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Original article

ANALYTICAL AND CONSERVATION TECHNIQUES FOR THE BOOK OF THE DEAD FROM THE PTOLEMAIC PERIOD

Tarek. A.[1,2], Abdel-Kareem, O.[3], Youssef, A.[4] & Abdel-Maksoud, G.[5,3(*)]

[1]*Objects Conservation dept., Brooklyn Museum, USA.*
[2]*Human Remains Lab. & Organic Materials, Conservation Center, Grand Egyptian Museum, Giza, Egypt.*
[3]*Organic Materials Conservation dept., Faculty of Archaeology, Cairo Univ., Giza, Egypt.*
[4]*Packaging Materials dept., National Research Centre, Dokki, Giza, Egypt.*
[5]*Heritage Science Programs, School of Humanities, Faculty of International Business & Humanities, Egypt-Japan Univ. of Science & Technology (E-JUST), New Borg El-Arab City, Alexandria, Egypt.*
**E-mail address: gomaa2014@cu.edu.eg*

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Abstract:
Sometimes, the various unsuitable environmental conditions in which papyrus is found in museums play an important role in its deterioration. This study aims to estimate the state of preservation of the Book of the Dead (No: JE: 95859) dating back to the Ptolemaic period, and it was held in various places before arriving at its current location in the Grand Egyptian Museum, Egypt. Specific conservation treatments were necessary to improve the properties of the papyrus. The analytical techniques used were digital Imaging, transmission Light, reflectance transformation imaging (RTI), scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy, hand-held X-ray fluorescence spectrometry (HH-XRF), and Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (FTIR-ATR). The conservation techniques used were cleaning, fixing the ink and pigments, facing, removing the old mounting, reassembling and lining, and drying/flattening. Detailed investigations revealed specific manufacturing characteristics including strip width variations of 1.5-2 cm, high-quality surface treatments, and evidence of the traditional right-over-left joining method. The study identified both structural advantages in the papyrus construction and deterioration patterns affecting fiber integrity. Analysis using EDX and XRF revealed the components of the ink (carbon ink), the red pigment (hematite), and the ground layer (calcium carbonate). Quantitative analysis showed carbon content of 19.15%, oxygen 62.06%, with trace elements including sodium (2.48%), magnesium (0.64%), aluminum (1.37%), and silicon (3.63%). SEM investigation showed some aspects of deterioration such as cracks and fiber shrinkage. The corrected FTIR analysis revealed that the peak at 1627 cm^{-1} represents surface water absorption in cellulose rather than carbonyl groups, indicating the papyrus retains significant moisture content. All the treatment methods mentioned above showed significant aesthetic improvement, and the placement of all the pieces of the studied papyrus in a sequential manner increased their attachment and strength.

Keywords:
Book of the Dead
Ancient Egyptian funerary texts
Hellenistic era
Degradation
Scientific analysis methods
Preservation methods

1. Introduction

Papyrus (Cyperus papyrus L.) was the most significant writing material in the ancient world, serving as the primary medium for recording religious, administrative, and literary texts throughout Egyptian civilization [1]. This aquatic plant, belonging to the Cyperaceae family, was not only economically valuable but also held profound cultural and religious significance in ancient Egypt [2,3]. The manufacture of papyrus writing material represents one of humanity's earliest industrial processes, with techniques that remained largely unchanged for over three millennia [4]. Papyrus was the most important plant in ancient Egypt, and it had considerable economic value [5]. It belongs to the Cyperaceae Fam family and is characterized by a three-legged stem. The clip grows to a height of 1.5: 3 m [6,7]. Recent archaeological discoveries have significantly expanded our understanding of papyrus production and use, particularly during the Ptolemaic period (332-30 BCE), when Greek and Egyptian traditions merged to create unique artistic and textual expressions [8]. Papyri contain some of the earliest writing in history, displaying invaluable insights into ancient Egyptian religion, astronomy, medicine, and daily life [9]. The writing material that was made of papyrus was the most important thing used by the ancient Egyptians [10, 11]. The Book of the Dead, a collection of funerary spells and religious texts, represents one of the most important categories of papyrus documents from this era, providing invaluable insights into ancient Egyptian beliefs about death and the afterlife [12,13]. Papyrus was used from the pharaonic period until the Greco-Roman and Byzantine eras, as well as the early Islamic era [14,15]. Papyrus was made using the strips method and the peeling method, as well as making papyrus rolls from individual sheets and joining them with a paste [16,17]. The chemical composition of the papyrus plant is primarily composed of cellulose (-54-60%), lignin (23-24%), and hemicellulose; these percentages are affected by factors such as age, manufacturing process, and environmental factors [18,19]. The factors of papyrus damage were classified into two categories. First, internal damage factors affect papyrus and affect its chemical and physical properties through aging. The chemical components of papyrus are the primary cause of its damage and decomposition, and their effect may increase or decrease depending on their relationship to other damage factors such as heat, relative humidity, light, and air pollutants, as well as their relationship to each other and the proportions of their presence. These factors do not have separate effects on papyrus, as they interact and collaborate to cause deterioration, which is represented by two types of damage processes. Physical damage includes changes in structure and dimensions, as well as the occurrence of cracks and deformations caused by the nature of the papyrus fibers and pressures caused by the expansion and contraction process and interaction with other damage factors. Chemical damage includes chemical reactions with the material's inherent compounds (cellulose, lignin, and hemicellulose) and the resulting hydrolysis and oxidation processes [20-25]. Second, there is external deterioration. Climate factors affecting papyrus include fluctuations in relative humidity and temperature, as well as the resulting deterioration. Light, which is a strong source of ultraviolet radiation, attacks the molecular structure of organic materials and causes photolysis. It affects the inks and colored materials used on papyrus and causes fading. This is in addition to the damage caused by the environmental conditions of the discovery site, which causes salt damage to the papyrus. One of the issues with the papyrus discovered under the soil is that salt crystals have become entrenched between the fibers, destroying the fiber fabric, surrounding fibers, and writing. It also includes air pollution and the acid gases and airborne particles that it contains, as well as volatile organic pollutants produced internally in museums, such as acetic acid, formaldehyde, and others, which are harmful to artifacts, as well as biological damage, which causes chemical, physical, and aesthetic changes to archaeological materials, including insect damage. The most important are those that attack sedge and feed on cellulosic materials in general and are damaged by microorganisms (fungi, bacteria, and actinomycetes) that can break down cellulose and convert it into simple materials that are easy to digest and use in metabolic processes. Finally, the human factors that contributed to damage to the papyrus include ancient use, papyrus storage methods, previous papyrus treatments, wrong maintenance handling, natural disasters, and fires [26-31]. The conservation of ancient papyri presents unique challenges due to the organic nature of the material and its susceptibility to various deterioration mechanisms [32,33]. Previous studies by Abdel-Maksoud et al. (2018) on Ptolemaic period papyri, Hassan et al. (2020) on pigment identification, and Mohamed et al. (2022) on non-destructive analysis techniques have established the foundation for current conservation practices [34-36]. This study used a method to remove the old unsuitable backings from the papyrus. To accomplish this goal, it was necessary to find a technique that could be carried out while using non-hazardous materials and causing no damage to the papyrus. After removing the old cardboard, the papyrus was remounted using a Japanese-style lining method as new support to reassemble the previously cut 35 pieces into one line. Several examinations were conducted to study the manufacture of this papyrus from a technical standpoint, using both traditional and advanced methods such as (RTI) and (MSI). Furthermore, analyses were performed to identify the type of pigments using (XRF) and (FTIR) for the pigments and binding material. This study aims to use some analytical and investigation techniques to study the papyrus components, estimate the deterioration that occurred and to apply some of the treatment methods that the papyrus needs to improve its appearance and give it future protection in its new place at the Grand Egyptian Museum, which has the highest standards of preservation and conservation [37-41].

