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THE TECHNOLOGY OF MANUFACTURING FUEL FOR OIL LAMPS IN THE HELLENISTIC PERIOD: AN APPLIED STUDY THROUGH THE FINDINGS OF THE ALEXANDRIA NECROPOLIS PROJECT OF SHATBY, ALEXANDRIA [2020–2023]

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BY

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ABSTRACT

تكنولوجيا صناعة وقود إضاءة المسارج بالعصر الهلينستي «دراسة تطبيقية من خلال مكتشفات مشروع جبانة الشاطبي بالإسكندرية 2020-2023

[AR]

يقدم هذا البحث دراسة تطبيقية وتجريبية لما تم الكشف عنه من بقايا مادة وقود الإضاءة التى كانت تستخدم للمسارج فى الفترة الهلّينستية، وكذلك دراسة بقايا لفتيل محترق عثر عليه ضمن مشروع ترميم وتطوير وحماية جبانة الشاطبى الأثرية، والذى نفذته جمعية الآثار بالإسكندرية بتمويل من مؤسسة أ.ج. لفنتيس القبرصية فى الفترة من 2020-2023م. تضمن المشروع إعادة استكشاف الجبانة الأثرية بإزالة الرديم المتراكم بها عبر الزمن. وجادت الجبانة بالعديد من القطع الأثرية تمثلت فى مسارج وأطباق فخارية وأوانى الحضرة وبقايا عظام بشرية. أثبتت التحاليل والفحوص أن الصخر الذى نحتت فيه الجبانة الأثرية أحد أنواع الحجر الجيرى، وأن المياه الجوفية الموجودة بالجبانة هى مياه تترواح نسبة المعادن الذائبة بها بين 1,7جم/لتر ودرجة أس هيدروجينى pH 7.1. تم تحليل مادة الوقود بالتحليل الكروماتوجرافى الغازى المزود بمطياف الكتلة، حيث أثبت أن مادة الوقود ذات أصل بترولى. واستخدم الفحص بالميكروسكوب الإلكترونى الماسح لفحص بقايا عينة الفتيل المتفحم، وتبين أنها جزء من ساق نبات البوط، وتم تأكيد النتيجة بفحص التركيب التشريحى لساقى نباتى البردى والبوط كجانب تجريبى.

[EN] This paper is an applied and experimental study on the remains of the fuel material that was used in oil lamps in the Hellenistic period, as well as the remains of a burning fuel and oil lamp wick. These remains are among the finds of the project of restoration, development, and protection of the archaeological cemetery of Shatby, conducted by the archaeological Society of Alexandria (2020-2023), funded by the A.G. Leventis foundation, Cyprus. The entire cemetery of Shatby is hewn in the a type of limestone called Calcarenite, which is a sedimentary rock. The groundwater at the site is slightly alkaline (pH 7.1), with the total dissolved solids (TDS) at 1.7 g/L. Remains of lighting fuel were found during the removal of the accumulated rubble in the ancient cemetery, where they were analyzed using gas chromatography mass spectrometry (GC-MS) analysis which proved that they are composed of crude oil. Using a scanning electron microscope to examine the traces of wick ash, it appeared that the wick was made of the culm of *Cyperus articulate*. Based on experimental work, this was also proven by light microscopy examination of the culms of *Cyperus articulate* and *Cyperus papyrus*.

KEYWORDS: *Cyperus articulate, Cyperus papyrus*, GC-MS, Hellenistic period, oil lamp, lighting fuel, Shatby Cemetery, wick,

I. INTRODUCTION

Shatby Necropolis is located directly beyond the eastern limits of the ancient royal (eastern) quarter of the ancient city of Alexandria, overlooking the shore of the Mediterranean Sea, in the modern district of Shatby. The cemetery is very important as it provides the earliest example of the Alexandrian-style burials carved into rock. This Ptolemaic cemetery dates back to the late 4th century BC and is thought to be the city's earliest cemetery, belonging to the first generation of Alexandrian families[1] **[FIGURE 1]**[2].

Evaristo Breccia, then director of the Graeco-Roman Museum of Alexandria, excavated the site between 1904 and 1910. His findings were published in a remarkably high standard article [1905] and a monograph [1912][3]. Nonetheless, his publication leaves a number of unanswered questions, and various archaeological features undocumented or undiscussed, presenting an opportunity for renewed archaeological research in the area.

Several archaeological field seasons were conducted in the Shatby necropolis area from 2010 to 2014, with the goal of finding explanations for some of the questions left unanswered by Breccia's publication[4].

The Hellenistic cemetery of Shatby has been completely upgraded as part of the Alexandria Necropolis Project [2020–2023], which began in 2020 by the Archaeological Society of Alexandria with funds from the A. G. LEVENTIS foundation of Cyprus and by permission and supervision of the Egyptian Ministry of Tourism and Antiquities. The Archaeological Society's mission was able to consolidate the excavation of the site and reach the original ground level by removing over two meters of layers of debris, dirt, and water. More than 300 artefacts were discovered, including human remains, some *Hadra Hydriai*, an inscribed miniature votive altar, and a huge amount of local and imported pottery in exceptional state of preservation.

