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The Coptic textiles of the Paul and Alexandra Canellopoulos Museum: an analytical approach

Os têxteis coptas do Museu Paul e Alexandra Canellopoulos: uma abordagem analítica

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Abstract

Paul and Alexandra Canellopoulos private collection was donated to the Greek State in 1972 and soon after (1976), the homonymous Museum was inaugurated. The collection includes more than 6,500 antiquities and works of art from different historical periods and cultures, including a remarkable number of Coptic archaeological textiles. These textiles survive today due to the Coptic custom of burying them with the dead and to the aridity of the Egyptian graves. The dry environmental parameters which all these items have been buried or stored gave us the opportunity to study them until nowadays. The Canellopoulos Museum houses 19 textile fragments, which date from the 5th/6th to the 12th century. The four fragments were chosen to a detailed analytical investigation. The selected textiles were subjected to a combination of non-invasive and slightly invasive analytical techniques to determine the type of the fibers, the inorganic components associated with them, and the dyes used for coloring them.

KEYWORDS
Coptic textiles
Analytical techniques
hh-XRF
Optical microscopy
UHLPC

Resumo

A coleção particular de Paul e Alexandra Canellopoulos foi doada ao Estado grego em 1972 e, pouco depois (1976), foi inaugurado o museu com o mesmo nome. A coleção inclui mais de 6500 antiguidades e obras de arte de diferentes períodos históricos e culturas, incluindo um número notável de têxteis arqueológicos coptas. Estes têxteis sobrevivem até hoje devido ao costume copta de os enterrar com os mortos e à aridez das sepulturas egípcias. Os parâmetros ambientais secos em que todos estes itens foram enterrados ou armazenados deram-nos a oportunidade de os estudar até aos dias de hoje. O Museu Canellopoulos abriga 19 fragmentos têxteis, que datam do século V/VI ao século XII. Os quatro fragmentos foram escolhidos para uma investigação analítica detalhada. Os têxteis selecionados foram submetidos a uma combinação de técnicas analíticas não invasivas e pouco invasivas para determinar o tipo de fibras, os componentes inorgânicos e os corantes a eles associados.

PALAVRAS-CHAVE
Têxteis coptas
Técnicas analíticas
hh-XRF
Microscopia ótica
UHLPC

Introduction

Coptic textiles represent a significant aspect of ancient Egyptian heritage, particularly during the transition from the Late Roman period to Christianity, which is marked by a distinctive evolution in textile production techniques and artistic expression. Emerging around the fourth century CE, the pertinent textiles are characterized by their elaborate designs and advanced weaving technologies. Coptic textiles were primarily used to create tunics which were commonly worn by men, women, and children [1].

These textiles were not only functional, they were often adorned with complex decorative motifs that reflected both the cultural and religious transformations occurring in Egypt during this period. The decorative motifs frequently included symbolic representations of animals, plants, and human figures, which were influenced by earlier Egyptian traditions but adapted and transformed to align with the early Christian beliefs [2]. Such textile artifacts found in archaeological sites are incredibly vulnerable due to their nature, making them scarce in the archaeological record, particularly in regions like Greece with a Mediterranean climate [3; 4, pp. 18-24].

The Pavlos and Alexandra Canellopoulou Museum (P & A Museum) houses 19 textile fragments, which date from the fifth/sixth to the twelfth century and belong to the aforementioned category of late antiquity period i.e. Coptic textiles [5-6] (Table 1). It shall be noted that the term "Coptic" derives from the word "qbt" or "qibt", which is the Arabic equivalent of the Greek word for "Egyptian". After the Arab conquest of Egypt in the seventh century, the Arabs used this term to distinguish the indigenous Egyptian population from other groups living in the country, such as Greeks and Romans. Consequently, Coptic textiles – and Coptic art in general – were not made exclusively for Christian Egyptians, but were used by all inhabitants of the region, regardless of their religion [7].

The significance of Coptic textiles extends far beyond their aesthetic appeal; they serve as vital historical materials that provide insights into the social and religious practices of the time they were manufactured and circulated throughout the Mediterranean. The burial customs of the Copts often involved dressing the deceased in multiple layers of clothing, including tunics and other textiles, which were placed in graves as part of the inhumation rites, contrasting with the mummification practices of earlier periods [8]. This practice emphasizes the importance of Coptic textiles in both daily life and ritual contexts, as they were integral to the identity and beliefs of the Coptic community.

In addition to their technical and artistic quality, Coptic textiles have gathered attention from scholars and collectors, particularly during the late nineteenth and early twentieth centuries when archaeological discoveries in Egypt led to an influx of these artifacts into international collections [9]. This strong interest in collecting these artifacts led to their dispersal across numerous public and private museums, often in fragmentary condition and without proper documentation regarding their provenance or excavation context. Besides, the nineteenth and twentieth century illicit trafficking of such artifacts had an immerse impact on their dissemination around the globe, and by the 1970s, it was estimated that over 150,000 Coptic textiles were scattered among various museums [10].

Today, Coptic textiles continue to be a subject of scholarly interest, with ongoing research focused on their iconography, dye composition, and the socio-cultural contexts in which they were produced and used. The study of Coptic textiles has evolved significantly due to the enhanced potentialities of the modern scientific techniques. Various techniques have been employed to identify features like weaving methods, fibers and dyes determination, degradation stage in archaeological textiles [11-15]. Recent advancements in the applied methods enable high-quality results without damaging the artifacts, often using extremely small samples obtained from already damaged areas or employing a non-invasive approach following ethical conservation principles [16].

Table 1. The 19 Coptic textiles of the P&A Museum, with their respective inventory number, dimensions and date (CE) [6].