2. Materials and Methods

2.1. *Historical background, condition, and the manufacture of the papyrus studied*

The studied papyrus (No: GEM: 15146/1-35) consists of 35 pieces, fig. (1-a, b) and is now stored at the Grand Egyptian Museum Conservation Centre (GEM CC); it came from the Egyptian Museum (EM) (No: SR IV: 958), and before that, it was in Boulaq Museum (No: JE: 95859). This papyrus dates back to the Ptolemaic period (BC 332-30) and belongs to ʿnḫ- Ṯkrt. The origin is unknown, and it is decorated with scenes and texts from the Book of the Dead (religion, funerary). The texts were written in Hieratic with Hieroglyphic captions, and it is decorated with vignettes and line drawings [42]. Black ink was used for the texts, with red ink highlighting the titles, colophons, and key points of the spells. This papyrus, like other papyri, was made in separate sections that were then joined together to form a single roll. In the nineteenth century, this papyrus was cut into 35 fragments, compromising the scroll's integrity. It is fragile, and the ink on the text is brittle. The papyrus had been glued to an unsuitable backing material for preservation (poor-quality cardboard with a highly acidic component). The glues (gelatin, starch glue, etc.) used to adhere the papyri fragments to backings can also accelerate papyrus degradation, and all of these materials are suitable for fungal growth. The manufacture of the papyrus and the papyrus roll were described by some authors [43]. The papyrus roll is made up of kollemata papyrus sheets joined together right over left to form a single roll. In all cases, the text and vignettes run smoothly over these joins. On the recto, the joins kolleseis were generally right over left, which matched the usual writing direction. This papyrus demonstrates high refinement in manufacture, indicating plant selection and the portion of the plant from which the regularity of the strips was taken. The joins between the sheets ranged from 1.5 to 2 cm, which was difficult to detect due to the high quality of the papyrus's final surface treatments.

Figure (1) **a.** the details of one of the 35 pieces of the studied papyrus mounted on cardboard, **b.** displays the 35 individual pieces of the studied papyrus mounted on cardboard

2.2. *New papyrus samples*

A standard papyrus sample was prepared using the traditional sliced method following the methodology described by Lucas and Harris, 1962 and Ragab, 1980. The papyrus strips were cut from the pith of Cyperus papyrus stems, arranged in perpendicular layers, and pressed to create sheets for comparative analysis with the archaeological specimen. The manufacturing process involved careful selection of plant material, precise cutting of strips to uniform width, and application of traditional joining techniques as documented in the literature [1,2].

2.3. *Radiocarbon dating (C14)*

Radiocarbon dating was performed to provide absolute chronological confirmation of the papyrus age and validate the Ptolemaic period attribution. A small sample of papyrus material was submitted to the University of Arizona LTRR & AMS Laboratory for accelerator mass spectrometry (AMS) radiocarbon analysis [44]. The sample underwent standard pretreatment procedures including acid-base-acid (ABAt) treatment followed by soxhlet extraction to remove potential contaminants. The carbon yield was 41.37% with a final carbon mass of 0.967 mg, which is sufficient for accurate AMS measurement. The δ13C value was measured to correct for isotopic fractionation effects [45]. Calibration of the radiocarbon age was performed using OxCal 4.4 software with the IntCal20 atmospheric calibration dataset [46]. Both 68% and 95% confidence intervals were calculated to provide comprehensive age ranges for archaeological interpretation [47].

2.4. *Digital imaging*

Digital imaging was done with a Canon DSLR 7D and a Sigma 17-50mm (F 2.8) lens. Two studio flashes (strobes) were used as light sources for all images, with two soft boxes installed. During imaging, a color checker was used for better color management. Then, for a better and more accurate representation of the colors and details, all photos were processed with the Color Checker program and Adobe Photoshop software [48,49].

