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An Archaeometric Approach to Reveal Organic Compounds via GC-MS Analyses of Two Discovered Incense Burners at Daba Al-Bayah

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ABSTRACT

This study focuses on two terracotta incense burners discovered in the Daba Al-Bayah necropolis in the Musandam Peninsula (Oman), associated with an Iron Age collective tomb (LCG-2). Through gas chromatography–mass spectrometry (GC-MS), the organic residues preserved within these artifacts were analyzed to investigate their use and environmental context. The unveiling results revealed a combination of fatty acids and plant-derived sugars, confirming the use of these vessels for burning aromatic substances, likely derived from resins or plant materials present in the area at the time. These findings shed light on ritual practices in the Iron Age Arabian Peninsula and provide new insights on the paleoenvironmental context and ancient trade networks.

1 | Introduction

1.1 | The Context of Discovery: Daba Al-Bayah Necropolis (Musandam, Oman)

Recent infrastructural initiatives within the Sultanate of Oman have facilitated the identification of multiple archaeological sites distributed across various regions of the country. Notably, excavation activities associated with the construction of the Daba Al-Bayah Sports Club, located in the Musandam Peninsula, have revealed an extensive funerary complex predominantly composed of collective burial structures. This site comprises two principal Long Collective Graves (designated LCG-1 and LCG-2), alongside several ritual pits attributed to the Early Iron Age, as well as a subsequent Parthian-period grave.

Distinct from other sites in the region, the collective tombs at Daba exhibit exceptional preservation and minimal postdepositional disturbance. Furthermore, preliminary data from a geophysical prospection suggest the existence of at least two additional burial structures analogous in morphology and scale to LCG-1 and LCG-2 (Genchi 2020). The cumulative archaeological evidence implies that this locale functioned as a monumental funerary landscape commemorating tribal alliances, chronologically spanning from the late 2nd to the conclusion of the 1st millennium BCE. Given its strategic geographical setting, Daba likely played a pivotal role in interregional exchange networks, potentially serving as a maritime hub through which extraregional goods were conveyed inland and to the western littoral.

LCG-2 constitutes a substantial, rectilinear above-ground tomb, measuring approximately 23 m in length and 4.5 m in width. The primary funerary chamber is partially subterranean, aligned along a north–south axis. The chamber walls comprise a minimum of five to six courses of stone masonry, extending to roughly 1 m above the present ground surface. The basal course consists of sizeable, regularly hewn stone blocks positioned vertically. On the eastern flank of the tomb—where preservation is particularly robust—the wall thickness reaches up to 2.10 m. Superstructural elements were constructed utilizing stone, mudbrick, and mortar, subsequently finished with a plaster coating, often employing a composite construction technique.

In the southeastern sector of the structure, the presence of plaster fragments may indicate the original inclusion of architectural elements composed of perishable materials. A rectangular ingress, situated along the eastern perimeter wall, measures 0.98 by 0.78 m, with a depth of 0.6 m. This entrance is framed by stone slabs on all sides and includes both a lintel and a doorstep. A short passageway, integrated within the wall, provides access to the internal chamber. This entryway was externally sealed using two large stone slabs—likely introduced during a modification phase in which the entrance corridor was repurposed as an extended burial space, reoriented along an east–west axis. An external rectangular enclosure, delineated by long stone slabs, demarcates an area surrounding the main entrance, which in a subsequent phase was also reutilized for interments (Genchi et al. 2022).

In the final structural phase of the tomb, the perimeter walls ceased to serve solely as boundary elements and were repurposed to accommodate additional interments, including primary burials in pits or niches formed by dismantling sections of the masonry. At least four subcircular burial chambers were integrated into the walls, some containing multiple individuals. Additional compartments were created by subdividing the elongated central chamber.

The original roofing likely consisted of flat stone slabs over corbelled walls. Some slabs were found collapsed within the tomb, whereas others may have been removed during later modifications or looting. The area surrounding the structure was also reused, with smaller stone or mudbrick features sealing burial pits, as well as clusters of human remains and grave goods—evidence of prolonged ritual activity, even after the main chamber became inaccessible.