Inventory number	Textile	Date (century)	Dimensions Height × Width (m)	Inventory number	Textile	Date (century)	Dimensions Height × Width (m)
D2547		5th/6th	0.195 × 0.185	**D2549**		7th/9th	0.052 × 0.130
D2552			0.265 × 0.235	**D2562**		7th/8th	0.095 × 0.065
D2551		7th	0.240 × 0.200	**D2560**			0.10 × 0.130
D2546		7th/8th	0.248 × 0.093	**D2554**			0.085 × 0.145
D2550		7th/8th	0.250 × 0.100	**D2559**		7th/9th	0.105 × 0.093
D2548		7th/8th	0.090 × 0.274	**D2555**			0.130 × 0.065
D2553		7th/9th	Overall: 0.180 × 0.150 Image: 0.145 × 0.125	**D2558**		7th/10th (?).	0.103 × 0.080

Inventory number	Textile	Date (century)	Dimensions Height × Width (m)
D2561		7th/9th	0.300 × 0.065-0.120 (at the widest point).
D2556		7th/10th	0.060 × 0.065
D2557		9th/11th	0.110 × 0.220
D2590		10th/12th	0.105 × 0.160
D2545		11th/12th	1.030 × 0.215

Such analyses not only enhance our understanding of the technical aspects of Coptic textile production but also contribute to the broader narrative of cultural ex-change and continuity in the Mediterranean region. As such, they remain a vital area of study for understanding the interplay between art, religion, and daily life in ancient Egypt, offering a window into the complexities of Coptic identity and heritage.

The main aim of this paper is to apply an array of analytical techniques such as Optical Microscopy (OM), handheld X-ray Fluorescence Spectroscopy (hh-XRF) and Ultra High Performance Liquid Chromatography (UHPLC) in order to identify the nature of the fibres used, to understand the inorganic components that are associated to the fibres and the dyestuff used on selected fragments of Coptic textiles from the collection of the Paul and Alexandra Canellopoulos Museum.

Materials and methods

The Coptic textiles

The Coptic textiles collection of the Paul and Alexandra Cannelopoulos Museum con-sists of 19 fragments with several iconographic motives (Table 1). From this collection we have chosen the four most interesting -in terms of iconography- fragments (samples D2550, D2554, D2557 and D2560,) that employ fibers with a variety of colours. In addition, from three out of the four textiles, namely D2550, D2554 and D2557 minute fiber samples were collected from lose areas without further damaging the fragment to investigate them using OM (Figure 1, bottom right). In total six fibers were removed from the three textile fragments exhibiting a variety in colours (Table 2).

Figure 1. Example of the minute fiber samples extracted from textile D2554: top right red fibers (D2554-4), and bottom right blue fibers (D2554-5).

Sample D2550 probably comes from a tunic and was part of its vertical decorative bands ("marks"). This piece bears a depiction of a hunting scene and dates at the seventh-eighth century CE. Sample D2554 is a rectangular section of fabric. On a dark blue background, three naked figures (Cupids?) march to the right with a dancing step holding unspecified objects (shields?); this piece dates at seventh-eight century CE. Sample D2557 probably comes from the sleeve of a tunic and dates at the ninth-tenth century CE. At a pale yellow background, two parallel rectangular oblong spaces with depiction (one reverse of the other) felines with a raised tail and birds grow in deep red. Finally, sample D2560 is a circular "point" from a tunic with stylized floral decoration. Externally has a circular green frame which grows towards inside in red depth colorful stylized floral decoration; the sample dates at the seventh-eigth century CE.

Analytical techniques

Optical microscopy (OM)

The OM was performed at the Laboratory of Physicochemical Analyses of the Department of Environment at the Ionian University. The optical observation was carried out using the Leica DM 2500M optical microscope at various magnifications.

Handheld X-ray fluorescence (hh-XRF) spectroscopy

Further to the microscopic study, hh-XRF spectroscopy was employed to study the components of the textiles, since this spectroscopic technique allows for the non-invasive detection of elements with Z > 12 (Mg). The analysis was performed in situ in the Cannelopoulos Museum using the Tracer 5 g, Bruker, spectrometer which is equipped with a Rh anode X-ray source (50 kV, 4 W, 1 μm graphene side window), a 20 mm^2 SDD detector and a 3 mm collimator. For each point of analysis two spectra were collected: the first spectrum was collected by operating the spectrometer at a setup of 15 kV and 30 μA (voltage and current respectively), and the second by a 50 kV and 30 μA setup with an additional employment of a Ti-Al filter. The collected spectra were subsequently evaluated and processed using the Artax software (Bruker). In particular, the total counts of each characteristic X-ray peak were calculated, allowing thus for the direct comparison across different spots of analysis because the spectra were collected under identical operating conditions [17-18]. This allows us to assess relative differences in elements' presence (i.e., whether a given element is more or less abundant in one sample/spot of analysis compared to another), even if absolute concentrations are not calculated.

Ultra high performance liquid chromatography and photo diode array detection system (UHPLC-DAD)
Finally, the identification of the dyes was performed using a UHPLC-DAD with Waters equipment [19] at the Textile Research Lab of the Koninklijk Instituut voor het Kunstpatrimonium-Institut Royal du Patrimoine artistique (KIK-IRPA, Brussels, Belgium).

The samples were extracted following established dye-extraction protocols [20-22]. Depending on the sample, acidic methanol extraction was applied alone or in combination with dimethylformamide (DMF), ethyl acetate (EtAc), EDTA, or formic acid. Extracts were dried under vacuum and re-dissolved in methanol/water (1:1, v/v), of which 20 µL was injected for analysis.

