy (FE-SEM) using a Quanta-FEG250 (Czech Republic) with an accelerating voltage of 20 kV.

2.2.2. Energy-Dispersive X-Ray Spectroscopy

The elemental content and distribution were investigated by surface energy-dispersive X-ray (EDX) spectroscopy unit (TEAM-EDX Model) connected to the scanning electron microscope. The EDX spectra were recorded at a work distance of 21 mm and an acceleration voltage of 20 kV.

2.2.3. Optical Microscope

The structure of the artefact fabric used in the pillow understudy was studied by optical microscopy on an Axiocam MRC5 camera (Imager M1, Zeiss).

2.2.4. Fourier Transform Infrared Spectroscopy

FT-IR spectra (transmission mode) were recorded by using the KBr disc technique on an FT-IR spectrophotometer (Nexus 670, Nicolet, USA). The measurements were reported between 4000 - 400 cm^{-1} using a 4.0 cm^{-1} spectral resolution.

2.3. Methods

2.3.1. Visual Evaluation

The naked-eye evaluation was applied to study the state of the external surface of an artefact.

2.3.2. Conservation Process

Depending on the assessment results of the various analytical techniques, the conservation process was performed to get rid of the deposits from the artefact fabric surface and to preserve it against future aging.

2.3.3. Microbial Deterioration

The microbial deterioration was monitored at the conservation center of Grand Egyptian Museum according to previously reported procedure [24]. The sampling process included several tools including cotton swabs, adhesive tape, and a grinding process. The isolation media of fungi was carried out using potato dextrose agar medium (PDA; Nissui) and Lignin cellulose medium (LCM; Nissui). In addition, modified Czapeck's medium was prepared by adding lignin cellulose as a carbon source instead of sucrose. This medium is composed of lignin cellulose (10.00 g·L^{-1}), potassium phosphate dibasic trihydrate ($KH_2PO_4 \cdot 3H_2O$; 1.00 g·L^{-1}), sodium nitrate ($NaNO_3$; 10.00 g·L^{-1}), potassium *chloride* (KCl; 0.50 g·L^{-1}), magnesium sulfate heptahydrate ($MgSO_4 \cdot 7H_2O$; 0.50 g·L^{-1}), ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$; 0.01 g·L^{-1}) and Agar (20.00 g·L^{-1}). All of the above media were amended with an antibacterial agent (chloramphenico) . The isolation media of bacteria included a nutrient agar medium (Nissui).

3. Results and Discussion

3.1. Archaeological Description and Visual Examination

In 1954, the largest boat in history (Khufu's first solar ship), which dates back to the ancient Egyptian state, was discovered inside an underground limestone hole, disjointed and arranged in layers. The first layer comprised four textile pillows among a group of boat paddles. The piece understudy is one of those pillows reported under the record number 320 in the Khufu Museum. In the place of discovery, the first layer was found loaded on a side wooden plate between the first and second paddles. According to the museum records, the dimensions of the piece at the moment of discovery were 66 cm in length and 36 cm in width. According to the archaeological description, the pillow was made of thick layers of fabric previously reinforced at the surface with Markon Resin 9 Low Viscosity (Scott and Bader Co. Ltd.) dissolved in acetone as described in **Figure 2**. According to Ahmed Youssef, the restoration team strengthened the pillow at the place of its discovery due to its weakness at the moment of discovery [25].

The visual examination is the first step to study the state of the external surface of an artefact. It was found through the visual examination of the pillow

Figure 2. The pillow at the moment of discovery and the shape of the fabric rolls and the rope in the middle area used to fix the piece to the wooden beam Dimensions of the piece (Height, width, and diameter ≈ 22, 11, and 9 cm respectively).

state, and compared to the documentary pictures at the moment of discovery, how weak, fragmented, and shattered the state of the pillow reached due to poor storage.

3.2. Morphological Properties

3.2.1. Optical Microscopy

It was proved by the optical microscopic examination that linen was applied in the manufacture of boat fenders. Through the microscopic examination, it became clear that the fabric was constructed from the fibers of the linen plant due to the presence of distinctive bronchioles as shown in **Figure 3**. Flax is one of the oldest plants grown in prehistoric Egypt. It was mentioned that the ancient Egyptian used a type of linen called Linum humile Mill from which all kinds of linen fabric were derived [24]. Linen fabric has been used a lot in the manufacture of boats, such as sails, and it was dyed with a variety of colors. It was also used in covering the cabins [26] [27].