Stratigraphic analysis revealed several phases of use, including architectural modifications and the creation of additional burial chambers (Genchi 2015). Radiocarbon dating places initial construction in Iron Age II (1016–916 BCE; 1130–1014 BCE), supported by diagnostic pottery, stone vessels, and metal artifacts. Later reuses occurred during the transition from Early to Late Iron Age (356–278 BCE; 328–198 BCE). The final use corresponds to the P.I.R. phase (first century BCE to fourth century CE), marked by a richly furnished burial along the western perimeter wall (277–338 CE; 54 BCE to 120 CE).

Six excavation campaigns have nearly fully documented the tomb, revealing at least three major phases. The final phase includes clusters of secondary or disturbed burials, followed by circular burial chambers along the perimeter. The earliest phase consists of internal stone structures used for multiple interments before the collapse of the outer walls.

One notable phase involved constructing small burial compartments along the eastern wall, sealed with stone slabs and containing overlapping interments. Simple pit burials using reused slabs were also identified.

Two incense burners recovered at the base of the LCG-2 corridor are of particular interest. One is associated with Burial 84, a richly adorned female individual accompanied by a bronze cauldron, mirror, and a terracotta incense burner featuring oryx imagery—an exceptional find and the first of its kind with such decoration. Second, the unassociated incense burner features geometric motifs and a perforated lid. Both contain combustion residues, sampled for further analysis, and represent the smallest incense burners known from the southeastern Arabian Peninsula.

1.2 | The Discovery of the First Essence Burners and the South-Arabian Incense Trade Routes

The term *incense burner* has been broadly applied to a range of Near Eastern artifacts, often without definitive evidence of their specific function (Oates 1974; Lapp 1975). An exception lies in certain Islamic-period cuboid earthenware examples inscribed with the names of aromatic substances and the plants from which they derive.

The Arabian Peninsula, historically referred to as *Arabia Felix*, has long been associated with the trade of aromatic resins, particularly frankincense and myrrh—products of *Boswellia* and *Commiphora* trees of the Burseraceae family. These resins became emblematic of Arabia, especially during the Hellenistic period, when their trade westward intensified. This prominence has led to the prevailing assumption that pre-Hellenistic Arabian trade centered chiefly on frankincense. This chapter explores the development of frankincense commerce through the material lens of the cuboid incense burner, a standard vessel for burning aromatics on the Arabian Peninsula since the late third millennium BCE.

Cuboid incense burners have been recovered across the Middle East, reflecting a wide-reaching network of aromatic trade extending from Arabia to the Mediterranean and East Asia. Although similar objects have been found in the Levant and Mesopotamia, the primary routes for incense trade originated in Arabia, reinforcing the cultural and economic significance of these vessels.

Excavations at Ra's al-Jinz, a coastal settlement in Oman, uncovered sandstone incense burners resembling those still used in the region today. Cleuziou and Tosi's analysis of these artifacts revealed three main findings: First, the burners were common domestic tools, indicating everyday use of incense; second, internal residues—burned layers and signs of reuse—confirmed their function; and third, the continuity in form between Bronze Age and modern burners underscores their cultural persistence.

By 2300 BCE, as trade with Mesopotamia expanded, Magan (modern Oman and the UAE) began producing incense burners. Ra's al-Jinz emerged as a key trade node, evidenced by the presence of Harappan ceramics linking it to the Indus Valley. The rectangular four-legged incense burner found there is the earliest of its kind in Arabia, discovered in a sealed archaeological context beneath collapsed architectural debris. Additional fragments of similar burners were found in earlier seasons. These artifacts were undecorated, utilitarian, and bore residues identified as *Boswellia sacra*, likely sourced from Dhofar—the principal region for frankincense harvesting.