Oil lamps were known in ancient Egypt. Castor oil, olive oil, sesame oil, animal fat, and other sources of fuel mentioned in historical sources were used, whose names may be pronounced without referring to the nature of the fuel. Linen or old clothes and some fabrics whose nature was not inferred were used to make wicks for oil lamps[5].

According to archaeological evidence, a lamp in ancient Greece was a small vessel made of stone, clay, metal, oyster shell, or glass. The lamp also included a wick and a liquid or liquefied fuel, such as vegetable oil or rendered animal fat. The wick was mostly made of flax, hemp, or other plant fibers. Lamps were classified into two types based on the position of the wick: spouted lamps and floating-wick lamps[6].

This paper aims to give the first assessment of a multidisciplinary study. It should be noted that the archaeological evidence and any relevant sources are sufficient to reconstruct these diverse aspects of the past if supported by examination, and with the

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[1] AMIN 2017: 73.

[2] A based on Adriani 1966. BOROWIK 2020: 76.

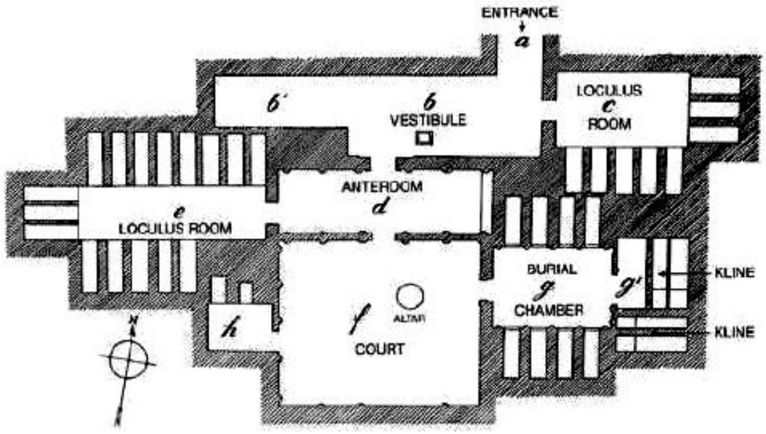
[3] BRECCIA 1912: XXXIV–XL; BRECCIA 1905: 55-106.

[4] RUMMEL & SCHMIDT 2015: 46; RUMMEL & SCHMIDT 2019:1154.

[5] ABD AL-SALAM 1987: 137-145; STRONG 2018 :102-104.

[6] MOULLOU et Al 2012: 238.

help of disciplines that use different methods and approaches, it can significantly improve our understanding to past technologies.



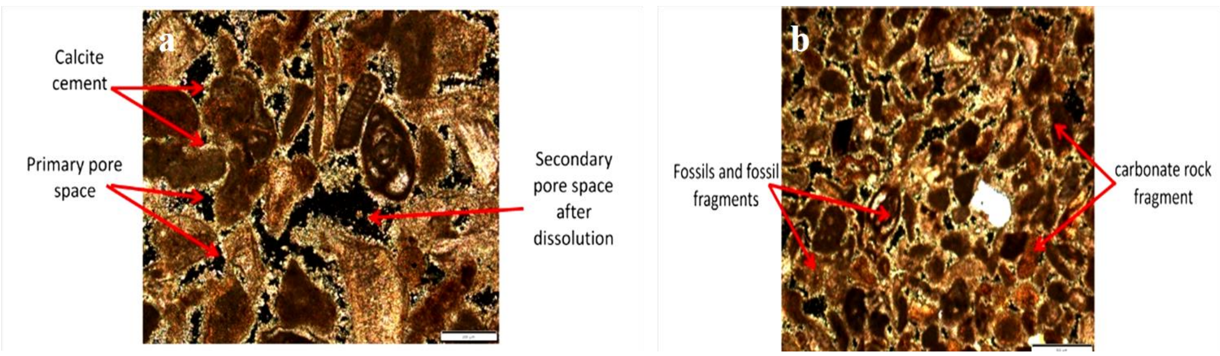
[FIGURE 1]: Shatby Necropolis, plan of Hypogeum.

III. MATERIALS AND METHODS

Mother Rock Investigation

The project examined a sample of the mother rock from which the cemetery chambers were carved, at the Department of Geology, Faculty of Science, Alexandria University. The rock was identified as a type of limestone called calcarenite, which is a sedimentary rock that has a white, creamy color, and is mainly composed of calcite and aragonite minerals ($CaCO_3$). It is composed of well-sorted, well-rounded, fine- to medium-sized carbonate grains, including different fossil fragments. All the grains are cemented together by a low to moderate amount of calcite cement. The rock has high porosity, up to 30% **[FIGURE 2].**

The limestone rocks are mainly composed of calcite and aragonite minerals. These minerals have high susceptibility to dissolution by certain types of groundwater (acidified water). Due to the fact that the groundwater at the site was slightly alkaline (pH 7.1), with the total dissolved solids (TDS) level of 1.7 g/L, it helped to protect the mother rock from erosion while also preserving the finds that were discovered in a good condition, such as oil lamps, wick residues, and pottery vessels.