2.5. *Examination with transmission light*

One of the traditional methods for examining manuscripts using the light table; this method helps reveal the physical structure of the papyrus [50].

2.6. *Reflectance transformation Imaging (RTI)*

Transformation of Reflection Imaging has been widely used to improve the surface details of cultural heritage objects. Surface details are emphasized in multiple digital images of the same captured area with the camera fixed in the same position by digital imaging with directed lighting from various angles. The captured surface details are then mathematically processed using the RTI builder software. The result is an interactive digital image that incorporates all lighting positions. Several enhancement filters could also be used in the RTI software viewer version to enhance and visualize surface details [51].

2.7. *Examination using SEM*

The surface morphology of the papyrus sample studied was examined using a scanning electron microscope (SEM) equipped with a JEOL-JXA-840A electron probe micro analyzer-Japan, at the National Research Center, Dokki, Giza, Egypt. The sample was conditioned for 24 hours under standard atmospheric conditions [52].

2.8. *Analysis using SEM-EDX*

The device (Oxford - INCA PentaFET-X3) within the Center for Research and Development of Metallurgy laboratories in Al-Tebbin, Cairo, was used to analyze the ancient papyrus sample, the subject of the study, to identify all the elements present in the papyrus sample.

2.9. *pH measurement*

pH measurements were conducted using pH indicator strips with distilled water extraction method to assess the acidity levels of both the papyrus and the backing paper materials. Small amounts of distilled water were applied to different areas of both the papyrus and the backing paper, and the pH was determined using calibrated pH indicator strips (pH range 1-14) [53]. The pH strips were placed in contact with the water extracts for the recommended time period, and color changes were compared against the standard color chart provided by the manufacturer. Multiple measurements were taken from various locations to ensure representative sampling of the materials' acidity levels. This non-destructive analytical method provides crucial information about the chemical stability and deterioration mechanisms affecting the papyrus [33].

2.10. *Portable X-ray florescence (XRF)*

XRF is a non-destructive method of analysis used to identify the dominant elements in a pigment sample. Portable or hand-held X-ray fluorescence has been used intermittently in archaeological science for the last few decades [54]. A hand-held Bruker Tracer spectrometer (40 kV high voltage, 20 µA anode current) for 60 seconds of live time irradiation.

2.11. *Examination ATR/FTIR for papyrus and KBr for adhesive*

The papyrus samples were analyzed using an ATR/FTIR analyzer at the Ministry of Antiquities - Research Center, with the following requirements: Bruker VERTEX 70 - ATR-FTIR spectroscopy made in Germany - Range 600-4200 [55]. The adhesive sample was analyzed using KBr pellets on an FTIR spectrophotometer (JASCO-FT/IR-6100, Range 400-4000 at Grand Egyptian Museum, Giza, Egypt) [56].

3. Results

3.1. *Radiocarbon dating (C14)*

The radiocarbon analysis (Laboratory number: AA116882) yielded an uncalibrated 14C age of 2,130 ± 12 years BP. The δ13C value was measured at -10.67‰, indicating the plant-based nature of the papyrus material and providing the necessary correction for isotopic fractionation [44]. Calibration of the radiocarbon date using OxCal 4.4 and IntCal20 provided calendar age ranges of 193-108 cal BC (68% confidence interval) and 340-57 cal BC (95% confidence interval) [46]. These calibrated dates fall entirely within the Ptolemaic period (332-30 BC), providing strong chronological confirmation of the historical attribution of the papyrus. The fraction of modern carbon was determined to be 0.7671 ± 0.0015, confirming the ancient age of the material and ruling out any modern contamination [57]. The high precision of the measurement (±12 years) provides excellent chronological resolution for archaeological interpretation and supports the museum's cataloging of this papyrus as a Ptolemaic period artifact, tab. (1) & fig. (2).

Table (1) the result of Radiocarbon dating (C14) dating (C14).

Parameter	Value
Laboratory Number	AA116882
Material	Papyrus
Carbon Mass	0.967 mg
Carbon Yield	41.37%
δ13C Value	-10.67‰
Fraction Modern	0.7671 ± 0.0015
Uncalibrated 14C Age	2,130 ± 12 years BP
Calibrated Age (68%)	193-108 cal BC
Calibrated Age (95%)	340-57 cal BC
Historical Period	Ptolemaic Period (332-30 BC)

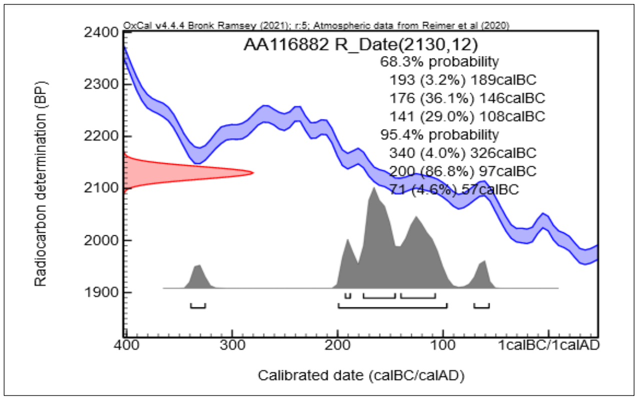


Figure (2) the chart of the Radiocarbon Dating (C14)

3.2. *Transmission light & RTI*

The papyrus is composed of small sheets joined together. Because of the double thickness at these points, the overlaps appeared slightly dark, and the strips used to form the sheets were nearly cut equal in width and showed transparency due to the thinness of the strips, fig. (3-a). RTI creates highly accurate and interactive images, where objects can be illuminated from different directions and through various filters to emphasize their surface texture and color, as an innovative tool for re-documentation and analysis of the texture of papyrus undergoing conservation treatments. In addition, we use a fast, precise, and non-destructive method to obtain detailed information on the geometry and morphology of the papyrus surface [58]. The data obtained, fig. (3-b) showed that diffuse gain reveals the sign of the edges of the sheet due to the beating process or flattening with a mallet, according to Pliny's description, and twisted part as manufacture defection during the manufacturing process due to pressing after drying [59].

