Journal of Archaeological Science 190 (2026) 106572

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: www.elsevier.com/locate/jas

Life histories of the dolia of Ostia: Insights into storage, use, and reinforcement in Rome's port city

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ARTICLE INFO

Keywords:
Dolia
Ostia
Garum (fish sauce)
Metals
Lead
Reinforcement
GC-MS and ICP-MS

ABSTRACT

Ostia, the port city of ancient Rome, played an important role in Rome's maritime commerce. The ancient port city was outfitted with massive warehouses that stored various foods necessary to supply not only the imperial capital, but also the workers living and working in Ostia. Some of these warehouses featured large ceramic storage jars known as dolia (singular dolium) that could hold over one thousand liters. Although the massive jars were useful and expensive, they cracked and were damaged easily. To extend their use, dolia were strengthened using metal, primarily lead, sometimes mixed with other metals. This paper is the first study that presents scientific evidence for the Ostian dolia's contents and reinforcements to shed light on these vessels' use and life histories in antiquity. Using gas chromatography-mass spectrometry (GC-MS) to study residues collected from eight dolia and inductively coupled plasma-mass spectrometry (ICP-MS) to study samples collected from metal additions found on four dolia from the three storerooms that are still accessible, we present evidence for how dolia of Ostia were used and maintained. Vessels were lined with pine resin and held degraded proteinaceous material, perhaps garum, at some stage during their use. They were also reinforced with lead and alloyed with other metals such as silver and tin. Compared to other dolium repairs and reinforcements, craftsmen were able to strengthen the dolia using additional, often more valuable, metals.

1. Introduction

The port city of Ostia served a vital role in Rome's economic development (Meiggs, 1973; DeLaine, 2016; Keay et al., 2017). Situated just 30 km from Rome, Ostia's harbor, which was connected to Rome via the Tiber River, became a point of entry for the capital of the empire starting in the fourth century BCE. During the first century CE, increased imports likely drove the further development of Ostia as well as the establishment of its neighbor, Portus, a massive artificial, hexagonal port that could accommodate larger ships, and in greater numbers. By the second century CE, major renovations of Ostia were undertaken to improve the facilities required for a growing population. Large warehouses were constructed in different areas of the city, storing food and other goods in concentrated amounts (Rickman, 1971; Keay et al., 2017). At least five warehouses were built that contained dolia (sing. dolium), very large utilitarian and undecorated ceramic storage jars capable of holding hundreds to over a thousand liters (Rickman, 1971; Van Oyen, 2020; Cheung, 2024, Fig. 1). At some point, as the population of Ostia began to contract, the warehouses and other facilities in the city that fostered the urban population were maintained less frequently and eventually fell out of use. When exactly this happened was unclear due to the site's long occupation, subsequent haphazard discovery, and hasty excavations especially during the first half of the twentieth century.

Although the dolia were discovered about a century ago, they have not been studied scientifically. Over one hundred and fifty dolia are still extant in three purpose-built warehouses at Ostia (Fig. 2). Their contents have been surmised – wine or olive oil – but never scientifically investigated. It is also unclear whether dolia in the same storerooms held the same or mixed contents. Many of the vessels were also damaged and then mended in antiquity using lead-based materials. This article presents scientific evidence for what several of the dolia stored at some point during their long use-life as well as the metals used to mend the vessels when they suffered damage (Peña, 2007; Cheung, 2021, 2024). One challenge, however, is that the dolia were long out of use and exposed before the site was abandoned as well as after their discovery. This is especially problematic in the preservation and identification of the organic substances because during their long exposure they could have held a range of substances, some of which might overshadow

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https://doi.org/10.1016/j.jas.2026.106572
Received 10 November 2025; Received in revised form 26 February 2026; Accepted 8 April 2026
Available online 21 April 2026

previous contents and some of which might have been contamination.

2. Materials and methods

2.1. Site description and materials

The Caseggiato dei Doli (Regio I, Insula IV, 5), a storehouse filled with thirty five dolia near the Ostia Antiquarium, was built during the second quarter of the second century CE, with some modifications during the early third century CE (Figs. 2 and 3). Excavators found that the dolia contained the remains of approximately four hundred terracotta molds, dated to the late second and early third century CE, all of which were then covered over with a rough pavement (Pasqui, 1906; Floriani Squarciapino, 1954; Salomonson, 1972; Bakker, 1999; Pavolini, 1983; Paroli, 1996). The building was presumably reused as a dumping ground until the fifth century. The dolia of this room were arranged close together into two main clusters, divided by a central path. The arrangement and type of dolia in this property suggest that they were installed in two phases. The first set of dolia, placed on the eastern side of the room, are similar to one another in fabric, morphology, size, and capacity. The dolia were large vessels with numbers incised on the vessels that indicated capacities of forty amphorae on average. The ten dolia placed on the other side of the room incorporated a miscellaneous ensemble of vessels and were likely installed at a later date. At least two of the vessels had a different ceramic fabric, are noticeably smaller than the other vessels (with capacities of approximately thirty amphorae), and featured more extensive damage that had been mended.