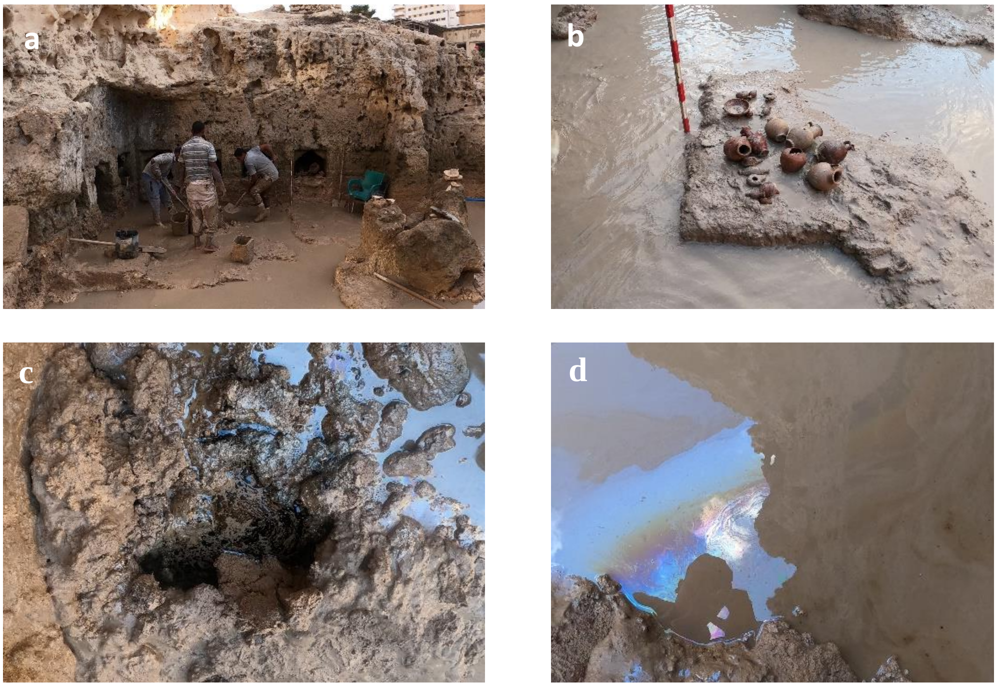
[FIGURE 2]: Photomicrographs of the rock thin section under microscope. A) calcite cement, primary pore space and secondary pore space after dissolution; B) Carbonate rock fragment, fossils and fossil fragments

IV. FUEL SAMPLE GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS) ANALYSIS

The chemical composition of the samples was determined using a Thermo Scientific GC-TSQ mass spectrometer with a direct capillary column TG-5MS (30 m x 0.25 mm x 0.25 m film thickness) (Thermo Scientific, Austin, TX, USA). The temperature of the column oven was initially held at 60°C, then increased by 5°C/min to 250°C withhold 2 minutes, then increased to 300 with 30°C/min. The temperature of the injector was kept constant at 270°C. Helium was used as a carrier gas at a constant flow rate of one milliliter per minute. The solvent delay was 4 min and diluted samples of 1 µl were injected automatically using Autosampler AS3000 coupled with GC in the split mode. EI mass spectra were collected at 70 eV ionization voltages over the range of m/z 50–650 in full scan mode. The temperatures of the ion source and transfer line were set to 200 °C and 280 °C, respectively. The components were identified by comparing their mass spectra to the mass spectral databases WILEY 09 and NIST14[7].

Fuel Sample Preparation

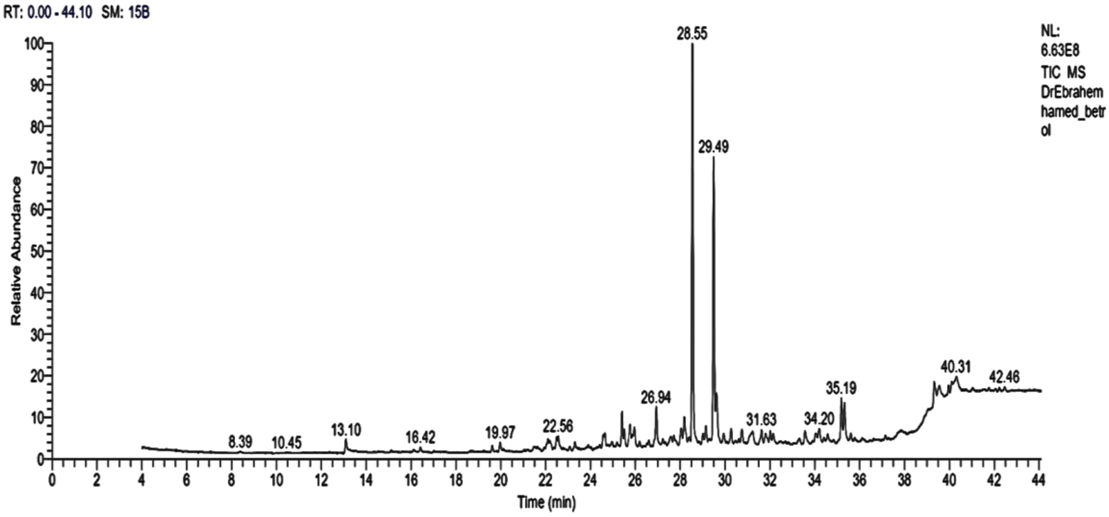
Residues of ignition fuel were found in the southwestern corner of room C, at the right side of the entrance, where they were picked up with absorbent cotton. The raw fuel seemed to be sticky like grease, as soon as it floated on the surface of the water around the room during excavations, until it disintegrated and spread on the surface of the water, giving the colors of the spectrum **[FIGURES 3/ A & D]**