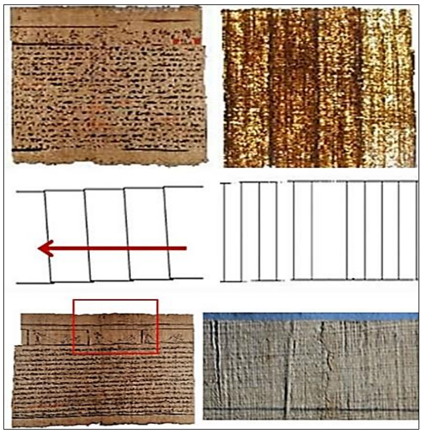


Figure (3) illustrates various examination techniques used on the studied papyrus; **a.** transmission light examination, **b.** reflectance transformation imaging (RTI).

3.3. *SEM*

The results showed the cellular organization of the standard papyrus sample structure, fig. (4-a). The cells appear to be arranged regularly, and the areas of overlap between the cell walls and the longitudinal vascular plates are still visible. For the archaeological papyrus sample studied, fig. (4-b), the effect of aging was clear based on dryness and shrinkage of the fibers, as well as laceration and collapse of the cell walls. There is separation between the longitudinal vascular plates and the appearance of cracks in various places, and the fibers appear weak and irregular due to the occurrence of a morphological change in the cellular organization [60-62].

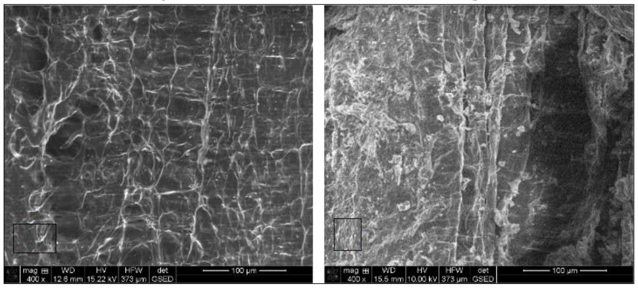
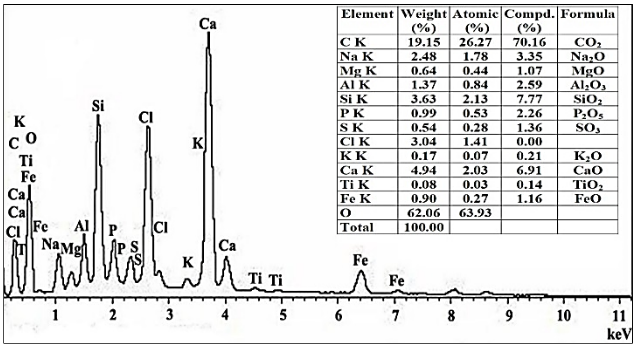


Figure (4) the surface morphology of new and archaeological papyrus samples; **a.** new papyrus sample, **b.** Archaeological papyrus sample.

3.4. *EDX*

The EDX analysis was conducted in different regions, and the elemental analysis results of the archaeological papyrus sample, fig. (5) revealed the presence of carbon (C), oxygen (O), sodium (Na), magnesium (Mg), aluminum (Al), and silicon (Si) in the sample, with percentages of 19.15%, 62.06%, 2.48%, 0.64%, 1.37%, and 3.63% respectively. Additionally, traces of phosphorus (P), sulfur (S), and calcium (Ca) were also detected [63-65].



Element	Weight (%)	Atomic (%)	Compd. (%)	Formula
C K	19.15	26.27	70.16	CO_2
Na K	2.48	1.78	3.35	Na_2O
Mg K	0.64	0.44	1.07	MgO
Al K	1.37	0.84	2.59	Al_2O_3
Si K	3.63	2.13	7.77	SiO_2
P K	0.99	0.53	2.26	P_2O_5
S K	0.54	0.28	1.36	SO_3
Cl K	3.04	1.41	0.00	
K K	0.17	0.07	0.21	K_2O
Ca K	4.94	2.03	6.91	CaO
Ti K	0.08	0.03	0.14	TiO_2
Fe K	0.90	0.27	1.16	FeO
O	62.06	63.93		
Total	100.00			

Figure (5) the results of EDX) analysis for elemental composition of the archaeological papyrus under study.

3.5. *pH measurement*

The pH strip measurements, tab. (2) revealed significant acidity in the backing cardboard materials, with indicator colors showing acidic conditions that pose a threat to the papyrus preservation [32]. The analysis demonstrated that the cardboard backing material exhibited acidic pH values as indicated by the color changes on the pH strips, confirming the inappropriate nature of this mounting system for long-term papyrus conservation [33]. Most significantly, the study revealed that acidity was migrating from the backing cardboard to the papyrus material, as evidenced by pH strip readings from different areas of the papyrus surface, creating a deterioration pathway that compromises the structural and chemical integrity of the ancient document [66]. This acid migration, combined with environmental factors such as moisture exposure, was observed to generate darkening and staining effects, resulting in visible color changes across the papyrus surface [67,68]. These findings underscore the critical importance of using pH-neutral or alkaline mounting materials in papyrus conservation to prevent further deterioration [48].