Following the discovery at Ra's al-Jinz, over 200 cuboid incense burners—primarily ceramic—have been documented across the Near East. These artifacts reflect a wide-ranging aromatic trade network extending from major Mesopotamian cities such as Ur, Nippur, and Babylon (during the late Neo-Babylonian and Achaemenid periods) to northern Euphrates settlements dating as far back as the Middle Bronze Age. Significant concentrations of these burners were found in domestic contexts at Uruk (ca. 50), Nippur (37), and Ur (31), suggesting the common use of aromatics in daily life and highlighting Arabia's far-reaching cultural influence. Their distribution, particularly along Upper Euphrates trade routes, indicates the existence of both overland and maritime networks for the efficient transport of incense prior to the widespread domestication of the dromedary.

The expansion of South Arabian trade reached its zenith in the first millennium BCE, coinciding with the use of dromedaries for long-distance caravans. This growth was propelled by three major economic transformations in the pre-Islamic Near East. The first occurred during the reign of Babylonian king Nabonidus (ca. 556 BCE) in Tayma, when trade between southern Arabia and the Neo-Babylonian Empire intensified.

This commercial rise was also supported by the emergence of four powerful kingdoms in southern Arabia—Sabaean, Minaean, Qatabanian, and Hadramitic—each named for its distinct script and centered in or near the Hadramawt region (modern Yemen). These states, flourishing from the early to mid–first millennium BCE, derived wealth from taxing and facilitating camel caravans along incense trade routes. Their prosperity and growing urban complexity helped define the cultural identity of *Arabia Felix*.

These kingdoms were strategically positioned along land routes that connected incense-producing regions to markets in the Levant and Mediterranean. The main caravan trail began at the port of Qana, passed through Shabwa (capital of Hadramawt), Timna (Qataban), Marib (Saba'), and Ma'in (Minaean kingdom) before reaching Tayma in northern Arabia and ultimately the Levant. During the Mukarrib period (eight century BCE), the Sabaean kingdom reached its peak influence, whereas Hadramawt became a major center for incense distribution. By the third century BCE, merchants from Shabwa had established a colony at Sumhuram (Khor Rori, Dhofar), exporting frankincense under Roman oversight.

2 | Material and Methods

2.1 | Incense Burners

The two incense burners at the center of our study come from the grave goods that accompanied two burials found at the bottom of the corridor-shaped burial chamber of tomb LCG-2.

The residues inside the small incense burners were limited to a thin layer of just over 2 mm of dark gray color with whitish shades. The sampling of the residues inside the small basin was carried out using a sterile scalpel, handled with latex gloves, to remove, by delicately scraping, a few grams of the substance that appeared very concretioned inside. The residue was then stored inside small hermetically sealed test tubes and further covered with paper tape.

The first (DA 53699) (Figure 1), was found among the grave goods of Burial 84. It is a primary deposition of a 20- to 30-year-old female individual in left lateral position. The burial is located at the center of LCG2, south of the entrance hall. The individual is oriented NS, facing E. The upper limbs were hyper flexed. The lower limbs were flexed. Several grave goods were recovered: a copper bronze mirror placed near the hands, a copper bronze razor near the right humerus, a beads bracelet on the right wrist and another one on the left wrist, a copper bronze ring on the right hand, a copper bronze ring and an iron ring on the left hand, a beads necklace, a soapstone vessel, a copper bronze vessel, and a cauldron placed above the lower limbs.

This is an earthenware container of rectangular shape (dimensions: 7.2 length × 5.4 width × 4.5 height) presumably used as an essence burner, given the widespread use of incense in the region. The long sides of the container feature an incised decoration bearing the outline of an oryx, whereas the short sides show a quadripartite panel with horizontal bands composed of quadrants filled with vertical strokes alternating with others plain. The rim is decorated with a band bearing a herringbone motif. The container must have had a lid with a central hole, as shown by the other specimen. The inner surface showed traces of burning organic material from which sampling was carried out by scraping the residue with a sterile spatula. The contents were stored in a sterile test tube.