Chromatography was carried out on a temperature-controlled reversed-phase C18 column following two protocols:

Protocol 1: Lichrosorb RP-18 (4.0 × 125 mm, 5 µm) with solvents (A) water, (B) methanol, (C) 5 % phosphoric acid in water; gradient 60A/30B/10C to 10A/80B/10C over 26 min at 1.2 mL/min.

Protocol 2: Grace Vydac DE C18 (3.2 × 250 mm, 5 µm) with solvents (A) acetonitrile, (B) water, (C) 0.1 % trifluoroacetic acid; gradient from 10A/70B/20C to 60A/40B/0C over 40 min, then 10 min isocratic at 0.4 mL/min.

Detection was performed with a Waters photodiode array detector (DAD) over the 200–600 nm range, and dye identification was based on comparison with the KIK/IRPA reference spectral database [19].

More details about the analytical protocol are described elsewhere [23].

Results

OM

The OM observation revealed the morphological characteristics of the fibers used for the construction of the textiles (Table 2). All fibers were made of wool and display the corresponding characteristic small scales on their surface (Figure 2). Regarding sample D2554, numerous dust and dirt deposits were observed on the surface of the red fiber (sample D2554-4), while several areas of damage attributable to poor preservation were observed on the blue fiber (sample D2554-5).

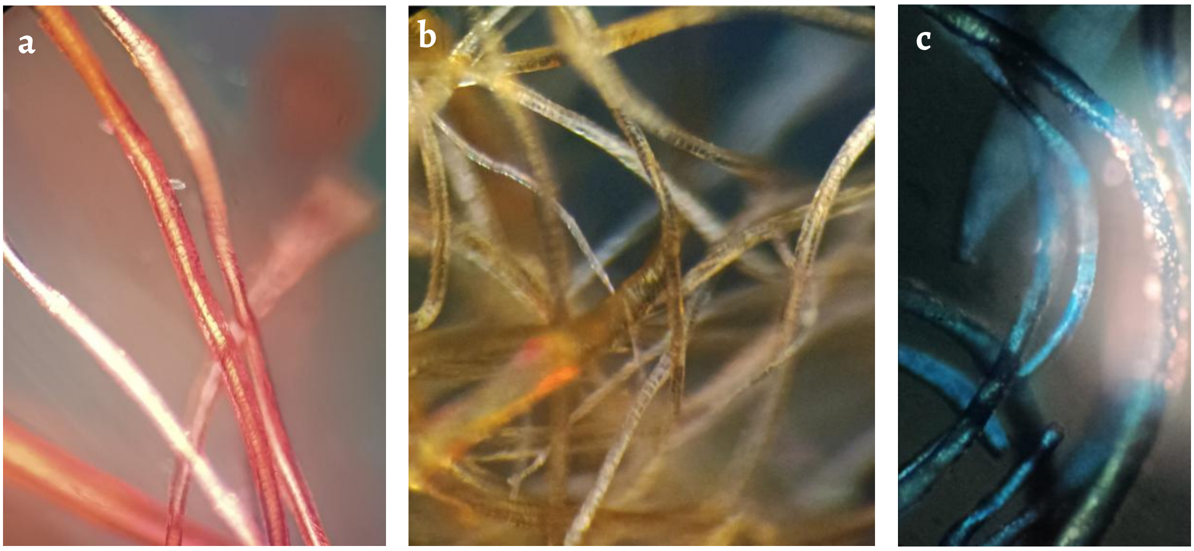

Figure 2. Characteristic photos of the samples: *a)* D2550-1 20× magnification; *b)* D2550-2 20× magnification; *c)* D2550-3 40× magnification.

Table 2. Fiber colour, the morphological characteristics and the fiber natures of the samples under analysis as determined through the use of OM.

Sample	Fiber colour	Morphological characteristics	Fiber nature
D2550-1	Red	Small scales on the fiber's surface	Wool
D2550-2	Yellow		
D2550-3	Black		
D2554-4	Red		
D2554-5	Dark blue		
D2557-6	Light yellow/white		

hh-XRF analysis

The analytical results from the hh-XRF measurements on the Coptic textiles (Figure 3) offer interesting insights regarding their elemental fingerprint. In particular, as discussed in detail in the Materials & Methods section, we followed a semi-quantitative approach that allowed for an objective comparison between the intensities (total counts) of the characteristic X-ray peaks of the elements detected on every single sample/ spot of analysis; the corresponding results are summarized in Table 3.

Figure 3. Selected Coptic textiles and indication of the areas analyzed by hh-XRF: *a)* D25550; *b)* D2557; *c)* D2560; *d)* D2554.

Table 3. Summary of hh-XRF analysis results, the elemental peak intensities have been expressed in counts (total counts).