Table (2) result of pH measurement

Samples	pH
Distilled Water Standard	7
Papyrus	6
Cardboard (lighter areas)	5-6
Cardboard (darker areas)	4

3.6. *Portable XRF*

XRF is a non-destructive method of analysis used to identify the dominant elements in pigment samples. The palette of pigments available to the ancient Egyptians has piqued the interest of many people over the years. Before beginning conservation, it is necessary to understand the nature of the pigments on artifacts to select the best treatment and display condition [69]. The results obtained, fig. (6) of X-ray florescence can be explained as follows: *Ground layer:* the results showed that the elements found in the ground layer were calcium with high percentages (88.83%), chlorine (8.63), sulfur (S), and silicon (Si) as impurities, Fe element was found with low percentage (2.54%). *Black ink:* XRF cannot detect amorphous carbon derived from powdered charcoal. The microscopic examination of the black pigment revealed opaque particles of varying sizes with fibrous structures, implying that the black pigment originated from a burnt vegetable, such as charcoal. *Red pigment: A* microscopic examination revealed the presence of single red pigment particles. XRF analysis of the red paint, aside from calcium (Ca), sulfur (S), and silicon (Si), a high intensity of iron was detected. The presence of iron (Fe) indicates the presence of iron-based pigments, implying the use of hematite.

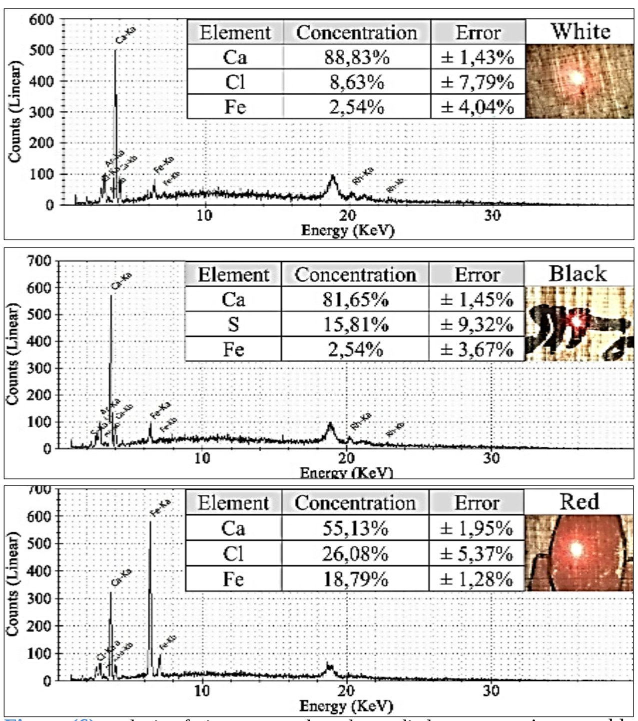


Figure (6) analysis of pigments used on the studied papyrus using portable X-ray florescence spectrometry (XRF).

3.7. *FTIR-ATR results of papyrus*

The results obtained, fig. (7-a & b) the O-H stretching group appeared at a wavelength of 3330 cm^{-1} in both the standard and archaeological samples. We notice a decrease in the absorption intensity of the OH hydroxyl group as a result of the oxidation process and the breaking of hydrogen bonds by aging [70]. The C-H stretching group appeared at a wavelength of 2917 cm^{-1} in the standard sample, while it appeared at a wavelength of 2912 cm^{-1} in the archaeological sample. We noticed a decrease in frequency and a decrease in the intensity of absorption due to the oxidation of cellulose [71]. The CH_2 symmetrical stretching group appeared at a wavelength of 2850 cm^{-1} in the standard sample, while it appeared at a wavelength of 2857 cm^{-1} in the archaeological sample. We noticed a displacement and a decrease in the intensity of absorption as a result of the oxidation of cellulose and hemicellulose due to aging [72]. The carbonyl group C = O appeared at a wavelength of 1732 cm^{-1} in the standard sample, while the characteristic spectrum of this group did not appear in the archaeological sample, which indicates the decomposition of hemicellulose as a result of natural aging [55,73]. The water absorption band appeared at a wavelength of 1627 cm^{-1} in the standard sample, while it appeared at a wavelength of 1632 cm-1 in the archaeological sample. This peak represents surface water in cellulose. Aromatic skeletal vibration in lignin appeared at a wavelength of 1518 cm^{-1} in the standard sample, while it appeared at a wavelength of 1550 cm^{-1} in the archaeological sample. We noticed a large shift in frequency with an increase in the intensity of absorption, which indicates that the object. was affected by aging [25,74]. The C-H group appeared in plane deformation at a wavelength of 1425 cm^{-1} in the standard sample, while it appeared at a wavelength of 1422 cm^{-1} in the archaeological sample. We noticed a decrease in frequency and a slight decrease in the intensity of absorption to break the bonds between cellulose chains, as it is an absorption region specific to regions crystallized in cellulose and also the result of oxidation by aging [75]. The presence of calcium carbonate functional groups in the old sample, represented by the group - carbonate CO_3 at 1422 cm^{-1}, may also be due to the breadth of the absorption band and its noticeable intensity in this spectrum due to its presence and the C-O-C bending group at 876 cm^{-1} and the bending at 711 cm^{-1}, which refers to calcite [76,77]. The characteristic C-O stretching group of cellulose and hemicellulose appeared at a wavelength of 1033 cm^{-1} in the standard sample, while it appeared at a wavelength of 1026 cm^{-1} in the archaeological sample. We noticed a decrease in frequency and a decrease in the intensity of absorption due to oxidation [78].