3.2.2. Scanning Electron Microscopy

Scanning electron microscope (SEM) images were applied to inspect the fabric characteristic morphological diagnostic features to identify the various manifestations of damage and judging the surface structure of the sample under study. Different studies of fibers at both microscopic and visual levels have a significant impact on exploring the behavior and deterioration of fabric as well as the properties of the fabric, which can help a lot in how to maintain them. There are three major factors that identify the properties of any textile, including the shape of the fibers, the source of the fibers, and how the final product is built. According to the external qualitative examination of the sample, it became evident that there was a severe cracking on the fabric surface as well as calcifications, dust, and dirt. Previous reinforcing materials covering the fabric surface were also

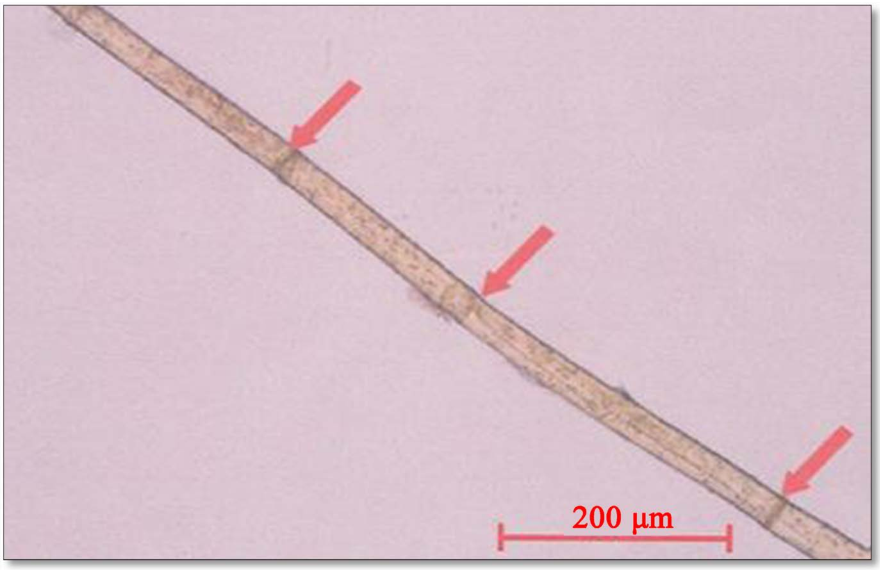

Figure 3. Optical microscope image displaying distinctive nodes on fibers.

monitored as shown in Figure 4. SEM images demonstrated that the fabric surface exhibited high roughness associated with damages, cracks, small holes, and slits. Microchannels of a diameter range between 5 - 50 μm were monitored. SEM images of the fabric exposed to conservation treatment indicated that the fabric surface was consistently coated with a film of Beva 371. The fabric thickness was in the range between 1.0 and 1.5 mm. The textile structure displayed a simple plain 1/1 weave with one over and one under interlocking of circularly twisted yarns.

3.3. Elemental Composition

Energy Dispersive X-Ray Spectroscopy

The elemental examination carried out on this type of artefact fabric led to a full understanding of its nature and element constituents, which helped in setting a plan to preserve this type of heritage. Energy-dispersive X-ray analysis (EDX) was applied to confirm the element structure of the linen. It was possible to study the changes that occurred in the original composition of the archaeological textile resulting from saturation with the reinforcing materials. Scanning electron micrographs were subjected to EDX mapping (Figure 5), while their corresponding EDX spectra representing the quantitative elemental composition of the heritage sample are shown in (Table 1). The total content results were taken before and after the consolidation process with Biva 371. A close-up view of both samples displayed high contents of both carbon (C) and oxygen (O) existing as major elements of linen structure. The other elements, including silicon (Si), aluminum (Al), magnesium (Mg), nitrogen (N), and calcium (Ca) were found through the samples which might be the constituent of the regular formation of