	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Cu	Zn	Pb	Sr
D2550														
Red	126	303	469	22875	4324	3247	14034	584	262	8023	149	148		692
Deep blue	124	363	464	22318	4134	3057	9612	607	470	8390	75	273		624
Gray	127	422	395	20346	4316	3124	14402	721	293	10977	80	373		594
Red-orange	119	494	223	19059	4134	3296	13832	698	351	11833	107	271		583
Yellowish	144	613	940	22088	4335	3278	15166	800	507	12443	98	243		521
Black	88	323	136	17379	4263	4008	13805	781	556	11865	152	177		930
Beige	109	320	145	22015	4300	3629	12743	1401	455	19178	102	122		659
Whitish	86	468	328	6513	4272	4047	19931	689	402	10159	66	177		458
D2554														
Support	117	157		1185	9021		11001	2889		12826				
Deep blue	487	2441	533	26149	9635	5179	46024	2852	1233	32117	295	212	1458	975
Off-white	1098	7998	914	2465	7551	8790	56186	5562	1429	64003	242	207		1413
Green	660	3053	1295	20635	8252	8593	37537	3266	1334	49593	606	268	337	2283
Yellow	908	6107	1039	18728	7487	8083	58031	5820	1704	64912	470	267	347	2061
Light blue	438	2318	1038	29067	22302	11771	52992	2097	1287	27894	149	191	253	1310
Orange	704	3048	1382	24051	38182	19913	49473	2477	1664	38542	446	305	236	4267
Purple	661	2954	1153	22074	24054	15142	34551	1988	1523	34570	509	277		3467
Red	340	1686	656	18778	11760	5952	38709	2084	881	19866	152	108		796
D2557														
Support	102	125		1270	9218		10197	2457	845	10888				
Off-white	319	1411	322	32371	8874	1999	33120	1418	810	14312	95	190		618
Red	517	1699	1098	29856	8970	2464	38546	1340	801	13839	141	172		875
Beige	581	3167	593	5431	49097	3449	23780	2486	704	24121	110	178		550
D2560														
Support	98	153		1264	8875	12076		2707		12187				
Off-white	232	699	347	35772	7261	14101	1780	1376	935	16532	168	178		
Green	332	1364	1735	31609	6873	14059	3987	1677	570	20283	140	247		659
Black	203	498	662	39504	7235	15617	2916	1182	1158	13405	137	167		
Red	337	864	1348	38010	7082	16454	3734	1340	1041	16777	134	289		505
Off-yellow	443	1258	2068	36131	6892	13965	4799	1654	1116	23087	132	211		419
Beige	324	810	1508	33579	7060	14332	5236	954	1301	14927	186	349		456
Light blue	258	1087	563	38282	7578	16482	3328	1912	992	19688	101	271		517
Light brown	253	887	553	39075	7161	19676	3774	2963	1415	45946	186	308		556

According to the data, it is obvious that the textile D2554 stands out due to the fact that it is the only to contain areas with detectable amounts of lead (Pb) as well as due to the notably enhanced elemental peaks of strontium (Sr) and silicon (Si) which were spotted in all the corresponding spectra/ points of analysis (Figure 4). The presence of silicon clearly pertains to contaminants like dust, dirt and soil contamination [24-25] while strontium might be relevant to soil contamination too; in fact, Sr-containing compounds like celestine ($SrSO_4$) are commonly associated with calcium sulfate and carbonate minerals [26-27]. Additionally, it is well known that traces of Sr are contaminated in wool fibers during wool growth, since this element is gradually incorporated in the body parts (including hair/wool) via the food consumption chain [28]. Therefore, the notably enhanced presence of Sr in case of the textile D2554 obviously suggests that this very fragment comes from a different – in comparison to the other fragments – origin.

On the other hand, it appears that certain other elements such as sulphur (S), potassium (K) and phosphorous (P) show very characteristic elevated values in all colours of the fibers for sample number D2560 compared to the other samples (D2550, D2554, D2557) (Figure 5). These and other chemical elements are minute components of wool and it has been demonstrated that their contents of can show significant variations among wool samples from different origins [29]. Additionally, elements like the aforementioned can also be presumably associated with the burial environment of this particular fragment, therefore the elevated intensities of the corresponding spectral peaks in case of fragment D2560 may hint to a potentially distinct provenance too (?). Moreover, it shall be noted that phosphorous enrichment takes place in soils that lay in proximity to decomposing corpses, a phenomenon which is very much affected by the environmental conditions [30]; therefore, elevated phosphorous might also be considered as a potential provenance fingerprinting clue. potassium (K) could indicate the use of an alkalizer in the form of plant/wood ash acting as a dyeing auxiliary [31].

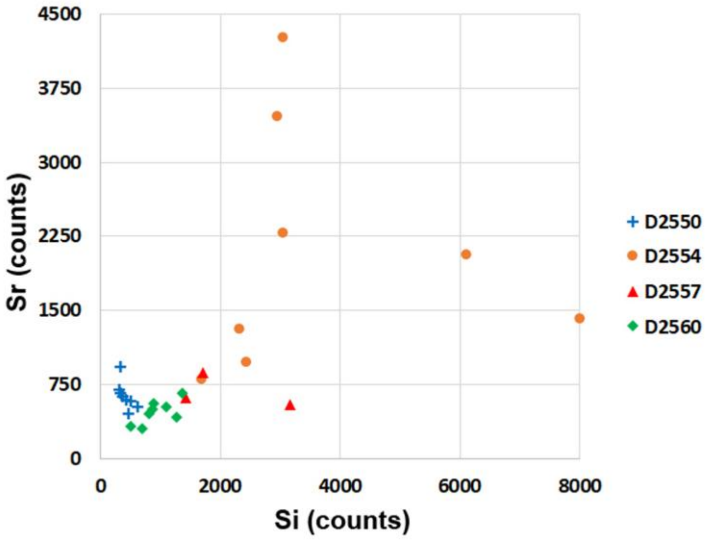

Figure 4. Total counts of the K-alpha elemental transition peaks of Sr versus Si in the analysed spots of the studied textiles; XRF data (Table 1).

Figure 5. The peak intensity (total counts) of phosphorus (P), sulphur (S) and potassium (K) for the red, yellow and blue fibers of samples D2550, D2554 and D2560 respec-tively. We notice that D2560 has elevated values of these elements in all colours.

As for sample D2554, it has been already highlighted that it stands out due to the intense presence of Sr (see above). What is more, this particular sample shows elevated values of elements such as silicon (Si), aluminum (Al), calcium (Ca), titanium (Ti), manganese (Mn) and iron (Fe) compared to the rest of the samples (Table 3 and Figure 6). These elements are higher in D2554 regardless of the colour of the analysed fiber. In combination with the dirt particles that were observed on the fibers of this very garment under OM, it is assumed that these may correspond to argillaceous soil contamination. A typical composition of argillaceous soils has SiO_2: 40-60 % (from quartz and clay minerals), Al_2O_3: 10-25 % (from kaolinite, illite, smectite, etc.), Fe_2O_3: 5-15 % (iron oxides/hydroxides, e.g. hematite, goethite), CaO: 1-5 % (carbonates, calcite, or gypsum if present) and TiO_2: ~0.5-2 % (mainly from rutile/ilmenite in clays) among others.