[FIGURE 3]: A)The removal of rubble to reach the level of the rocky floor in room C of hypogeum A; B) Some pottery vessels and oil lamps of various shapes and sizes found in room C; C) The black adipose material floats to the surface in the southwest corner of room C after reaching close to the original bedrock; D) The agglomerations of the black fatty substance, as soon as they float to the surface, disintegrate, giving the colors of the visible spectrum© Taken by the researchers

[7]ABD EL-KAREEM et Al 2016: 14.

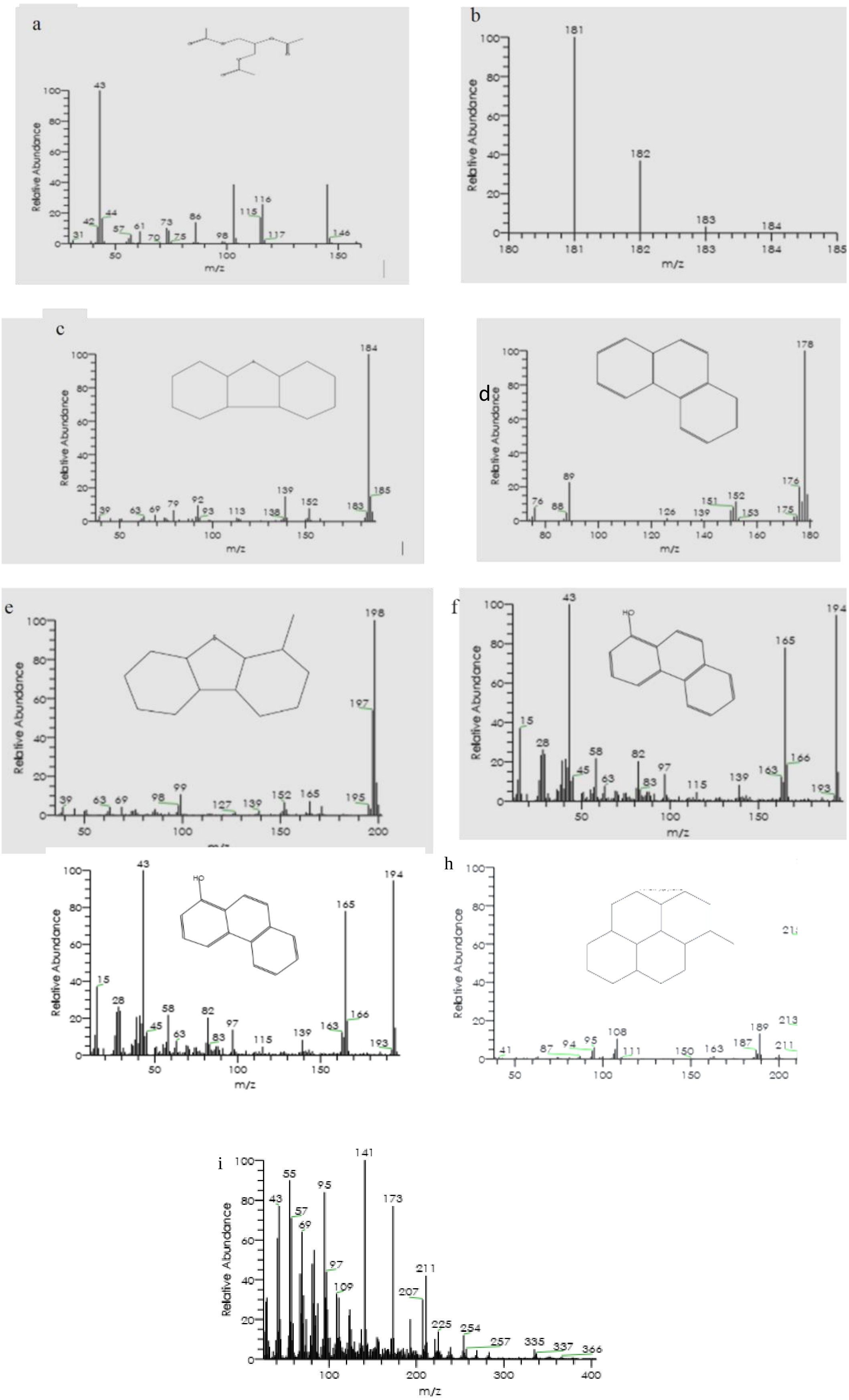
It is noteworthy that samples similar to the collected fuel sample appeared in Philoteknos room in the northeast corner of hypogeum A, to the right of the entrance, also. The sample was dissolved in 50 mL hexane, filtered on filter paper, and transferred to GC-MS **[FIGURE 4].**