The Magazzino dei Dolii (Regio III, XIV, 3), approximately 10 × 10 m, was originally connected to the Caseggiato di Annio (III, XIV 4), a large property that was built during the Hadrianic period and later modified during the third century (Ceci, 2001; 2003, Fig. 4). The property was close to the river and must have served as an important nexus between the port and town of Ostia. Along with several other rooms of the house, the storeroom was originally connected to the house but was disconnected from the rest of the property in the late second century or early third century as entrances and passages were blocked to build two apartment residences, which were decorated with fresco wall paintings, converting the property from a commercial building to one with a mixed function.

The storeroom contained twenty-one dolia, but the dolia are now buried to the rim because the floor level had been raised approximately 1.4 m in a later phase of use for the building; in antiquity they might not have been buried at all. The property's exterior facade preserves three incised and painted terracotta plaques, the left plaque with the word OMNIA, the center plaque with FELICIA, and the plaque on the right with ANNI, all of which were in tabulae ansatae format to extol Annius' fortunes. This Annius was probably a merchant who celebrated his profession in the decoration of his property. Two other decorative terracotta plaques praise and inform us of Annius' occupation: one terracotta plaque portrays a man standing between two, probably buried, dolia; the other portrays a man rowing a boat containing a dolium.

Located south of the Decumanus Maximus, the Magazzino Annonario (Regio V, Insula XI, 4-5) was a major storeroom in a trapezoidal shaped building built during the Hadrianic period (Fig. 5). It was connected to several rooms in a building that occupied a busy street. To the north of the storeroom was a large hall that was later modified into several rooms, perhaps for a workshop facility. A central corridor connected this space to the storeroom, which was a large open area with more than one hundred dolia that were buried to their shoulders. When the storeroom was uncovered in 1939, excavators also found a number of dolium lids, one of which was stamped with a maker's stamp (*CIL* 1013: IANVARIUS/ DOMIT.LUCILLAE), giving the Magazzino Annonario a *terminus post quem* of 108 CE. A number of these storage vessels were both damaged and repaired in antiquity. Some of the damaged dolia were repaired on their exterior walls with double dovetail tenons to remedy cracks that must have formed on the vessels during the drying phase of the production process.

2.2. Materials

Several samples were taken to identify organic residues absorbed by the dolia as well as the metals used to strengthen dolia. From Caseggiato dei Doli (I, IV, 5), three samples for residue analysis were taken from dolia on both sides of the path in this storeroom: sample 1 was taken from the inner wall of the shoulder area of dolium no. 18; sample 2 was taken from the inner wall of the shoulder area of dolium no. 17; and sample 3 from the inner wall of the belly area about 70-80 cm below the rim from dolium no. 25. Almost half of the dolia have visible metal additions, either in the form of simple fills, which comprised lead added to cracks at any point in the vessel's life, or as elaborate supplements in the shape of double dovetails, sometimes multiple ones connected by strips of lead, which were often made in the workshop during the dolium's production (Peña, 2007; Cheung, 2021, 2024). To understand more about how craftsmen might have made and perhaps strengthened the lead elements, samples were taken from two dolia that were extensively mended in this storeroom to analyze the composition of metals: sample 4

Fig. 1. Various dolia from shipwrecks, Ostia. Photograph by AlMare./Wikimedia Commons/CC BY-SA 3.0

was taken from the double dovetail tenon on the shoulder of dolium no. 28 (one of the anomalous dolia) and sample 5 was taken from a dovetail tail on the rim of dolium no. 17. From Magazzino dei Dolii (Regio III, XIV, 3), Sample 6 was taken from the inner wall (c. 70 cm below rim) of dolium no. 17 and Sample 7 was taken from the inner wall (c. 45 cm below rim) from dolium no. 3. From the Magazzino Annonario (V, XI, 4-5), three samples of ceramic material were taken to identify absorbed organic residues and two samples were taken from dolia to identify the metals used: Sample 8 was taken from a metal element on the middle exterior of dolium no. 96; Sample 9 was a trace amount of ceramic material taken from the inner wall near the base from Dolium no. 37; Sample 10 was a trace amount of ceramic material taken from the inner wall near the base of dolium no. 24; Sample 11 was a trace amount of ceramic material from the inner wall near the base of dolium no. 7; Sample 12 was a small sample from double dovetail tenon on the middle exterior wall from dolium no. 2.