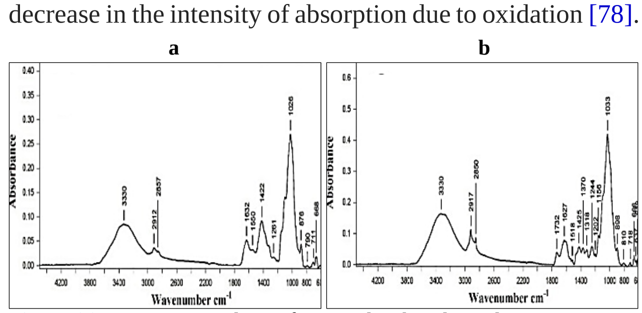


Figure (7) FTIR-ATR analysis of new and archaeological papyrus; a. new papyrus, b. archaeological papyrus.

3.8. *FTIR-KBr results of adhesive*

Gum Arabic is the most commonly used gum in paint preparation. It is a dried, amorphous exudate produced by the stems of several Acacia trees found in tropical and subtropical regions. Gum Arabic is entirely soluble in hot and cold water, resulting in a viscous solution. Gum Arabic was used in the first known inks [79]. The results obtained, fig. (8) showed that FTIR absorption bands with characteristics of Gum Arabic appeared at 3600-3200 cm^{-1}, which refers to O-H stretch band, 3000-2800 cm^{-1} refers to C-H stretch band, 1650 cm^{-1} refers to O-H bending band, 1480-1300 cm^{-1} refers to C-H bending band, and 1300-900 cm^{-1} refers to C-O stretching bands [80,81].

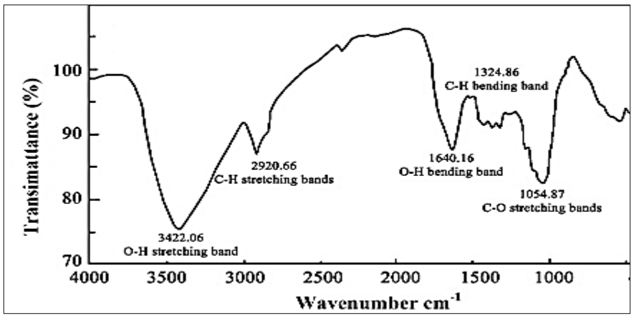


Figure (8) FTIR-KBr analysis of adhesive.

4. Discussion

The radiocarbon dating results provide crucial independent verification of the papyrus's Ptolemaic period origin, with calibrated dates (193-108 cal BC at 68% confidence) falling squarely within the expected chronological range [57]. This absolute dating confirmation strengthens the archaeological and art historical analysis of the Book of the Dead text and iconography, which are consistent with Ptolemaic period funerary practices [82]. The excellent preservation of organic carbon (fraction modern = 0.7671) despite the papyrus's age of over 2,000 years demonstrates the effectiveness of the Egyptian burial environment in preserving organic materials [83]. The integration of radiocarbon dating with analytical and conservation techniques provides a comprehensive approach to papyrus authentication and preservation, establishing best practices for future studies of ancient Egyptian manuscripts [84]. The transmission light examination results align closely with previous research on Ptolemaic period papyrus manufacturing techniques. The observed join widths of 1.5-2 cm are consistent with the findings of Leach and Tait (2000), who documented similar measurements in contemporary papyri from the same period [32]. The high-quality surface treatments that make joins difficult to detect reflect the sophisticated manufacturing standards described by Ragab (1980) and confirm the premium grade of this Book of the Dead manuscript [2]. SEM analysis revealing calcifications and surface sedimentation parallels the deterioration patterns documented by Abdel-Maksoud et al. (2018) in their study of Ptolemaic papyri, where burial environment contamination was identified as a primary factor in papyrus degradation [34]. The fibrous tissue deterioration observed is consistent with the cellulose degradation mechanisms described by Area and Cheradame [33], where environmental factors accelerate hydrolysis and oxidation processes. EDX elemental composition results show remarkable similarity to previous analytical studies of ancient Egyptian papyri. The presence of carbon and oxygen as primary components confirms the findings of Hassan et al. (2020), who identified similar elemental profiles in their comprehensive analysis of Egyptian manuscripts [35]. Carbon (C) was likely from organic materials like papyrus itself or the black carbon ink, possibly derived from charcoal or soot. Oxygen likely originated from the organic matter in the papyrus. The detection of sodium, magnesium, aluminum, and silicon aligns with the burial environment contamination patterns [85]. Sodium may indicate the presence of sodium chloride, possibly from the burial environment. Magnesium (Mg), aluminum (Al), and silicon (Si) could come from the soil where the papyrus was buried. The presence of silicon and aluminum suggests clay used in papyrus manufacturing. The muddy Nile waters used in papyrus production may have contributed to the presence of aluminum. Particularly significant is the presence of aluminum and silicon, which supports the clay contamination hypothesis proposed by Leach and Tait (2000) regarding Nile mud incorporation during papyrus manufacturing [32]. Phosphorus (P) and sulfur (S) could be from soil contamination or environmental conditions. Chlorine (Cl) may refer to sodium chloride or calcium carbonate. Traces of titanium and iron suggest contamination. Calcium (Ca) may indicate the use of calcium carbonate as a whitewash or calcium phosphate from burned bones in black inks. Gypsum, a form of calcium sulfate, could be present due to processing discarded papyrus material for mummy cases. Calcium may also result from environmental factors affecting the papyrus. The pH strip analysis results provide crucial insights into the deterioration mechanisms affecting the studied papyrus. The identification of acid migration from inappropriate backing materials, as demonstrated through systematic pH strip testing across different areas, confirms previous research on the detrimental effects of acidic mounting systems on organic archaeological materials [66]. The observed color changes and staining patterns align with documented cases of acid-induced degradation in cellulosic materials, where low pH conditions accelerate hydrolysis reactions and promote chromophore formation [67,68]. This finding validates the conservation decision to remove the acidic backing and implement pH-neutral Japanese paper lining, which represents current best practice in papyrus preservation [48]. The calcium carbonate identification through XRF analysis confirms the widespread use of this material as a ground layer in ancient Egyptian manuscripts, as extensively documented by Lucas and Harris (1962) and recently validated by Burrows (2010) using similar analytical approaches [1,36]. The transformation of calcium carbonate to calcium sulfate under unsuitable environmental conditions, evidenced by sulfur presence, corroborates the degradation mechanisms described by Whitmore and Bogaard (1994) [67]. The hematite identification for red pigmentation confirms the continued use of traditional Egyptian red pigments throughout the Ptolemaic period [85]. The carbon-based black ink composition aligns with the charcoal ink studies by Christiansen et al. (2017) on Egyptian manuscript inks [86]. The black-painted layer's XRF spectrum revealed a strong peak of calcium (Ca) with minor peaks of sulfur (S), silicon (Si), and chlorine (Cl). These elements recommend using calcium carbonate with a trace of calcium sulfate. As a result, pulverized charcoal was combined with calcite. The FTIR analysis results showing oxidation processes and water loss are consistent with the cellulose degradation studies by Strlič et al. (2000) and Łojewski et al. (2010), who documented similar spectroscopic changes in aged cellulosic materials [68]. The identification of Gum Arabic as a binder confirms the findings of previous studies by Bonaduce et al. (2016) and Degano et al. (2014), who identified this material as the primary binding medium in ancient Egyptian painted manuscripts [87,88]. These analytical results collectively support the conclusions of recent conservation research emphasizing the importance of understanding original materials and degradation processes for developing appropriate treatment strategies, as advocated by the current literature in papyrus conservation [34-36].