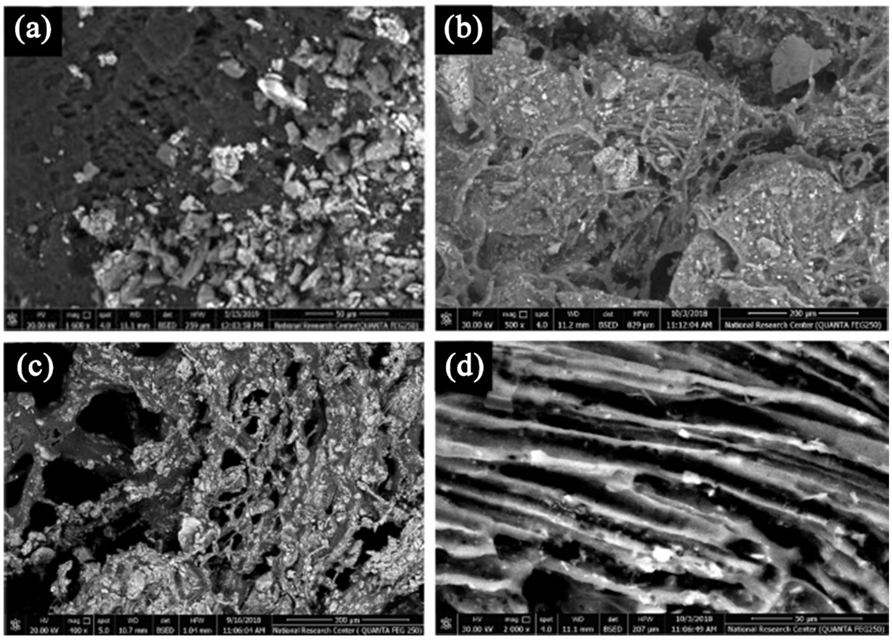

Figure 4. SEM images of the ancient Egyptian fabric from King Khufu's first boat before ((a) & (b)) and after ((c) & (d)) conservation.

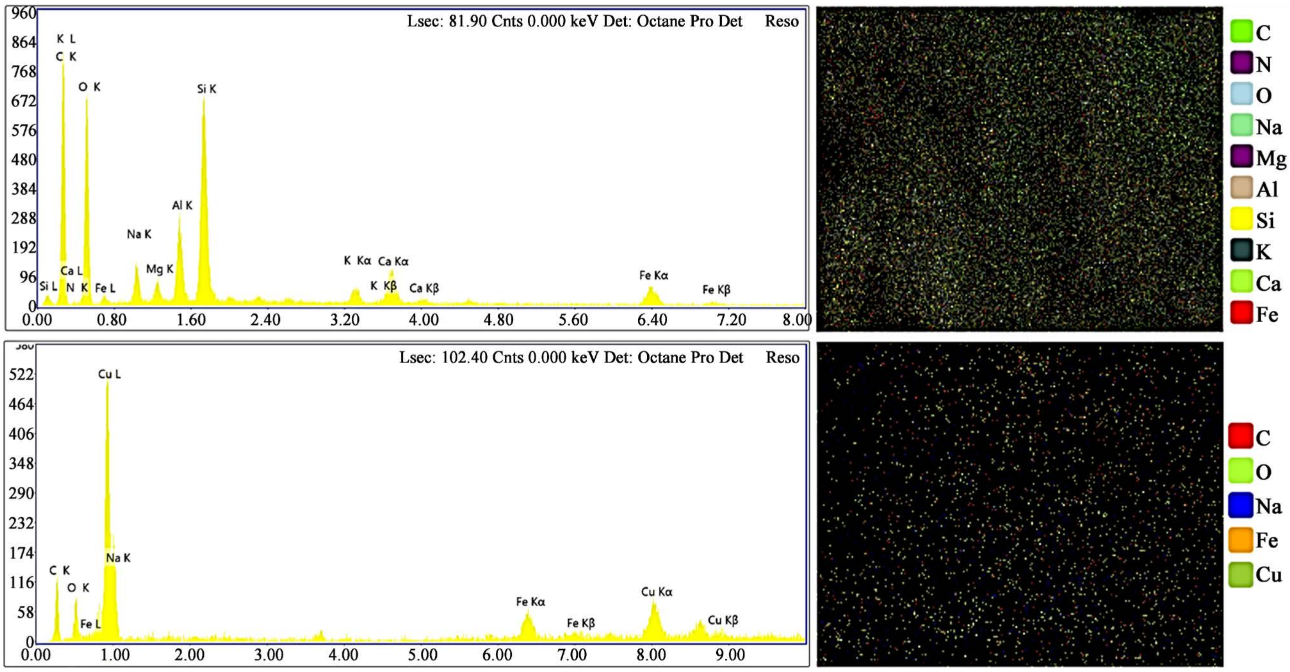

Figure 5. EDX diagram and elemental mapping of the fabric before (top) and after (bottom) Biva 371 conservation.

Table 1. EDX results of the fabric before and after Biva 371 conservation.