Additionally, calcium, which is detected in every textile and in every colour, can also act as a dyeing auxiliary. Usually, its elevated presence may indicate the use of a calcium source to alkalise the dyeing vat through the use of burnt shells which is a commonly accepted procedure [19].

The assessment of potential use of dyeing auxiliars like mordants is a rather difficult task and it is true that a more thorough analytical investigation (that must include detailed elemental analysis, like e.g. EDS) is needed in order to reach into conclusive results. Nevertheless, the herein presented XRF data turned out to be a sound background for a well-aimed first approach on this issue. First of all, the absence of tin (Sn) excludes the possibility of the use of mordants like stannous chloride. Similarly, despite the detection of minute copper in most of the XRF spectra (Table 3), it is rather difficult to state whether a copper-containing mordant was indeed used or not. In fact, copper is often detected in archaeological textiles and its presence can pertain to the employment of a pertinent mordant ($CuSO_4$), or to contamination due to the use of bronze vessels [32] for dying or proximity to Cu-containing objects in the burial environment [25]. In our case, only the XRF spectra collected from specimen D2554 show notably enhanced Cu elemental peaks, therefore it seems possible that a Cu-bearing mordant might had been used in this instance (Table 3 and Figure 7).

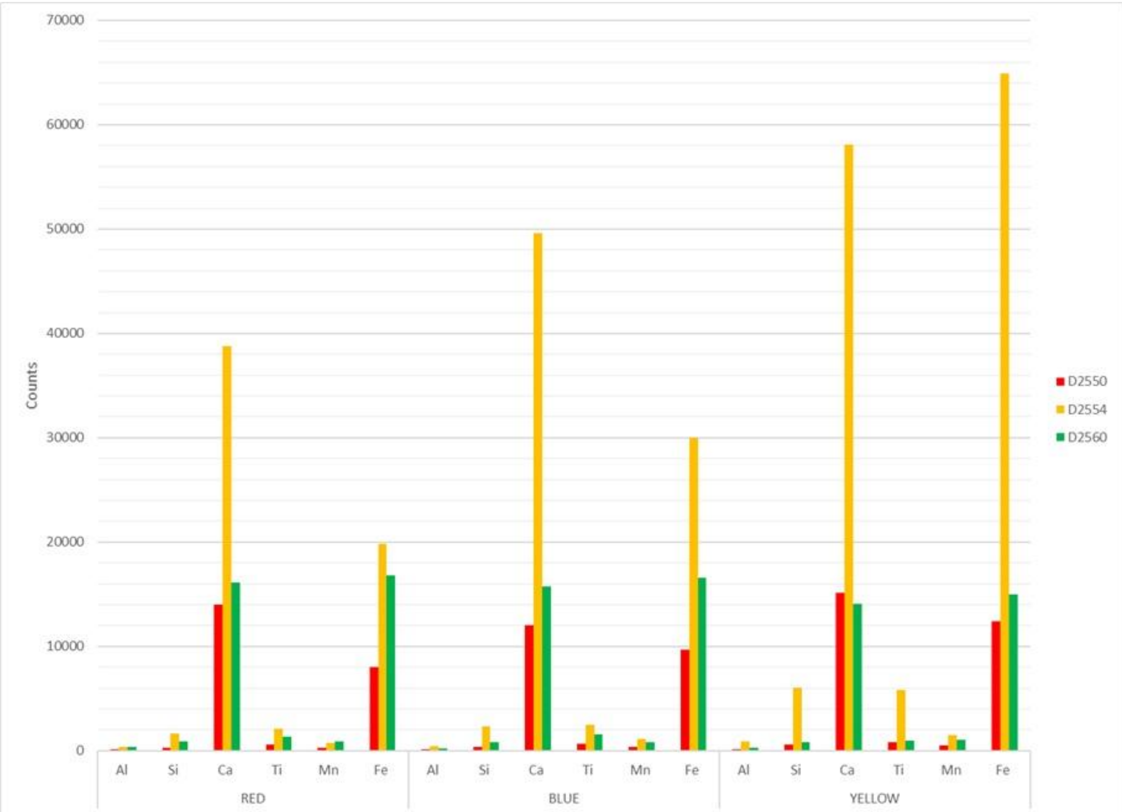

Figure 6. The relative intensities of characteristic XRF peaks of aluminum (Al), silicon (Si), calcium (Ca), titanium (Ti), manganese (Mn) and iron (Fe) for the red, yellow and blue fibers of samples D2550, D2554 and D2560.