2.3. Methods

2.3.1. Sample preparation for GC-MS analysis

Dolia fragments were placed inside a beaker and to each one of them were in order added: 3 ml of methanol, 3 ml of chloroform, and 3 ml of hexane. After the addition of each one of the three solvents, the beaker was subjected to magnetic stirring at a temperature of 40 °C. The three extracts were then pooled and dried under nitrogen flow. Each sample was subjected to a transesterification protocol by adding a solution of methanol and acetyl chloride (1:20, V/V) and incubated at 90 °C for 16 h. Samples were then dried under nitrogen flow, resuspended in hexane and directly analysed by GC/MS.

Although the extraction protocol differs from the commonly employed acidic methanol or chloroform/methanol methods, the approach proved effective for the recovery of fatty acids and diterpenoids. However, inter-study comparison should be made cautiously.

2.3.2. GC-MS analysis

GC-MS analyses were performed on a 6890 MSD quadrupole mass spectrometer (Agilent technologies) equipped with a gas chromatograph by using a Zebron ZB-5HT Inferno (5%-Phenyl-95%-Dimethylpolysiloxane) fused silica capillary column (Column 30 m × 0.32 mm x 0.10 μm) from Phenomenex.

The injection temperature was 250 °C, the oven temperature was held at 50 °C for 3 min and then increased to 150 °C at 12 °C/min, increasing to 230 °C at 18 °C/min, to 280 °C at 10 °C/min and finally to 300 °C at 30 °C/min and held for 3 min. Electron Ionization mass spectra were recorded by continuous quadrupole scanning at 70eV ionization energy, in the mass range of m/z 30-450.

2.3.3. Sample extraction for inductively coupled plasma mass spectrometry (ICP-MS) analysis

About 3 × 3mm of each sample was subjected to mineralization procedure as follows: samples were accurately weighed into glass tubes. Concentrated nitric acid (7.0 mL) and hydrogen peroxide (1.0 mL) were added to each sample. The reaction was conducted for 3.5h at 90 °C. After the hydrolysis, the solution was filtered on 0.45 μm Millex filter (Millipore, Merck, MA, USA) and diluted to 25 mL with Milli-Q water. 5 mL of the solution was transferred into an ICP-MS vial for the analysis.

2.3.4. ICP-MS analysis

Analyses were performed on an Agilent 7700 ICP-MS instrument (Agilent Technologies Santa Clara, CA, USA) equipped with a frequency-matching radio frequency (RF) generator and 3rd generation Octapole Reaction System (ORS3) operating with helium gas in ORF. The following parameters were used: RF power: 1550W, plasma gas flow: 14L/min; carrier gas flow: 0.99L/min; He gas flow: 4.3 mL/min 103Rh isotope was used as an internal standard (final concentration: 50 μg/L). Metals concentrations have been measured with three replicates and the average values were reported in Table A.2.

Fig. 2. Dolia embedded in a storeroom, Caseggiato dei Doli (Regio I, Insula IV, 5), Ostia. Archivio Fotografico del Parco Archeologico di Ostia Antica.

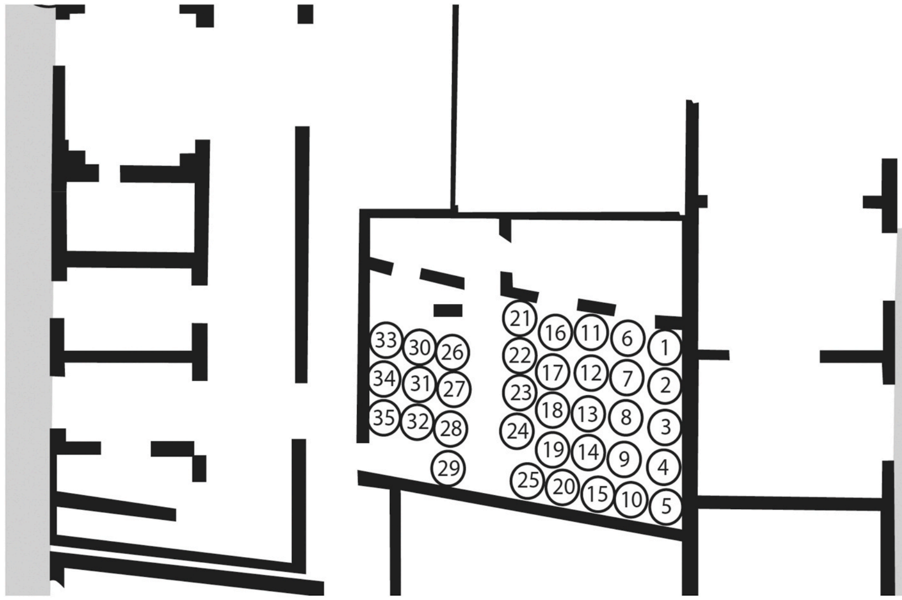

Fig. 3. Plan of Caseggiato dei Dolia (Regio I, Insula IV, 5) with numbered dolia, Ostia. Illustration by Gina Tibbott.