[FIGURE 4]: The GCMS chromatogram of the fuel sample © Analyzed by the researchers

Peak Report			
ID	RT	Name of compound	Molecular weight
1	13.09	Triacetin	218
2	19.97	Pyridine	210
3	23.30	Dibenzothiophene	184
4	23.30	Phenanthrene	178
5	24.96	Dibenzothiophene, 4-methyl-	198
6	25.17	1-Phenanthrenol	194
7	28.55	Fluoranthene	202
8	31.63	Pyrene, 1-methyl-	216
9	40.31	Docosanoic acid,8,9,13-trihydroxy-, methyl ester	402

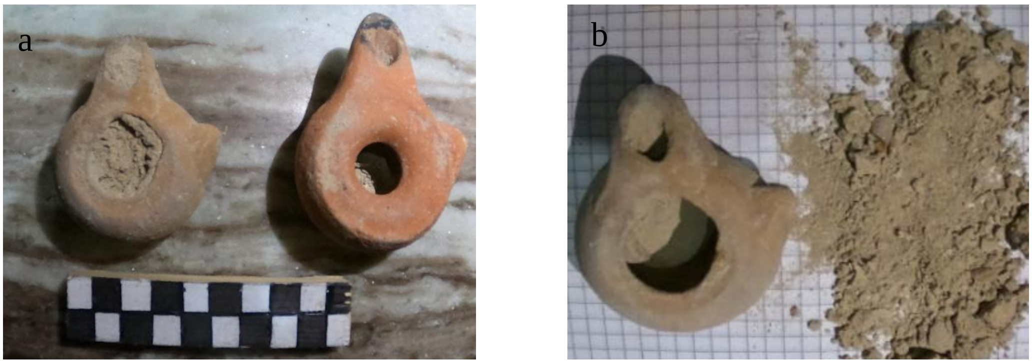
[TABLE 1]: The most important compounds of GCMS chromatogram of the fuel sample ©Done By the researchers



[FIGURE 4]: A)The mass spectrum of Triacetin; B) The mass spectrum of Pyridine; C) The mass spectrum of Dibenzothiophene; D) The mass spectrum of Phenanthrene; E) The mass spectrum of Dibenzothiophene, 4-methyl-; F) The mass spectrum of 1-Phenanthrenol; G)The mass spectrum of Fluoranthene; H) The mass spectrum of Pyrene, 1-methyl-; I) The mass spectrum of Docosanoic acid,8,9,13-trihydroxy-, methyl ester

V. SCANNING ELECTRON MICROSCOPE EXAMINATION

The traces of wick ash that were found in an oil lamp in the same location in room C **[FIGURES 5/ A & B]** were examined with a scanning electron microscope / FEI QUANTA 3D 200 I at the Grand Egyptian museum's laboratory-at 750x magnification. The samples were glued to a sample holder with conductive adhesive and then sputtered with a thin layer of gold for 180 seconds using an Edwards Scan Coat Six device.

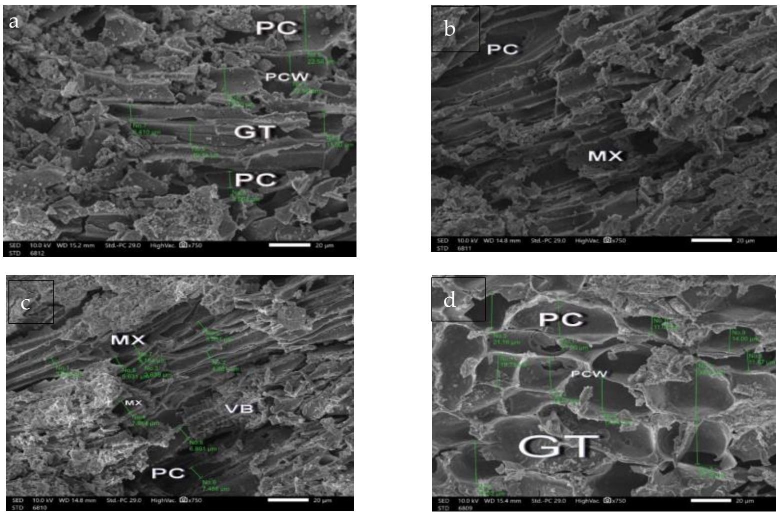


[FIGURE 5]: A) Two oil lamps filled with rubble, one of which was found with the remains of the ashes of the burning wick, as they were discovered among another group in the southwestern corner of room C; B) After drying, the ashes were emptied to find the remains of the burning wick. © Taken by researchers

VI. EXPERIMENTAL METHOD

1. EVIDENCED RESEARCH

Upon the preliminary results of the examination of SEM images obtained, samples of suspected plants with the similar anatomical characters of two *Cyperus* spp., namely, jointed flat sedge *C. articulate* and papyrus *C. papyrus,* were collected for the determination of their specific gravity as well as their anatomical characteristics **[FIGURES 6/ A & D]**.