5. Conservation Procedures

It can be said that the treatment and restoration processes for the studied papyrus are complicated, and this was due to the state of damage to the papyrus, as previously explained in the analysis and investigation techniques used. The intervention was taken into account with great care and according to what was required in order to preserve the authenticity of the papyrus without changing anything, and in a way that shows the aesthetic value of it. The number of pieces composing this papyrus was 35, and therefore it was required to treat each piece individually, perform surface cleaning, and fix the inks and pigments. The old cardboard also presented a major problem due to its high acidity and its effect on large parts of the papyrus pieces. It was necessary to make facing, and then remove the old cardboard. Drying and flattening were also done. The treatment processes of the studied papyrus can be explained as follows:

5.1. *Cleaning*

Cleaning is one of the most important treatment processes. Abdel-Maksoud [89] reported that the cleaning in its various techniques (mechanical, chemical, etc.), aims to reduce or stop the potential for damage to the manuscript cleaned; increase the chemical stability; improve the readability of the documents or manuscripts; and it is a necessary preliminary to a further treatment, as when preparing a surface before consolidation, disinfection, etc. Very soft brushes (from camel hair) sizes 0 and 1 was used for surface cleaning in areas devoid of writing with inks and pigment, as some of them were in a weak state and therefore friction from the brush would cause the ink and pigment to fall off. Vinyl and powdered drafting erasers were also used in the surface cleaning to remove very light dirt found on the borders of some pieces of the studied papyrus. Erasers were also not used in places of writing with ink and pigments used.

5.2. *Ink and pigments fixing and facing*

Fixing the ink and pigments was accomplished using Sturgeon bladder glue (Isinglass) 1% w/v solution (Kremer Pigmente GmbH & Co. KG, Aichstetten, Germany, Product No. 63050, pharmaceutical grade, CAS Number: 9000-70-8, purity >95%) [90]. The adhesive was prepared by dissolving the isinglass powder in isopropanol and distilled water (1:1), fig. (9-a) at room temperature to achieve a 1% concentration, resulting in a neutral pH solution (6.0-7.0) with appropriate viscosity (15-25 mPa·s at 20°C) for conservation applications [91]. This natural protein-based adhesive was selected for its excellent reversibility, minimal aging characteristics, and compatibility with ancient organic materials, representing current best practice in papyrus conservation [92,93]. The isinglass solution was applied using fine brushes to areas where ink and pigment consolidation was required, with a working time of 15-20 minutes and complete drying achieved within 2-4 hours at ambient conditions [94]. For facing, fig. (9-b), we used Gampi paper $17g/m^2$ (Japanese paper), distinguished by its high moisture responsiveness, soft natural fibers, intense contact, transparency, smoothness, and strength. Klucel G (1% dissolved in ethanol) was used as an adhesive for applying Gampi paper to the surface of the papyrus. Gampi paper was cut into rectangular pieces to cover the surface of the papyrus by overlapping the edges with 5 mm as joins until surrounding the entire papyrus, including 2 cm from each side. A second layer of facing was applied using two large pieces of Gampi paper to cover the whole surface of the papyrus. The papyrus was left at room temperature for drying [95-97].

a b

Figure (9) illustrates treatment techniques used in the conservation of papyrus; **a.** fixing of ink and pigments, **b.** demonstrates the facing of the papyrus using Japanese paper (Gampi).

5.3. *Removing the old mounting*

To remove the old cardboard, the majority of cardboard used for mounting papyri has a layered structure that can be separated with a semi-sharp spatula. This process was repeated several times to reduce the thickness of the cardboard [98]. The last layer of cardboard adjacent to the adhesive, as well as the old adhesive, is removed chemically using Laponite RD. Laponite RD is a synthetic silicate that hydrates to form a clear, colloidal gel. Laponite gel is used to humidify by introducing moisture within the adhesive layer to dissolve it after the backing cardboard has been reduced to a very thin layer. Using Funori 1% dissolved in Isopropyl alcohol, we removed the facing and cleaned the papyrus by removing adhesive residues and performing primary consolidation for the fragile fibers, fig. (10) [95-97,99].