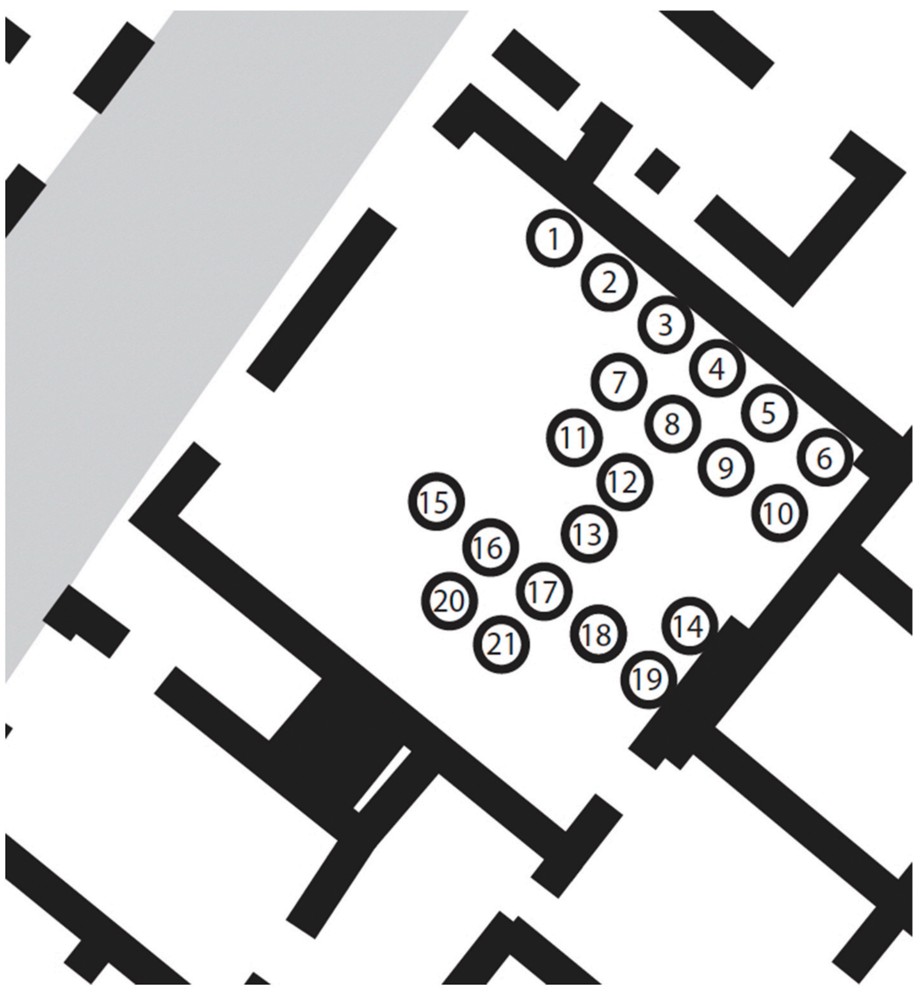

Fig. 4. Plan of the Magazzino dei Dolii (Regio III, XIV, 3) with numbered dolia, Ostia. Illustration by Gina Tibbott.

3. Results

To identify the nature of the materials originally contained within the dolia, as well as the composition of metal additions, a combined analytical approach employing gas chromatography–mass spectrometry (GC–MS) and inductively coupled plasma–mass spectrometry (ICP–MS)