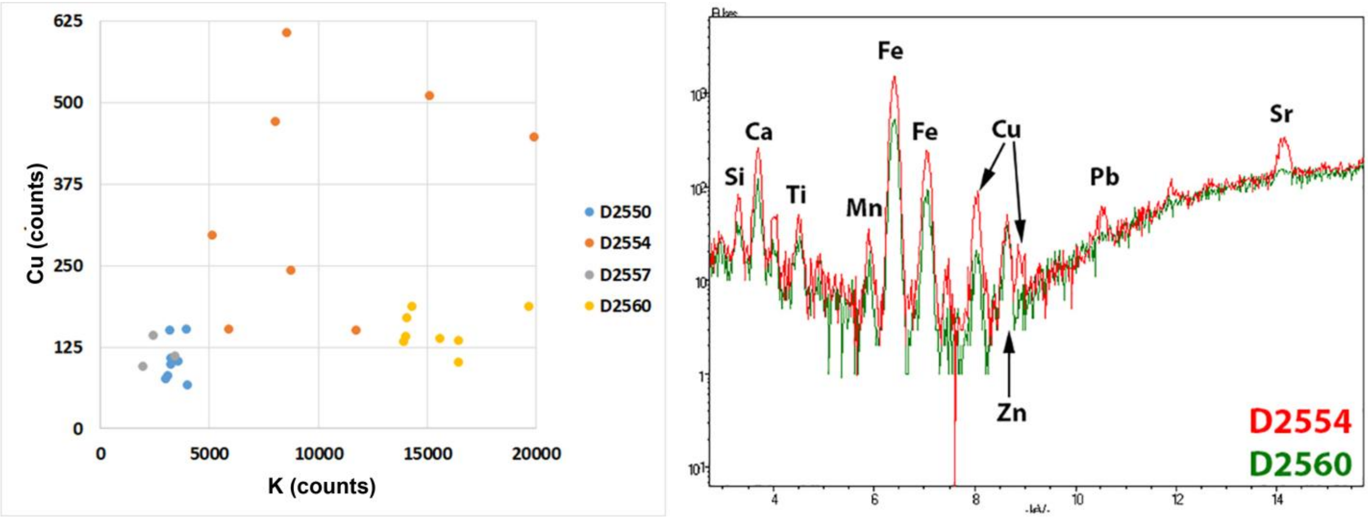

Figure 7. XRF analysis: *a)* XRF data, the intensities (total counts) of the elemental peaks of K versus Cu; *b)* XRF spectra from green coloured fibers of the fragments D2554 (red) and D2560 (green); note the difference in Cu peak intensities. Spectra in logarithmic scale.

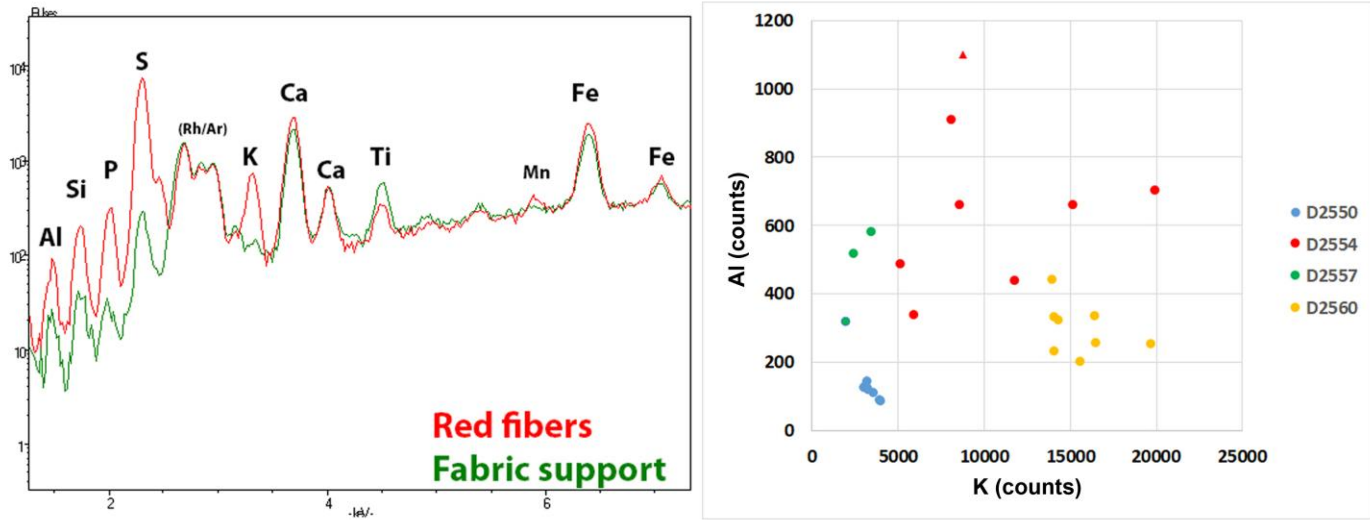

Figure 8. XRF analysis: *a)* hh-XRF spectra (logarithmic scale) from the background textile and the red colored fibers of artifact D2560 (note the differences in the peak intensities of aluminium, phosphorous, sulfur and potassium); *b)* XRF data, the intensities (total counts) of the elemental peaks of Al versus K.

On the contrary, the assessment of whether an alum type materials was used as mordant in the studied textile fragments is challenging due to the spectrometer rather low sensitivity to aluminium (Al). In fact, due to the employment of the graphene side window in the used spectrometer Al is indeed detected and corresponding peaks are spotted in all the spectra collected from Coptic textiles (Figure 8a). However, it has been demonstrated that the presence of Al can be considerably underestimated by the employed instrumentation [33], hence it is particularly difficult to ascertain the presence of alum-type mordants in the framework of the current study. Nevertheless, upon plotting the intensities of the elemental peaks of Al versus K (Figure 8b) it appears that the studied textile fragments show obvious and substantially deviating elemental composition trends. In particular, the spectra collected from areas of different colour of the fragment D2550 show practically identical and notably low intensities of Al and K elemental peaks, a fact that might allow for the exclusion of the use of alum in this instance. Contrarily, the spectra from fragments D2554, D2557 and D2560 show varying yet enhanced intensities of Al and K in comparison to those of the previously mentioned fragment, therefore employment of alum is possible. Additionally, it shall be noted that iron (Fe) may also pertain to a mordant, yet on the basis of the currently available analytical data it is not possible to exclude the possibility that its presence in the textiles under investigation pertains exclusively to soil contamination [34]. Besides, this assumption is corroborated by the fact that elevated iron was detected on the fragments' supports too, i.e. on the fabrics on which the fragments have been stitched in the framework of their conservation/preparation for exhibition (Figure 8a).