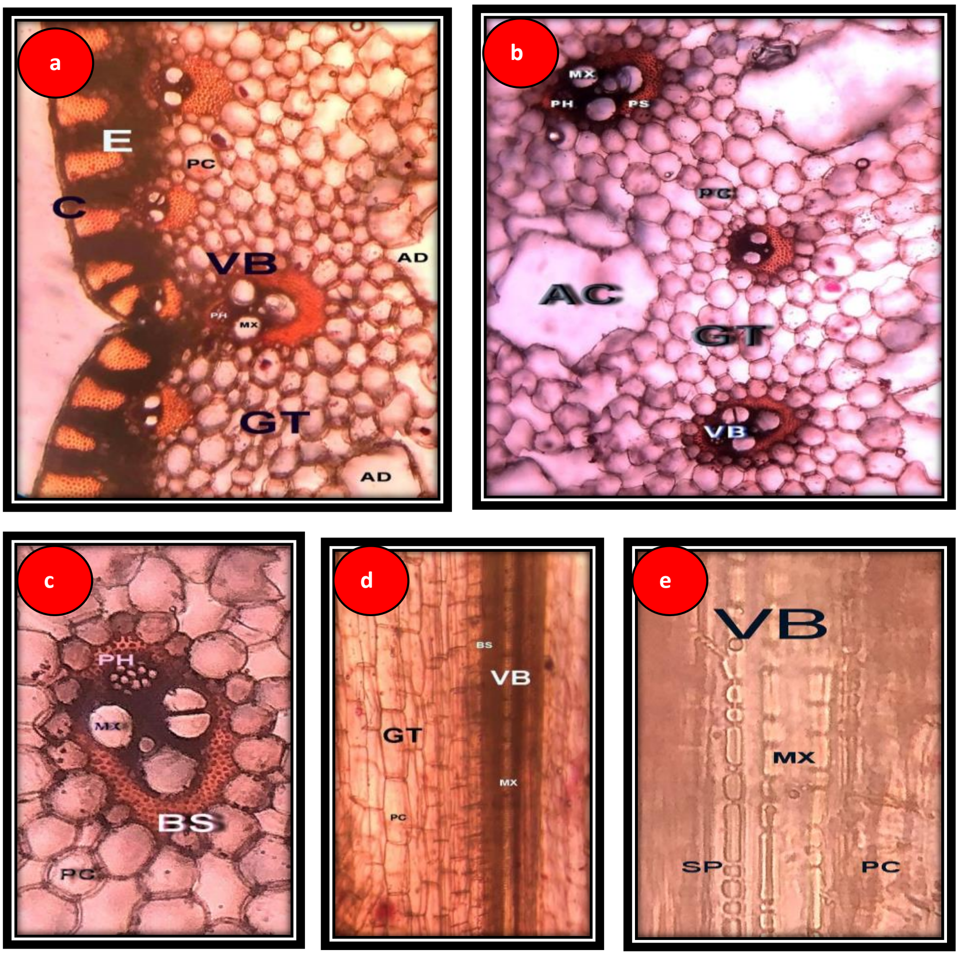
[FIGURE 6]: Scanning electron micrograph of burnt wick obtained from the oil lamp. A) Side (longitudinal) view of an intact plant tissue covered with ash and impurities. MX is the metaxylem of vascular bundle (VB) and PC is the parenchymatous cell of the primary cell wall (PCW) of the ground tissue (GT); B) Intact plant tissue covered with ash and impurities. MX is the metaxylem of vascular bundle (VB) and PC is the parenchymatous cell; C) Intact plant tissue covered with ash and impurities. MX is the metaxylem of vascular bundle (VB) and PC is the parenchymatous cell; D) Transverse view of an intact plant tissue. PC is the parenchymatous cell of the primary cell wall (PCW) of the ground tissue (GT).

2. Determination of Specific Gravity

Samples of culms of *C. articulate* and *C. papyrus* were cut into 3-cm-long segments to determine the specific gravity according to the method described by Smith [1954]. Five replicates were used in a complete randomized design, and the data obtained were statistically analyzed[8].