The second object (DA 53698) (Figure 2), was found to be a short distance from the previous one, not in direct association with a burial. However, it is likely to have been part of the grave goods of one of the burials at the end of the corridor. It is a rectangular earthenware container (dimensions: 6.8 length × 5.1width × 4.3 height) presumably used for the same function as the previous one. Both the long and short sides have a geometric decoration consisting of a bipartite motif with a series of triangular motifs alternating with horizontal parallel lines. In addition, the rim is decorated with a band bearing a herringbone motif. The container has a lid with a central hole. The inner surface showed traces of combustion of organic material from which the sampling was made.

Organic molecules of plant and animal origin are adsorbed to ceramic walls and can persist for a long time as adsorbed during the storage and/or processing of food products (Evershed 2008). The detection and identification of molecules trapped in ceramic, incense burners or other residues are crucial to better understand the uses of specific objects as well as dietary habits and secondary activities over a given period. In order to detect residual organic compounds inside the censers, we used GC-MS (gas chromatography–mass spectrometry) analysis, which is one of the standard methods in organic residue analysis (Reber, EA., 2022) thanks to its high sensitivity in detecting trace compounds.

FIGURE 1 | DA 53699.

FIGURE 2 | DA 53698.

2.2 | Fatty Acid Analysis by GC-MS

The fatty acid content of the samples was determined by GC-MS technique after lipid extraction and transmethylation. Powder samples (about 200 mg) were transferred to a 2-mL vial, and 1 mL of a 2:1 mixture of chloroform:methanol was added. The mixture was manually agitated for 5 min and sonicated for 15–20 min (Eerkens 2005). The solvent mixture was separated by centrifugation, transferred to a clean 2-mL vial, and gently evaporated under vacuum.

The transmethylation occurred with the addition of BF_3-methanol solution by heating at 70°C for approximately 20 min. The extraction of the fatty acid methyl esters (FAMEs) was performed with the addition of n-hexane. The analyses were performed by using a gas chromatograph coupled with a mass spectrometer Clarus 500 model Perkin Elmer (Waltham, MA, United States), equipped with a FID (flame ionization detector). Two microliters of each sample were injected into the column (Varian Factor Four VF-5) in splitless mode. The applied conditions of GC were the following: The injector was set to 280°C, and the oven temperature was programmed from 170°C with the rate of 3°C/min to 260°C for 15 min. The mass spectrometer was operated at 70 eV (EI) in full scan mode in the range 40–550 m/z. The ion source and the connection parts temperature were set at 180°C and 200°C, respectively. To identify the compounds, the MS-fragmentation pattern obtained was compared with those of pure components stored in the NIST11 mass spectra library database. Further, the linear retention indices (LRIs) were calculated using a mixture of *n*-alkanes (C_8–C_{30} aliphatic hydrocarbons) injected into the column under the same operating conditions and compared with those available in the literature. The relative amounts of the components were expressed as a percentage of the FID (flame ionization detector) signal peak area to the total peak area, without the use of an internal standard and any factor correction. All analyses were carried out in triplicate.

2.3 | GC-MS Analysis of Trimethylsilyl Derivatives

To describe the chemical content of solid residues, about 0.5 mg of both samples was added of 150 μL of pyridine and 50 μL of bis-(trimethylsilyl) trifluoroacetamide (BSTFA) with heating at 70°C for 1 h; 1 μL of the silylated samples was manually injected at 270°C into the GC injector in the splitless mode. The oven temperature program was as follows: 70°C, then a gradient of 6°C/min to 170°C for 1.0 min, and a gradient of 8°C/min to 250°C for 30 min. Mass spectra were acquired in an electron ionization mode. The identification of compounds was based on the percentage of similarity plus comparison of mass spectra (MS) with the percentage of total ion chromatograms (TIC%) using software NIST data library. Relative percentages for quantification of the components were calculated by electronic integration of the GC-FID peak areas, and no response factors were calculated. The analyses were carried out in duplicate.