Element	Before conservation		After conservation	
	Wt%	At%	Wt%	At%
C	45.5	57.2	29.68	55.2
N	1.37	1.48	-	-
O	33.91	32	9.95	13.89
Na	2.36	1.55	14.75	14.33
Mg	0.68	0.42	-	-
Al	2.7	1.51	-	-
Si	6.93	3.73	-	-
K	0.71	0.27	-	-
Ca	2.39	0.9	-	-
Fe	3.44	0.93	11.2	4.48
Cu	-	-	34.43	12.1

the wash layer. The indication of iron (Fe), sodium (Na), and potassium (K) was obtained as minor elements. The existence of oxygen suggests that the majority of elements exist as oxides. Alumina (from old conservation materials) and cupper-based conservation materials (from the current conservation materials) have been known as stiffening agents. The elements including calcium, silicon, and iron suggest that the fabric might be painted with natural pigments such as calcium carbonate (calcite) and metal oxides, which is reliable with the previously reported results in the field of Archaeology [28].

3.4. Fourier-Transform Infrared Spectroscopy

FT-IR spectra were employed to verify the functional groups of the ancient fabric. The distinctive peaks of linen within the FT-IR chart are displayed in Figure 6. The detected bands were consistent among blank/pristine linen samples and the artefact fabric before and after conservation treatment. The characteristic broad peak for the vibration stretch of hydroxyl substituents (-OH) was monitored at 3428 $cm^{−1}$. The vibration stretch of the ether groups (-C–O-) appeared as an acute intense peak at 1030 $cm^{−1}$. Aliphatic CH groups appeared at 2924 $cm^{−1}$. All of the fibers in the linens display bands typical of cellulose. These include broadband between 3600 and 3200 $cm^{−1}$ attributable to hydrogen-bonded OH stretching, a band around 2900 $cm^{−1}$ which is related to CH and CH_2 stretching vibrations, and numerous bands in the region from 1500 - 1200 $cm^{−1}$ that are related to vibration modes of OH and CH groups. The decrease in peaks intensity was detected after treatment. While pure cellulose might not display any bands in the region from 2000 - 1500 $cm^{−1}$ except one at around 1635 $cm^{−1}$, the presence of bands around 1700 $cm^{−1}$ is indicative of C=O moieties stemming from cellulose oxidation or esterification. There are many bands in the region of 1300 - 900 $cm^{−1}$. This part of the spectra is called the fingerprint region, and small differences in this area can be linked to structural changes in the cellulose.

3.5. Treatment and Conservation

The real purpose of the treatment process is to preserve the artwork for the next generations to study its value. The current artefact piece was subjected to poor storage conditions leading to its secession into multiple pieces in addition to the secession of fabric layers, weakness. and extreme fragility that made it vulnerable to loss. The research is concerned with maintaining and stabilizing the piece understudy, and stopping the continuous bleeding of the fabric fibers. The stages

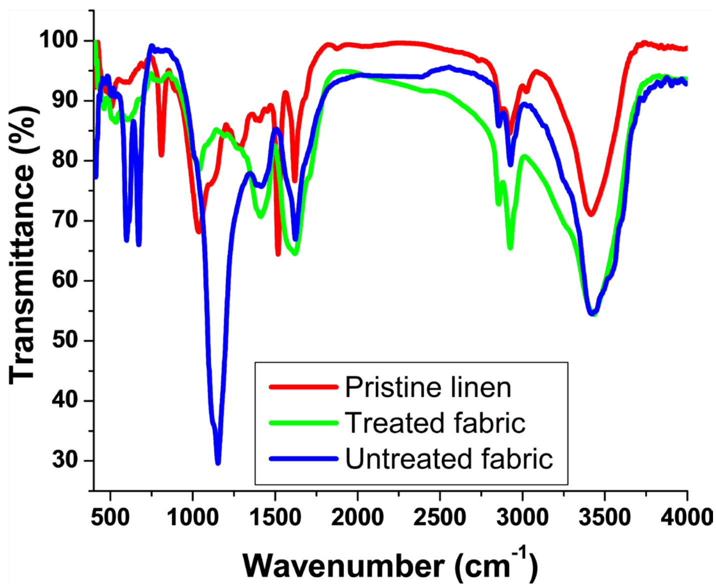

Figure 6. FT-IR spectra of blank linen, treated and untreated artefact fabric.

of treatment were as follows:

3.6. Methods of Handling and Transportation of the Textile Artefacts

The linen pillow under study was found as one piece with dimensions of 66 cm length and 36 cm width. The bad storage conditions led to the fragmentation of the linen pillow into 28 pieces. Each piece was recorded separately and its dimensions were determined without subjecting the piece to pressure or touch. The lengths of the fragmented parts ranged between 4.5 to 17 cm, while the widths were in the range between 2.3 and 7.0 cm. Precision and extreme caution when dealing with decomposed linen textiles are crucial to maintaining the artwork because those types of artefacts have a deceptive appearance of force upon discovery. By examination and analysis, the artefact condition was confirmed and its severe weakness and fragility were difficult to deal with by hand. Therefore, it was necessary to use specialized methods to transmit and address this artefact. Panels made from safe materials were designed to facilitate the handling of the artwork until the completion of the restoration work and transfer them to the place designated for them either for museum display or storage. The carrier panels were made from safe acid-free materials, such as cardboard and foam, equipped with cotton handles. The type of panel was chosen according to the size, thickness and weight of the artefact piece. It was preferred to use a thin and fine polyethylene, known as Volara Foam, for weak and fragile linen bits. Finger-holds were cut on each side of the panel for easy transportation of the artefact. Japanese papers were also used to cover the carrier panels for artefacts that suffered from fragility (**Figure 7**).

3.7. Mechanical Surface Cleaning

This is the most important initial step to remove dust and dirt stuck to the surface of the artefact. The mechanical cleaning stages were performed with great care due to the fragility and weakness of the artefact. The vacuuming process was performed with a low-power cleaner equipped with a rubber-based nozzle. The hand blower was applied at enough distance away from the artefact to prevent volatilization of the detached textile parts (**Figure 8**).

Figure 7. Preparation stages of carrier panels (left) and the process of packaging using lined drawers (right).

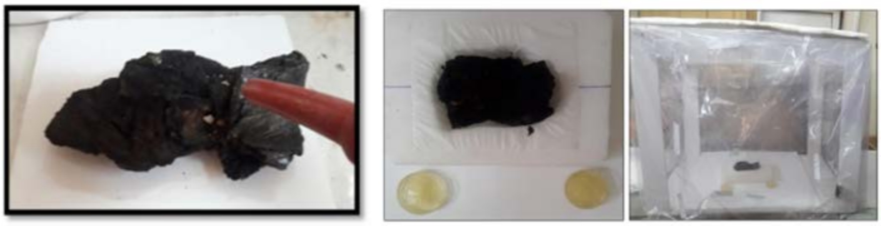

Figure 8. Mechanical cleaning process (left) and fumigation process using cedar oil inside polyethylene closed room (right).

3.8. Sterilization Process

Textiles are made of organic materials which can be easily exposed to fungal infection. Thus, the sterilization work was done using cedar oil as a natural substance used successfully to sterilize against infectious fungi by placing cedar oil inside a tightly closed room containing the artefact for a period of two weeks. The closed room was prepared from polyethylene, inside which the sterilization stage was completed.

3.9. Strengthen Procedure

Due to the extreme weakness of the fabric; it was necessary to perform rapid strengthening works to preserve the artefact and to prevent continuous deterioration. The strengthening process was carried out using Beva 371, which is one of the materials that have been used successfully in the process of textile strengthening [29] [30]. Beva 371 is a heat-activated adhesive that dissolves in non-polar solvents and can be applied at ambient conditions as it does not require a heating procedure. It does not cause any softening or shrinkage to the applied material making it safe to apply to the most sensitive materials. The application also gives a smooth surface after application introducing a natural feeling to the treated fabric as it is a retrieval material that can be easily removed by solvents without fabric deformation. The strengthening process was done by spraying and injecting technology in some parts depending on the fabric condition (**Figure 9**).

3.10. Packaging and Storage

The artefact condition under study is one of the cases that need serious attention after the strengthening and treatment processes. The procedures for the future preservation of the artefact were carried out in the restoration laboratories at the conservation center of Giza Solar boat *museum*. A scientific packaging method was adopted using the lined drawers. This is done by making a stand that takes a drawer shape, lined from the inside with two layers of polyethylene. The first polyethylene layer was fixed to the bottom of the drawer and the second layer was formed by making a cavity that takes the shape of each piece to be placed in it. The cavitation method is one of the excellent methods used with small-sized artefacts, which are usually one artefact and are transferred periodically. The cavity should not too tight to handle the artefact easily through it. It is preferred

Figure 9. The Consolidation process by spraying and injecting technology.

for the highly weak and brittle pieces to use thin and smooth polyethylene with fingerprint engraving on each side for easy portability. Upon designing and constructing the panels and drawers, several aspects must be taken into consideration:

- Lining the panels and drawers with polyethylene material and cotton gauze or acid-free textiles, provided that it is well fixed with a double-sided adhesive tape or glue gun. Japanese papers can also be used in the lining process.
- Using acid-free cardboard.
- Using a tape or rope handle made of nylon or cotton.