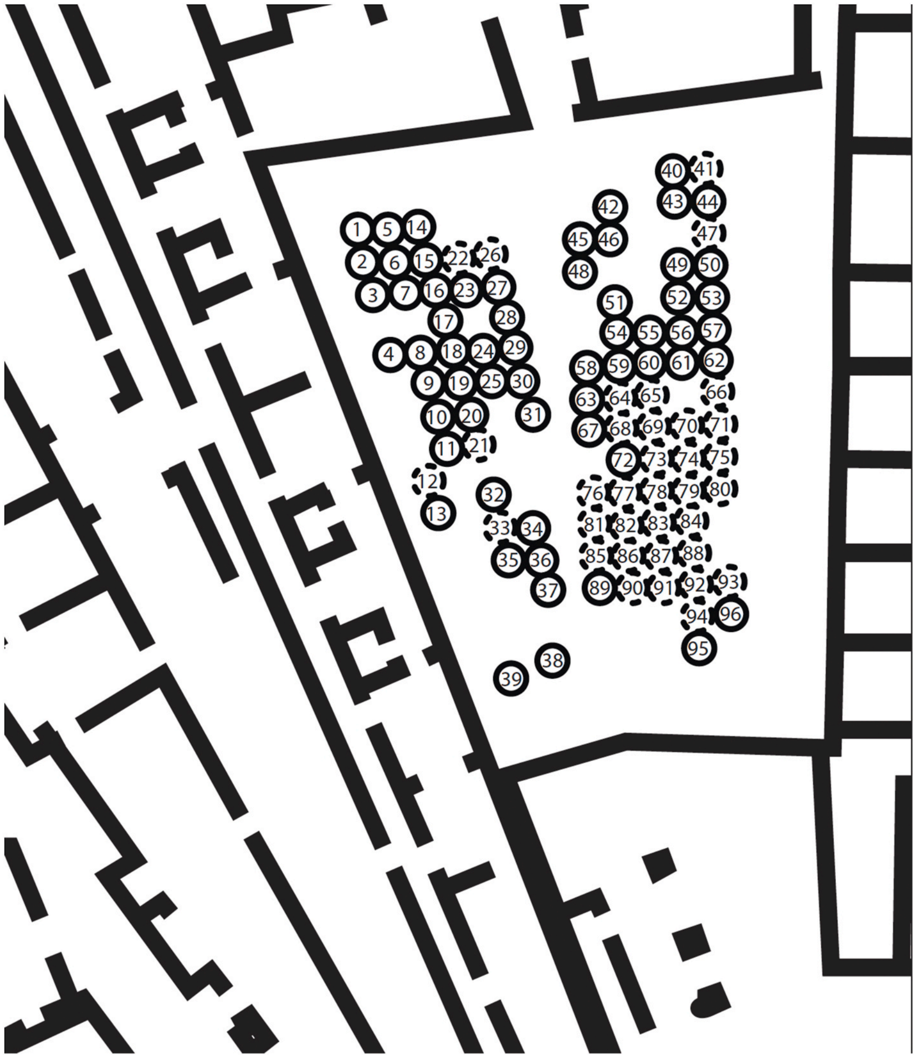

Fig. 5. Plan of the Magazzino Annonario (Regio V, Insula 4-5) with dolia numbered, Ostia. llustration by Gina Tibbott.

was undertaken. The GC–MS analyses were conducted following a sequence of three extraction steps using solvents of decreasing polarity, thereby maximising the recovery of compounds with a wide range of chemical affinities. This multi-solvent approach enabled the extraction of both polar and non-polar molecular species, ensuring a comprehensive representation of the organic residues preserved on the ceramic surfaces. To improve the volatility and stability of the extracted molecules, as well as to mask their polar functional groups, a mild transesterification treatment was performed under controlled conditions prior to instrumental analysis. The resulting extracts were analysed by GC–MS, where compounds were separated chromatographically and subsequently fragmented using an electron impact (EI) ionization source. The characteristic fragmentation patterns obtained were compared with reference spectra contained in the NIST mass spectral library, allowing the reliable identification of the analytes. The complete results are summarised in Table A.1.

The following compounds were identified in nearly all samples: alanine TMS; myristic acid TMS (FFA) C14:0; pyroglutamic acid TMS; palmitic acid TMS (FFA) C16:0; stearic acid TMS (FFA) C18:0; Dehydroabietic acid TMS; Hydroxycinnamic acid TMS; valeric acid (FAME) C5:0; dodecenoic acid methyl ester (FAME) C12:1; palmitic acid methyl ester (FAME) C16:0; cinnamic acid; oleic acid methyl ester (FAME) C18:1; stearic acid methyl ester (FAME) C18:0; linalool oxide TMS; myristoleic acid methyl ester (FAME) C14:1; linoleic acid TMS (FFA) C18:2. From the analysis of the data obtained, it was possible to formulate hypotheses on the putative content of the pottery under investigation and thus on the type of use. The identification of stearic acid (for example) could be due to the presence of dried meat (1), whereas we did not identify any markers for the presence of wine, such as tartaric acid or resveratrol isomers (Regert et al., 2003).

In parallel, ICP–MS analyses were carried out on the same samples to determine their elemental composition on the metal additions detected on some dolia (Table A.2, Fig. A.1). This technique enabled the quantification of major and trace elements, including calcium, magnesium, iron, and other metallic species.

Together, these analyses allowed for a detailed chemical characterisation of the materials once stored within the dolia, contributing to the reconstruction of their original contents, manufacturing processes, and possible post-depositional alterations.