3 | Results and Discussion

3.1 | Fatty Acids Content

The GC-MS analysis highlighted the presence of three fatty acids such as palmitic, oleic, and stearic acid (Table 1). Both samples showed palmitic acid as the major component followed by stearic and oleic acids. Although saturated fatty acids (C16:0 and C18:0) have been defined as specific biomarkers of plant oils (Charters et al. 1995), due to the strong similarity of the compositional profile of the various oils, it is quite difficult to distinguish the source of the oils. However, the survival of lipids in association with many archaeological materials is widely documented (Evershed 1993).

TABLE 1 | FAs content (percentage mean value ± standard deviation) of the solid residues, as determined by GC-MS.

No.	Component[a]	LRI[b]	LRI[c]	DA53698	DA53699
2	Palmitic acid, C16:0	1970	1973	47.6 ± 4.1	51.7 ± 3.3
4	Oleic acid, C18:1*n*9	2166	2152	21.2 ± 1.4	19.8 ± 1.7
5	Stearic acid, C18:1*n*9	2140	2178	31.2 ± 2.6	28.5 ± 2.8
	SUM			100.0	100.0
	Saturated FAs			47.6	51.7
	Unsaturated FAs			52.4	48.3

[a]The components are reported according to their elution order on apolar column (VF-5 ms).
[b]Linear retention indices measured on apolar column.
[c]Linear retention indices from literature; data are means ± standard deviation of three ($n = 3$) replicates.

TABLE 2 | Metabolites identified (percentage mean values ± SD) in the solid residues after derivatization as determined by GC-MS.

No.	Component	DA53698	DA53699
Carbohydrates			
1	Glycerol	4.7 ± 0.03	12.3 ± 0.09
2	D-fructose	4.1 ± 0.04	4.6 ± 0.05
3	D-glucitol	8.4 ± 0.05	10.0 ± 0.08
4	D-psicofuranose	17.0 ± 0.07	18.9 ± 0.11
5	D-tagatofuranose	7.9 ± 0.04	Tr
6	D-glucose	21.3 ± 0.10	23.6 ± 0.10
7	D-mannitol	11.3 ± 0.06	12.5 ± 0.08
8	D-talopyranose	20.8 ± 0.12	13.2 ± 0.22
Carboxylic acids			
9	Fumaric acid	2.3 ± 0.04	2.5 ± 0.04
Others			
10	Hydroquinone	2.2 ± 0.03	2.4 ± 0.03
	SUM	100.0	100.0

Abbreviation: Tr, percentage mean values ≤0.1%.

The analysis conducted on the silylated extracts from solid residues allowed the detection and identification mainly of sugars (Table 2). The carbohydrate profile was almost superimposable between the two samples, except for D-tagatofuranose, which was detected only in trace amounts in 2408 sample.

The biomass combustion process, through a series of intermediate phases such as hydrolization, oxidation, and pyrolization, leads to the formation of important classes of sugars, which are therefore specific to the source (Roberts 1970). Biogenic sources of monosaccharides mainly include microorganisms, plants, and soil; for example, glucose is considered a marker for plant materials (such as leaves and pollen) (Otto and Simpson 2007). Furthermore, sugar alcohols were found in significant concentrations in leaf burning samples (Schmidl et al. 2008).

4 | Conclusion

The GC-MS analyses conducted on organic residues preserved within the two terracotta incense burners from the necropolis of Daba Al-Bayah provide compelling evidence for their functional use in the combustion of aromatic substances, likely in the context of ritual practices associated with Iron Age funerary customs. The identification of key lipid biomarkers, as palmitic, oleic, and stearic acids, together with pyrolysis-derived sugars and polyols such as glucose, mannitol, and glucitol, strongly suggests the deliberate burning of plant-based materials, including resins, foliage, and woody tissues. These data not only substantiate the interpretation of the artifacts as incense burners but also allow for a partial reconstruction of the paleoenvironment in which they were used.

The molecular profile indicates the exploitation of aromatic flora, potentially including frankincense, myrrh, and other xerophytic species such as Acacia, Tamarix, and Ziziphus, which are consistent with a semiarid ecological setting. At the same time, the presence of traces of imported resins underscores the participation of the area in broader exchange systems. The typological characteristics of the burners, their association with a prestigious burial assemblage, and close parallels with contemporaneous artifacts distributed across southern Arabia and Mesopotamia collectively support their integration within long-distance trade networks. These routes linked incense-producing regions, particularly Dhofar and Hadramawt, with major cultural hubs in the Levant, Mesopotamia, and the Mediterranean.