UHPLC-DAD analysis

Regarding the dyestuff sources used for the analyzed fibers the collected data revealed the employment of rather typical – for both the type of artifacts and the era – dyes [35]. The corresponding analytical results are be summarized in Table 4.

Some of the dyes that were identified include madder and weld -which are among the most common mordant dyes in Coptic textiles- indigo, and sappanwood. The dyeing of textiles with mordant dyes has been a well-known technique for centuries. Indeed, Pliny the Elder describes the mordant dyeing process followed by Egyptians; therefore, it is obvious that this method was established in Egypt well before the first century AD. This technique was used in Roman and pre-Roman Europe but disappeared during the Middle Ages, only to reappear in the first half of the eighteenth century (1742) through the descriptions of Jesuit missionaries from India and the East. During the same century, textiles in Spain were dyed using mordant dyes, a technique introduced by the Arabs, who in turn had adopted it from the Romans and Greeks [35].

Perhaps the most widely used red dye in history is madder. Madder (*Rubia tinctorum* L.) is derived from the roots of the plant, which is native to various regions around the world, from Europe, the Mediterranean, and the Near East to China and Japan. References to its use date back to antiquity. Herodotus mentions its application by an Egyptian woman around 450 BCE, while Pliny the Elder also discusses it in his work Natural History [36]. Madder has been found in numerous excavated and archaeological textiles from Egypt, as well as in Persia, Arabia, and Mesopotamia. The main coloring compounds in madder that were identified in the Canellopoulos Museum textiles include alizarin, purpurin, pseudopurpurin, and xanthopurpurin [37].

Weld (*Reseda luteola* L.) is obtained from the leaves and stems of the plant, which thrives in various parts of Central Europe and has also been cultivated in India. Its history is among the oldest known; documented as far back as the Neolithic period [38-39], weld was valued both for producing a brilliant yellow color and for creating stable green shades in combination with other dyes. Even before the discovery of America (1492), weld was the most widely used yellow dye in Western Europe. However, after around 1500, another plant-based dye, fustic, which produces indigo-derived colors, gained prominence. For a time, both dyes were used equally to produce yellow shades. The main chromophoric compounds in weld that were identified in the Canellopoulos Museum Coptic textile samples from the museum are the flavonoid compounds luteolin and apigenin [35].

Table 4. UHPLC-DAD analyses. Detected dye composition and related dye sources.

Sample	Date	Colour	Extraction	Dye composition	λ(nm)	Dye sources
D2550-1	7th-8th c. AD	Red	HCl	4 munjistin, 51 alizarin, 31 purpurin, 1 munjistin', 13 nordamnacanthal	255	**Madder**
D2550-2		Yellow	HCl	7 urolithin C, 73 luteolin, 3 apigenin, 1 chrysoeriol, 16 alizarin	255	**Weld,** madder, sappanwood
				94 luteolin, 5 apigenin, 1 chrysoeriol	350	
D2550-3		Black	HCl	Peaks at 8.6 - 9.5 – 10.6 rt (max 595-600 nm)	255	Synthetic dyestuff: **acid black 1**
			DMSO	-	255	
D2254-4	7th-8th c. AD	Orange	HCl	+ munjistin, 62 alizarin, 38 purpurin	255	**Madder**
D2554-5		Dark blue	HCl	64 isatin, 32 indigotin, 4 indirubin	255	**Indigoid dye stuff**
				22 isatin, 76 indigotin, 2 indirubin	288	
				100 indigotin	600	
			DMSO	100 indigotin	255	
				100 indigotin	288	
				100 indigotin	600	
D2557-6	7th-8th c. AD	White	HCl	-	255	No dyes detected

Furthermore, indigo and woad both have a rich historical significance as natural dyes. Indigo, a very common dye derived primarily from *Indigofera tinctoria* L. plants, has been exploited as a dye since antiquity. Archaeological evidence suggests that indigo was in use as early as the mid of third millennium BCE in Egypt as it was identified in mummies [40]. Woad, obtained by *Isatis tinctoria* L. plants, has also a long history as a dye stuff, particularly in Europe. The earliest prove of the application of woad on textiles dates back approximately 3500 years and it was discovered in Hallstatt, Austria [41]. The long history of both dyes highlights their importance in the production of early and later textiles and the dyeing techniques employed have been thoroughly documented in historical texts and trough experimental archaeology [42].

D2550-1 red sample

In a red fiber from sample D2550, the detection of the antraquinone dye molecules like alizarin, purpurin, and minor compounds like munjistin and nordamnacanthal points to the use of the roots of cultivated or dyer's madder (*Rubia tinctorum* L.) for red dyeing of this sample [40]. This plant belongs to the Rubiaceae family and is native to Europe, the Mediterranean, and parts of Asia. It has been cultivated for centuries for its ability to produce a range of red hues, from bright orange-red to deep crimson, depending on the dyeing technique and mordants used [35].

The chromatographic results for the anthraquinone dyes must be interpreted with caution, since several Rubia species can yield overlapping profiles. Previous work has shown that *Rubia peregrina* L.is generally characterised by low alizarin content (0-21 %) and relatively high rubiadin levels, whereas *R. tinctorum* L. typically presents more balanced proportions of alizarin and purpurin and lacks rubiadin (Wouters et al. 2008). Our samples with statistically lower alizarin values and relatively higher purpurin may therefore be consistent with the use of *R. peregrina* L., although alternative explanations such as dyeing technology (e.g., top-dyeing over indigo) or degradation processes cannot be excluded. Conversely, samples in which alizarin and purpurin are present in approximately equal amounts are more compatible with *R. tinctorum* L..