4. Discussion

4.1. Organic residue analysis

GC-MS analysis identified a series of saturated and unsaturated fatty acids (C12:0–C18:2), amino acid derivatives including pyroglutamic acid, and diterpenoid compounds such as dehydroabietic acid. The latter is a well-established biomarker for pine resin and indicates that the interior surfaces of the dolia were treated with a resinous lining. Pine resin has been widely documented in Roman storage vessels and is associated with both wine and fish products, where it functioned as a waterproofing and preservative agent (Formenti, 1991; Bernal-Casasola, 2015).

The lipid fraction is characterized primarily by palmitic (C16:0), stearic (C18:0), oleic (C18:1), and myristic (C14:0) acids. These compounds are common degradation products of both plant and animal lipids and are not diagnostic of a specific commodity. The presence of pentadecanoic acid (C15:0) may reflect bacterial alteration of original lipids rather than a primary ingredient, as odd-chain fatty acids are frequently observed in degraded archaeological residues.

Pyroglutamic acid was detected in multiple samples. This compound may derive from the cyclization of glutamic acid during protein degradation and therefore indicates the prior presence of proteinaceous material.

Residue analysis of the dolia identifies the presence of chemical markers which taken together could suggest the putative presence of vegetable oils, fish, and pine resin in all the dolia, suggesting that the vessels might have once held garum or some other fish product. Garum was a highly valued liquid fish essence, made by fermenting the non-flesh parts of fish for several weeks with various aromatics and then pressing or squeezing the mixture to extract an amber colored fish essence (Curtis, 1983, 1991). Although not unequivocally, our data (combined to other archaeological finds and to literature data) are compatible with the presence of garum.

Notably, long-chain polyunsaturated fatty acids (e.g., C20–C24), which are often associated with marine oils, were not identified. These compounds are particularly susceptible to oxidative degradation and may not survive prolonged burial and exposure conditions. Nevertheless, their absence limits the specificity of interpretations regarding marine-derived contents.

Previous biomolecular studies of Roman fish-processing contexts have demonstrated that the identification of fish sauces relies on specific marine lipid biomarkers, including isoprenoid fatty acids (e.g., phytanic and pristanic acids) and ω-(o-alkylphenyl) alkanoic acids (APAAs), which form through heating of polyunsaturated marine fats (Regert et al., 2003). Residue analyses from the Garum Shop at Pompeii similarly identified degraded fatty acids in combination with contextual evidence for fish sauce production (Pecci et al., 2018). In the present study, GC-MS analysis detected saturated and unsaturated fatty acids (C12:0–C18:2), amino acid derivatives such as pyroglutamic acid, and dehydroabietic acid indicative of pine resin. However, diagnostic marine biomarkers such as APAAs or isoprenoid fatty acids were not identified. The detected fatty acids (e.g., C16:0, C18:0, C18:1) are common degradation products of both plant and animal lipids and are not specific to fish-derived commodities (Regert et al., 1998). Likewise, pyroglutamic acid reflects degraded proteinaceous material but is not a recognized biomarker for fish fermentation.

Consequently, while the combined presence of degraded lipids, protein derivatives, and resin lining is compatible with the storage of fish products, the chemical evidence alone does not permit definitive identification of garum. The residue profile is consistent with vessels that may have contained fish-based commodities, plant oils, wine, or multiple successive contents over their use-life. The attribution of garum must therefore remain provisional.

Further archaeological context points to garum as a likely content of the dolia. The only previously known evidence of garum from Ostia is a single garum amphora sherd with a painted label (*titulus pictus*) "G (arum) OST(iense)" from Magdalensberg in Noricum (Egger, 1969: 412; Curtis, 1991: 90; Berdowski, 2003: 48; Marzano, 2018a: 98); jars containing fish paste, another highly prized fish condiment in the Roman world, from Ostia/Portus have also been found in Arles (Marzano, 2017, 2018b: 442-443). No ancient sources discuss Ostia as a garum production center. Instead, ancient authors mention Pompeii and Spain as places known for their garum, such as Barcino in Tarragona, Monte Molião in Guadalquivir, and various sites in Baetica, and many recovered amphorae with *tituli picti* attest to the high volume of garum exported from Spain (Rueda Prunell and Járrega Domínguez, 2024; Tremoleda Trilla and Rueda Prunell, 2024; Beltrán de Heredia, 2001; Beltrán de Heredia and Comas, 2009; Viegas and Arruda, 2013; Bernal-Casasola et al. 2015; Bernal-Casasola et al 2024); Baetica and Lusitania were especially known for garum and dolia were used for garum storage, though garum production was usually done in vats or tanks known as *cetariae*. Although Ostia has not been mentioned in textual sources as a garum production site, it was the ideal location for this production activity: it was a good location for fishing, and fishing boats have been found, while it was also known for its salt pans (Boetto et al. 2017; Boetto et al., 2012; Boetto, 2006,2008,2009,2010;Karivieri, 2020). Several inscriptions testify to the importance of fishermen and fishmongers, some of whom might have also been salting the fish (Marzano, 2018b: 442-445; *CIL VI*, 1872, 29700, 29701, *CIL XIV* 409; Tran, 2006: 151, 158-160, 190-191, 230, 301, 316-318, 339-340, 354; Meiggs, 1973: 267; Cébeillac-Gervasoni et al. 2000: 276-279).