Long-distance exchange and cross-cultural interaction were fundamental to the socioeconomic and cultural evolution of prehistoric South-Eastern Arabia (Frenez 2019).

Geochemical data and Sumero-Akkadian cuneiform sources identify the Oman Peninsula as a major copper supplier from at least the late fourth millennium BC (Begemann et al. 2010; Laursen and Steinkeller 2017). Although copper exploitation began in the Late Neolithic, large-scale production developed during the Hafit period (ca. 3100–2700 BC), a phase marked by major transformations including the emergence of oasis agriculture (Charbonnier 2017), collective cairn-based funerary practices (Bortolini and Munoz 2015, 65–67), and the construction of large stone platforms or “towers,” whose functions remain uncertain (Döpper and Schmidt 2017). Socioeconomic complexity intensified during the Umm an-Nar period (ca. 2700–2000 BC), characterized by expanded sedentary settlement, increasingly elaborate funerary architecture, widespread tower construction, and sustained, diversified intercultural exchange (Frenez 2019, 12–29).

The tombs of Daba have produced a range of objects originating in the Near and Middle East that may be classified as high-value grave goods, including seals, amulets, and personal ornaments. Detailed assessment of these artifacts—drawing on iconographic evidence, production characteristics (such as raw materials and forms), and relevant ancient textual sources—allows interpretation of exchange practices beyond their purely economic or esthetic dimensions. The assemblage of high-value imported objects recovered from tomb LCG-1 at Dibbā al-Bayah indicates an exceptionally affluent and influential community integrated into exchange networks connecting Kassite and Elamite cultural spheres across the Gulf. The probable contemporaneity of these artifacts with the use of the tomb, together with the selective appropriation of specific objects and iconographies and the local production of forms inspired by exotic models, points to relatively direct cross-cultural interactions rather than prolonged, down-the-line exchange (Frenez et al. 2020).

The “incense road” has long symbolized the Arabian Peninsulas cultural interconnectedness with neighboring regions.

These trade routes facilitated the movement of aromatics and other goods across vast deserts, enabling settlements and oases along their paths to flourish as dynamic centers of exchange (Macdonald 1997; le Maguer 2016; Zimmerle 2021). Owing to the economic importance of such commodities, studies of the incense trade have often focused on textual sources from classical antiquity. A landmark contribution is the 1997 publication Profumi d'Arabia, edited by Alessandra Avanzini, which provides an interdisciplinary analysis of premodern sources encompassing itineraries, texts, vocabulary, anthropological data, and archaeological evidence. Despite the breadth of this research, commerce-related studies remain the most numerous and prominent within the volume (Avanzini 1997, 18).

In this light, incense burners from Daba Al-Bayah are not simply ritual objects but also serve as material indicators of the multiple cultural, economic, and environmental interactions that shaped Bronze and Iron Age societies in the Arabian Peninsula.

Author Contributions

Conceptualization: Stefania Garzoli. Methodology: Vittorio Vinciguerra and Stefania Garzoli. Formal analysis: Vittorio Vinciguerra and Stefania Garzoli. Investigation: Francesco Genchi and Stefania Garzoli. Resources: Francesco Genchi. Data curation: Francesco Genchi, Federica Spagnoli, Vittorio Vinciguerra, and Stefania Garzoli. Writing – original draft preparation: Francesco Genchi, Federica Spagnoli, and Stefania Garzoli. Writing – review and editing: Francesco Genchi, Federica Spagnoli, Vittorio Vinciguerra, and Stefania Garzoli. Supervision: Francesco Genchi and Stefania Garzoli. Project administration: Stefania Garzoli. Funding acquisition: Francesco Genchi and Stefania Garzoli. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data that support the findings are available in the article.

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