D2550-2 yellow sample

The main dye compound detected in the yellow fiber from D2550 sample is the flavone luteolin. It is found together with apigenin and chrysoeriol, which is characteristic to dyeing with the yellow dye plant weld (*Reseda luteola* L.) [43-45]. In addition, alizarin is also present, indicating a mixture with madder. Furthermore, evidence is found for a second red dye source based on the detection of urolithin C. This is a marker compound for dyeing with soluble redwood [46]. Given the historical context of the textile, this concerns sappanwood, the heartwood from tropical trees such as *Caesalpinia sappan* L. from the Orient. As this dye source is known to be less lightfast, the original colour of this currently yellow yarn must have been more red [47].

For the luteolin-based yellows, it is likewise difficult to assign the source to a single plant, since luteolin is present in a wide range of dye plants (e.g., *Reseda luteola* L., *Genista* spp., *Anthemis* spp.). Nevertheless, comparison with reference profiles and the known dye repertoire of the region suggests that weld (*Reseda luteola* L.) is the most plausible source, although other flavonoid-containing plants cannot be ruled out.

D2550-3 black sample

The black colour of the black fiber from textile D2550 (Figure 9) was obtained by dyeing with a dyestuff from synthetic origin. The spectral data of the detected peaks is very similar to the one of acid black 1, also known as amidoblack (Colour Index number 20470), a diazo dye first developed by M. Hoffmann in 1891 [48]. A second analysis was done on a DMSO solvent extract of the black sample which confirmed the absence of any indigoid dye compound in the sample. This might be an indication of a modern conservation treatment on the textile using a modern synthetic fiber.

Figure 9. Textile D550 and the detail where the sample D2550-3 was taken.

D2554-4 orange sample

For the orange fiber coming from the textile D2554 the detection of alizarin, purpurin, and munjistin refers to the use of the roots of cultivated or dyer's madder (*Rubia tinctorum* L.) in this very sample. As mentioned above, dyer's madder can produce a range of red hues, from bright orange-red to deep crimson, depending on the process [47].

D2554-5 dark blue sample

The analysis of a dark blue fiber from textile D2554 reveals the presence of indigotin, indirubin and isatin indicating thus employment of an indigoid dye source. Based on this result, a second analysis on a DMSO solvent extract of the same yarn was performed to obtain an improved extraction of (either or not brominated) indigoid dye compounds. This analysis confirmed the presence of indigotin but did not reveal any brominated compounds. Hence, it can be concluded that the dark blue was obtained by dyeing with either indigo (Indigofera or Polygonum species) or woad (Isatis tinctoria L.) [47]. As the same dye compounds are found after chromatographic analyses of textiles dyed with both types of plants, distinction between the two is not possible.

D2557-6 white sample

Finally, for a white fiber from sample D2557 as expected, no evidence for dyeing of the white sample was found.

Conclusions

The use of different scientific techniques, such as OM, hh-XRF and, UHPLC, has proven to be incredibly valuable in studying ancient textiles and in particular Coptic textiles. These complementary analytical methods play a significant role in helping researchers understand the materials, production techniques, and the history behind these fabrics.

In this study, OM was used to confirm that wool, as the raw material most commonly used in Coptic weaving tradition, was also used in the Coptic textiles from the Paul and Alexandra Canellopoulos Museum.

XRF analysis provided further insight by revealing the presence of different elements in the textiles in a non-invasive manner. Of particular interest is the detection of Sr: this element that can be used as a provenance indicator, and in the current study the corresponding data clearly show that one of the studied fragments deviates substantial in regards to Sr content. Elements such as iron, copper, calcium, potassium and aluminum, offer evidence about the dyeing methods used in antiquity and the environmental conditions that affected the textiles over time. Some of these elements, like aluminum and potassium, likely pertain to mordants, namely the substances that were used to fix dyes to the fabric and enhance color durability. In particular, a single fragment (D2554) shows notably enhanced Cu content which can be related either to particular burial conditions (i.e. proximity to bronze item), or to the use of a Cu-containing mordant. Nevertheless, since other elements like silicon, calcium, titanium and manganese pertain to contamination from the soil where the textiles were buried for hundreds of years, a further and more elaborate analysis is required in order to reach to conclusive results as for the employed mordants.

Ultra High-Performance Liquid Chromatography (UHPLC) was particularly useful for identifying the dyes in selected samples. This method helped confirm the use of well-known historical dyes commonly found in Coptic textiles. In particular, madder (*Rubia tinctorum* L.) was used to create red shades, indigo (Indigofera species) provided blue tones, and weld (*Reseda luteola* L.) was likely responsible for yellow hues. These findings align with traditional dyeing practices in Egypt and the surrounding Medi-terranean region during late antiquity and the early Islamic period. Additionally, the detection of modern synthetic dyes highlights the existence of previous conservation interventions.

By combining these different techniques, it was possible to gain a deeper understanding of how these textiles were made, dyed, and preserved over the centuries. The ability to analyze ancient fabrics without affecting the state of preservation and integrity of the artifacts is crucial for both archaeological research and textile conservation.

In the context of conservation, the analytical characterization of the Coptic fragments has direct implications for their care and management within the museum environment. The identification of specific fiber types and dye materials enables conservators to anticipate deterioration mechanisms and to design appropriate preventive measures regarding light, humidity, and pollutant control. Furthermore, the recognition of original manufacturing techniques and later alterations offers valuable guidance for future conservation treatments and display decisions. Thus, the study not only enriches the historical understanding of these textiles but also provides a scientific foundation for their sustainable preservation.

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