3.11. Microbial Deterioration

The results of studying the microbial deterioration revealed that there is a strong fungal infection in all examined samples. Four fungal genera were isolated and identified from the objects on different types of media, including potato dextrose agar medium (PDA) and Lignin cellulose medium (LCM). The ability of fungi to grow on LCM medium revealed their lingocellulosic activity and hence their ability to grow on fabric (**Figure 10** and **Figure 11**). Bacterial infection was also found as represented by gram-negative bacilli displayed in **Table 2**. Thus, mechanical cleaning is an important step before microbial treatment as it leads to decreased microbial load and therefore decreases the dose required for treatment. Also, chemical treatment is needed to overcome microbial problems.

4. Conclusion

In the present study, an archaeological textile sample from King Khufu's first solar ship dating back to ancient Egypt state was analyzed and subjected to a deep restoration process. The non-destructive identification techniques indicated that ancient Egyptian used linen as boat fenders. The analysis with different techniques including optical microscopy, elemental mapping, energy dispersive

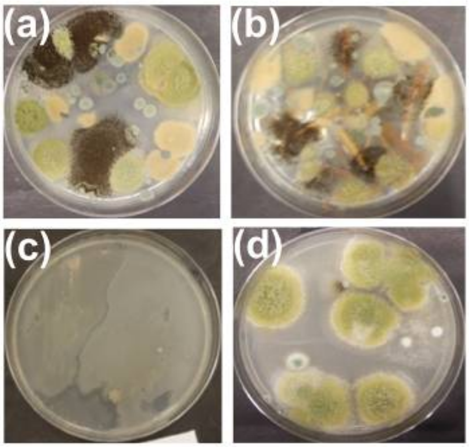

Figure 10. Microbial deterioration in different media including (a) PDA, (b) LCM, (c) nutrient agar, and (d) air sample.

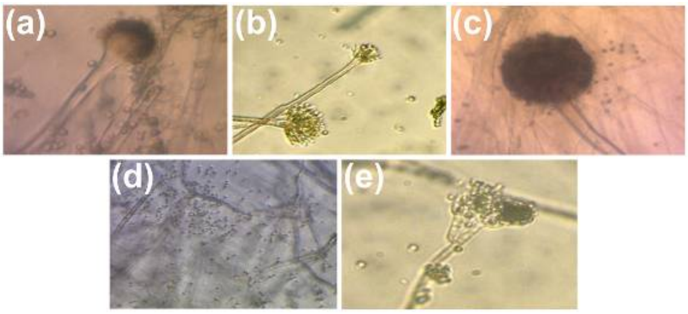

Figure 11. Microorganisms under light microscope; *Aspergillus flavus* (a), *Aspergillus midulans* (b), *Aspergillus niger* (c), *Paecilomyces variotii* (d), *Penicillium* sp. (e) (Magnification X 500).

Table 2. Colony counts of microorganisms in different media.

Medium	Microorganism	colony count
PDA	*Aspergillus flavus*	7
	Aspergillus nidulans	1
	Aspergillus niger	3
	Paecilomyces variotii	6
	Penicillium sp.	26
LCM	*Aspergillus flavus*	10
	Aspergillus niger	5
	Paecilomyces variotii	8
	Penicillium sp.	27
Nutrient agar	Gram-negative bacilli D	Uncountable
	Gram-negative cocci	1
	Gram-negative bacilli A	2
Air sample examination	*Aspergillus flavus*	12
	Penicillium sp.	9
	Ulocladium sp.	1

X-ray analysis, scanning electron microscope, and infrared analysis allowed the identification of the original materials, and the substances added during the previous restoration process. This helped in removing previous restoration substances that disturbed the authenticity of the fabric and to select the most proper cleaning and strengthening measures. The current applied materials and methods were extremely efficient for strengthening and stability of the fabric without causing harmful effects to the original materials. The mechanical cleaning process provided a safe technique to be employed in fabric conservation. The fabric was successfully conserved and ready for displaying or storing in the Giza Solar boat museum.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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