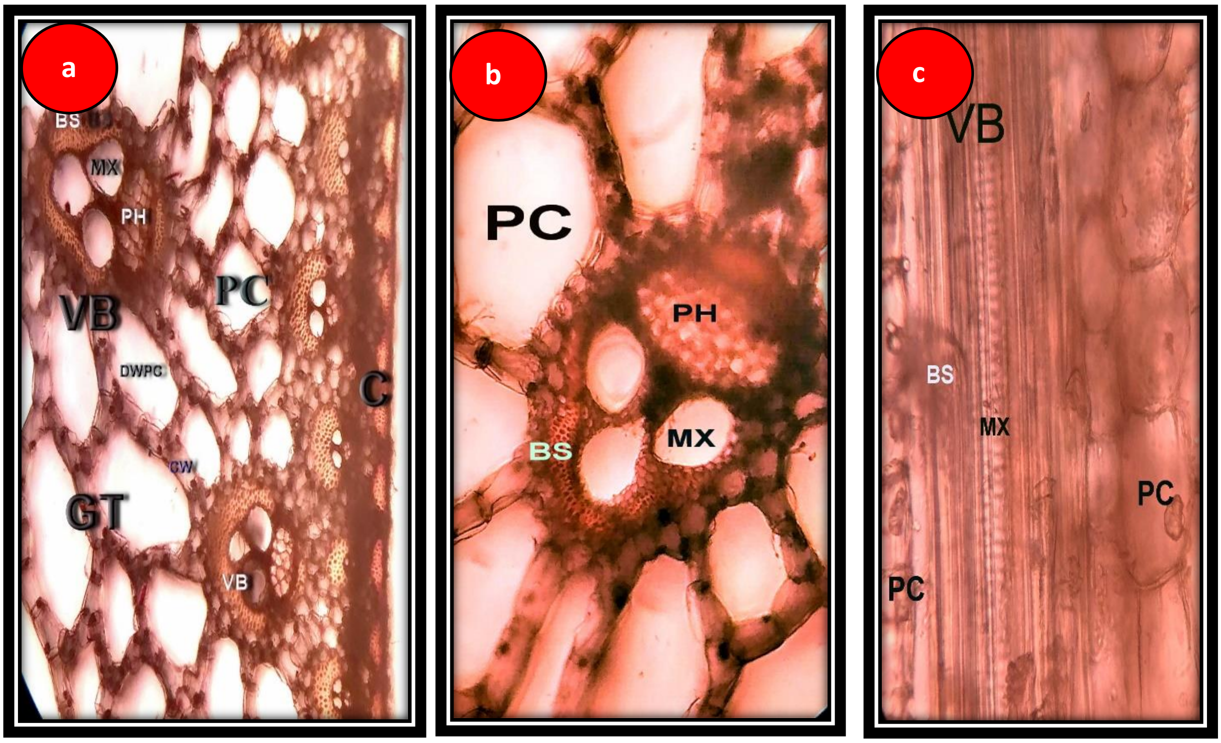
3. Anatomical Studies

Green samples of culms of *C. articulate* and *C. papyrus* were cut into 2-cm-long segments, softened in hot water, then transverse and longitudinal hand sections were taken, stained with safranin stain, rinsed in distilled water, and eventually fixed in slides with glycerin for microscopy examination **[FIGURES 7/ A & D] & [FIGURES 8/ A & C].**



[FIGURE 7]: *Cyperus articulatus*: A) Transverse section (TS) of *Cyperus* sp culm shows the scattered vasular bundles with ground tissue of thin (single) walled parenchymatous cells and noticeable longitudinal air duct (AD); B) TS of *Cyperus* sp culm indicats the thin-walled paranchymatous cells of the ground tissue, vascular bundles and longitudinal air channel (AC); C) vascular bundle composed of metaxylem, phloem and bundle sheath; D) longitudinal section (LS) of *Cyperus* sp culm shows vascular bundle and groud tissue ; E) LS of *Cyperus* sp culm shows metaxylem member and simple pits (SP) of its wall. C is the cuticle, E is the epiderms, GT is the ground tissue, PC is parenchymatous cells, BS is the bundle sheath, VB is vascular bundle, MX is the metaxylem, PH is the phloem tissue, AD is the longitudinal air duct or air channel (AC).

[8] SMITH 1954: 2.



[FIGURE 8]: *Cyperus papyrus*: A) Transverse section (TS) of *Cyperus* sp culm showing the scattered vasular bundles with ground tissue of thick- (double) walled parenchymatous cells; B) TS of *Cyperus* sp culm indicats double-walled paranchymatous cells of the ground tissue, vascular bundle composed of metaxylem, phloem and bundle sheath; C)longitudinal section (LS) of *Cyperus* sp culm shows vascular bundle and metaxylem of scalariform pitting and ground tissue of parenchymatous cells.

C is the cuticle, CW is the cell wall, GT is the ground tissue, PC is parenchymatous cells, VB is vascular bundle, BS is the bundle sheath, MX is the metaxylem, PH is the phloem tissue and DWPC is the double-walled parenchymatous cell.

4. Anatomical Studies

The preliminary scanning electron microscopy examination indicated that the wick is just an intact tissue of a plant that belongs to the monocot plants, since the ground tissue of single-walled parenchymatous cells was detected in addition to vascular bundles **[FIGURE 6].**

5. Specific Gravity (SG)

On the basis of the data obtained regarding the specific gravity (SG) of culms, it was found that the SG was 0.128 and 0.197 for the culms of *Cyperus articulate* and *C. papyrus*, respectively.