The results of this study therefore shed light on a possible hitherto unknown activity in Ostia. When this activity took place is unclear and indeterminable without further evidence. There is no way to date the residues identified. Furthermore, the abandonment of the vessels, the hasty excavations of the site, and the long period during which the vessels were exposed make it impossible to know when the vessels contained the contents that have been detected, and whether there were other contents that were not detected because their organic residues have not been preserved. The vessels might have contained wine or some other food at some point, but their use for holding garum exposed them to such high amounts of certain organic materials that might have overshadowed other organic residues from previous uses. Tartaric acid which is characteristic of wine, for example, is faint and difficult to detect, especially because it is readily soluble in water (Pecci et al., 2013; Barnard et al., 2011). Pine resin was often used as a protective sealant for ceramic vessels, such as dolia and amphorae, and has been primarily associated with wine and fish sauce (Bernal-Casasola, 2015: 69; Formenti, 1991, 1993). The dolia might have been used initially as wine vessels with their inner walls coated with pine resin as a sealant and then later reused as containers for garum or used for garum with wine added for flavoring, such as the dolia installed at the Bottega del Garum in Pompeii where traces of garum, wine, and pine resin were detected (Pecci et al., 2018). Another, though unlikely, possibility is that dolia had been used for garum storage as soon as the vessels were installed in the warehouses, but ancient authors do not mention this aspect of Ostia's production despite its sheer volume of over 150,000 L. Furthermore, most of the warehouses were set up not by the river, but a bit inland and away from points where fish would be unloaded and processed. Another unlikely possibility is that the high amounts of oils and fish fats in the sampled dolia are a result of contamination during their long exposure after the storerooms were no longer in use; the consistent presence of pine resin, on the other hand, was the result of intentional processes to (re)seal the vessel walls.

Taken together, the organic residues are consistent with degraded lipid and proteinaceous materials in resin-lined storage vessels. The chemical profile does not allow a definitive identification of garum. However, the combined presence of degraded animal/plant lipids, protein derivatives, and pine resin lining is compatible with the storage of fish products, with that possibility that plant oils, wine, or a succession of commodities were stored over the vessels' use-lives. What seems most likely, based on archaeological, textual, and scientific evidence, is that the dolia of these storehouses held garum at some point in antiquity. The dolia were installed in the second century and were later modified in at least two of the storerooms, the Caseggiato dei Doli and the Magazzino dei Doli: several dolia of various sizes were added in the Caseggiato dei Doli to expand its storage capacity, while the floor level might have been raised in the Magazzino dei Doli. Perhaps it was after this reorganization that the dolia were used for garum.

4.2. Use-life and functional interpretation

Residue analysis cannot distinguish between production and storage activities. The dolia were installed within warehouse contexts rather than in facilities clearly associated with fish processing, such as vats or salting installations. While Ostia possessed access to marine resources and salt pans, there is no direct archaeological evidence that these specific storerooms functioned as primary production facilities. It is therefore more prudent to interpret the dolia as storage containers that may have held fish products at some stage rather than as installations for garum manufacture.

The repeated detection of pine resin suggests intentional sealing of the vessel interiors. Resin linings are widely documented in Roman amphorae and large storage containers and may indicate efforts to preserve or flavor contents. Such treatments are compatible with both wine and fish-based products and further support the interpretation of the dolia as long-term storage vessels subject to reuse.

Given the long occupational history of the warehouses, the abandonment processes, and early excavation practices, it is also possible that the vessels contained different commodities over time. Residue signatures may represent cumulative or overlapping use phases rather than a single product.