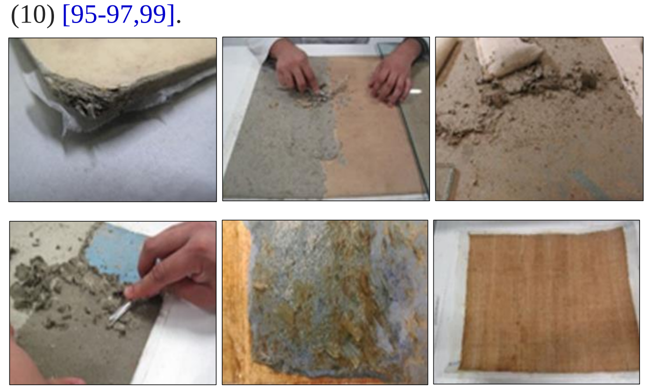


Figure (10) removal of old cardboard using a scalpel and other chemicals.

5.4. *Reassembling, lining, drying and flattening*

Mechanical and physical property changes can also affect the visual and surface appearance of the papyrus, resulting in a loss of elasticity due to contraction between the papyrus and the cardboard. The adhering of a material as a support to the original work of art or artifact is referred to as lining (or backing). Using Tengujo Mounting, Japanese style lining provides more compatible and reversible support, representing a conscious conservation and aesthetic choice, especially with long and fragile papyri to facilitate handling, storage, display, reversibility, aging, and aesthetic aspect [95,99,100]. Tengujo paper 9g/m^2 (Japanese paper) is the lightest weight paper, made entirely of Kozo. Kozo papers are frequently used for lining because they have the longest fibers, are porous, absorbent, and have an even surface. The lining was done on or against a Mylar sheet, with the Kozo sheet being the exact size of the piece of papyrus, plus 5 cm on each side. Then, we applied the adhesive to the papyrus using Klucel G dissolved in 95% ethanol, fig. (11-a) [95-97]. The lining was dried by sandwiching it between Reemay sheets (with the smooth sides facing the Kozo), blotting papers and felts, and placing it under glass weight, fig. (11-b) [95-97]. Finally, fig. (11-c & d shows the studied papyrus after the conservation treatment processes.

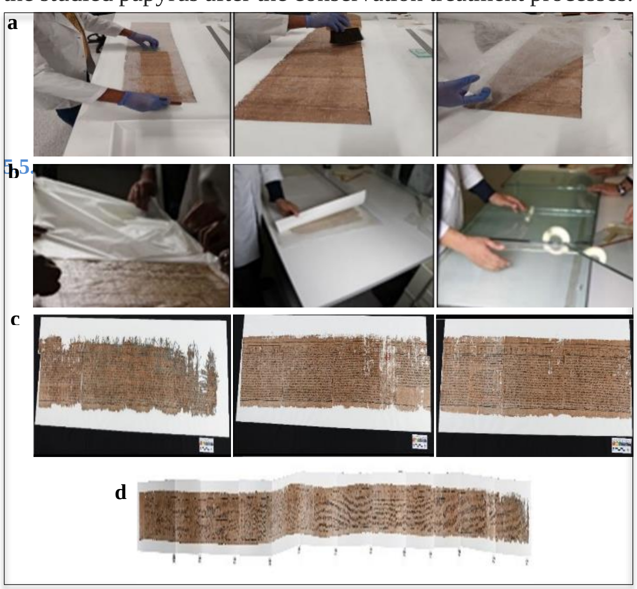


Figure (11) various treatment techniques for preserving documents; **a.** the reassembling and lining process, **b.** demonstrates the drying and flattening procedures, **c.** the reassembling and lining process, **d.** the drying and flattening procedures.

6. Conclusion

The radiocarbon dating results provided independent confirmation of what we suspected from the stylistic analysis. The calibrated dates of 193-108 cal BC place this papyrus squarely within the Ptolemaic period, validating our initial assessment. Examination revealed that this papyrus was manufactured to exceptionally high standards. The joins between sheets, measuring 1.5-2 cm, were so skillfully executed that they remain difficult to detect even today. The right-over-left joining pattern observed is consistent with other contemporary papyri and demonstrates the continuation of traditional Egyptian methods. The black ink was carbon-based and likely derived from charcoal. The red pigment proved to be hematite. The ground layer contained calcium carbonate. Gum Arabic was used as the binding medium. The FTIR analysis revealed that the archaeological papyrus had been exposed to an oxidation process, as indicated by the peak at 1627 cm^{-1} showing carbonyl groups. However, further analysis showed that it actually represents water absorption in the cellulose. This finding was important because it indicated that the papyrus still retains significant moisture, which affects how we approach conservation treatments. This study found the extent of acid damage from the old cardboard backing, which may have caused the staining and discoloration over time. This finding made removing the old backing a top priority in the conservation process. The methodological approach we developed here could certainly be applied to other papyrus conservation projects. The combination of traditional examination techniques with modern analytical methods provides a robust foundation for making informed treatment decisions. We've also demonstrated that even severely compromised papyri can be successfully treated when appropriate methods are carefully applied. The conservation treatment itself required careful planning and execution. It started with gentle surface cleaning, being particularly cautious around areas with fragile ink and pigments. For consolidation, isinglass at 1% was chosen because of its excellent working properties. The facing process using Japanese Gampi paper provided the protection needed during the backing removal process. The acidic cardboard was removed using Laponite RD gel to soften the old adhesive, working slowly and methodically to avoid any damage to the papyrus. All traces of the old mounting system were removed. The remounting process allowed us to reassemble the 35 individual fragments into a coherent whole for the first time in over a century. This was perhaps the most rewarding aspect of the entire conservation process - seeing the papyrus restored to something approaching its original appearance. The new Japanese paper lining provides stable, pH-neutral support while allowing for natural dimensional changes. Now that the papyrus is prepared for display and storage at the Grand Egyptian Museum, it should remain stable for many years to come. The controlled environment there will help ensure that conservation work continues to be effective.

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