VII. CONCLUSION

By analyzing the fuel sample, it was found that it was composed of crude oil compounds (TABLE (1) AND **[FIGURE 4/A & I]**. It is of no surprise that crude oil and bitumen derivatives were used in this era; since an increase in bitumen use was apparent during the Third Intermediate Period, where it reached the peak of use in Ptolemaic and Roman times on mummy balms[9]. Bitumen and crude oil were both utilized for lighting in ancient times. For instance, bitumen-soaked rushes were used to make torches in ancient Babylon, and during the Roman era in Sicily, liquid asphalt was used in lamps in place of olive oil[10]. Triacetin [$C_9H_{14}O_6$], a triester of glycerol acetic acid, could be used as an additive to biofuel. A byproduct of the manufacture of biodiesel is glycerol. Triacetin boosts the density and viscosity of the blend, according to a recent study on the substance's effects. However, the blend's octane number, heating value, and flash point decreased[11].

Pyridine has the chemical formula C_5H_5N and a benzene-like structure. It is a weakly basic, transparent «yellowish», water-soluble heterocyclic aromatic compound with a distinct and unpleasant odor. Many of the different substituted pyridines exhibit similar properties[12].

Naphthalene, fluorene, phenanthrene, dibenzothiophene, and their alkylated isomers, as well as anthracene, fluoranthene, benzopyrenes, and aromatic steranes, are examples of aromatic hydrocarbons found in crude oil[13].

The oil lamp was the most effective type of lighting in the ancient societies. Oils used as fuel included olive, bituminous oils like petroleum, and vegetable oils[14]. The crude oil stains during the removal of the debris from the southwestern corner of Room C floated on the water in the form of small black lumps, and as soon as they stopped flowing, they spread on the surface of the water, giving the colors of the rainbow **[FIGURE 2/ B & D]**. A type of slick appearance illustrated in rainbow sheens have different physical origins than other thickness-appearance relationships, according to research. Hornstein investigated various slick phenomena and came to the conclusion that the rainbow sheen was caused by constructive and destructive interference between light reflected from the oil surface and that reflected from the water surface. This is a one-of-a-kind indicator of oil thickness[15].

The wick's remnants lack the smooth surface with dislocations, polygonal cross section, and other traits of bast fibers like flax or jute. Instead, the wick is still visible by SEM with a surface that resembles parenchymal tissue and sporadic vascular tissue. The fibers might be remnants of unprocessed plant stems because they do not seem to have been altered. The fiber of plants in the rush family (Juncaceae) appears to be the closest comparison yet discovered, because they exhibit highly comparable features **[FIGURE 6]**.

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[9] CLARK et Al 2016: 2.
[10] FORBES 1936: 79.
[11] ZARE et Al 2015: 1.
[12] SILVAA et Al 2021: 1.
[13] ONYEMA & OSUJI 2015: 526.
[14] PETERSON 2013: 98.
[15] FINGAS 2021: 6.

Lamp wicks, however, might be reportedly and frequently manufactured in antiquity from plant crude fibers including flax, hemp, common rush (*Juncus effusus* L.), papyrus, or mineral asbestos, according to ancient authors. Pliny the Elder makes a point of stating that the rush pith is used for this purpose[16].

Cyperus is a large genus with about 600 species that is found all over the world. Cyprus spp. has three taxa (*Cyperus alopecuroides, C. articulates and C. papyrus*) are naturally growing on the Nile delta canal banks in Egypt[17].

Light microscopy examination of the culms of *Cyperus articulate* and *C. papyrus* **[FIGURES 6-7]**, which belong to monocot plants, revealed that the former species (*C. articulate)* is closer to that recognized in the wick examined by SEM, notably its single-walled parenchymatous cells of the ground tissue that distinguish it, compared with that manifested in *C. papyrus*, are characterized with double-walled parenchymatous cells.

It is concluded, however, to a great extent, that the wick used for the lamp was taken from the culm of *Cyperus articulate,* which has a lower specific gravity (0.128), which enables the diffusion and flow of the fuel through its vascular bundles and air channels easily; also, SEM micrographs of C. articulate show its cell shape, concave periclinal walls, and indistinct silica bodies[18]. Additionally, *C. papyrus* has significantly reduced vascular tissue[19].

VIII. ACKNOWLEDGEMENT

The researchers would like to thank **Prof./ Mona Haggag**, President of the Alexandria Antiquities Society and Director of the restoration project, development, and protection of the archaeological cemetery of Shatby. The primary researcher is also a member and is in charge of the restoration project.

[16] BASSO & GLEBA 2016: 354.

[17] EL-AMIER & ABD EL-GAWAD 2017: 294-299.

[18] SHALABI & GAZER 2015: 2339-2346.

[19] AMINI RAD & SONBOLI 2008: 8.

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