4.3. Metal reinforcements and production practices

ICP-MS analysis demonstrates that the metal reinforcements consist predominantly of lead (Pb), consistent with widespread Roman practices of repairing large ceramic vessels. Metal additions found on different types of pottery were made of lead because of the ease in using the material as well as its abundance and low cost (Peña, 2007; Cheung, 2021, 2024). Due to its low melting point, a simple flame could soften or even liquify the metal, allowing the craftsmen to shape it accordingly to repair the vessel's damage (Rando, 1996; Peña, 2007; Cheung, 2021, 2024). Lead was commonly used to mend or reinforce dolia and other storage jars (Carroll, 2022, Carroll et al., 2021; Giardino, 2012; Rotroff, 2011; Carrato 2017). However, the Ostian examples also contain measurable quantities of silver (Ag) and tin (Sn), elements rarely reported in comparable dolium or pithos repairs elsewhere.

Morphological analysis indicates that many of the double dovetail reinforcements were cut into the vessels prior to firing, suggesting that these were not ad hoc repairs but deliberate structural reinforcements integrated during production. The controlled and symmetrical shaping of the cut grooves supports intervention at the leather-hard stage of manufacture rather than post-firing repair (Cheung, 2024, 2021; Peña, 2007; Rando 1996, Fig. 6).

The addition of silver and tin to lead may reflect an intentional alloying strategy to improve hardness and durability. The similarity in elemental composition across vessels from different warehouses suggests shared technical knowledge or standardized workshop practices in the Tiber River Valley (Cheung, 2024).

These findings shift interpretation from episodic "repair" toward planned reinforcement embedded within production sequences. The dolia were conceived not merely as large storage containers but as engineered installations designed for longevity in demanding commercial environments.

5. Conclusion

This study represents the first comprehensive scientific analysis of dolia at Ostia, providing a significant contribution to our understanding of the city's economic life, storage practices, and technological capabilities during the Roman period. Through the combined use of GC-MS and ICP-MS analyses, this research offers new evidence about both the contents once held in these vessels and the materials used in their maintenance.

The GC-MS (Gas Chromatography–Mass Spectrometry) results revealed chemical residues consistent with degraded protein. Although not definitive of fish sauce (garum), the constellation of evidence – the identification of pitch as lining for the dolia, the presence of amino acid derivatives and degraded protein, and ancient Ostia's salts pans and fishing activity – suggests that at least some of the dolia were used for the storage of this highly valued Roman commodity. This finding sheds light on a previously undocumented aspect of Ostia's economy, indicating that the port city played a more direct role in the storage and distribution of fish products than previously thought. Such evidence aligns with Ostia's position as a crucial maritime hub connected to Rome and the wider Mediterranean trade network.

The ICP-MS (Inductively Coupled Plasma–Mass Spectrometry) analysis provided further insights into the metallurgical practices associated with vessel maintenance. The study identified that the reinforcements made to the dolia were composed of lead alloyed with tin and silver, a deliberate mixture designed to enhance the strength,

Fig. 6. Double dovetail tenon made of lead, silver, and tin on shoulder of dolium, Caseggiato dei Doli, Ostia.

durability, and longevity of the metal reinforcements. This not only reflects the technical expertise of Roman craftsmen but also underscores the economic value attributed to these storage containers, which were evidently worth reinforcing and reusing rather than discarding.

Together, these findings deepen our understanding of Ostia's economic complexity and its inhabitants' practical responses to the challenges of storage, transport, and trade. The results demonstrate how material science can illuminate aspects of daily life and commerce in antiquity that are otherwise invisible in the archaeological record, revealing the dynamic and adaptive nature of Roman industry and economy.

Data availability statement

All data GC-MS and ICP-MS generated during this study are provided in the Supplementary Materials. No embargo or access restrictions apply.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors did not use generative AI.

Funding sources

This project was funded by the Archaeological Institute of America's Kathleen and David Boochever Endowment for Fieldwork and Scientific Analyses for their financial support.

CRediT authorship contribution statement

Caroline Cheung: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Andrea Carpentieri:** Conceptualization, Data curation, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank the Parco Archeologico di Ostia Antica, particularly Paola Germoni, Tiziana Sòrgoni, Cinzia Morelli, and Flora Panariti, for allowing us to extract samples and conduct this study.

Appendix

Table A.1
Identification of fatty acids from dolia samples.

Compound	caseggiato dei doli			annio		mag annonario		
	sample 1	sample 2	sample 3	sample 6	sample 7	sample 9	sample 10	
alanine TMS	x	x	x	x	x		x	
myristic acid TMS (FFA) C14:0	x	x	x	x	x	x	x	
pyroglutamic acid TMS	x	x	x	x	x	x	x	Fatty acids, fish fats and oils (including olive oil)
palmitic acid TMS (FFA) C16:0	x	x	x	x	x	x	x	Degraded protein
stearic acid TMS (FFA) C18:0	x	x	x	x	x	x	x	pine resins
Dehydroabietic acid TMS	x	x	x	x	x	x	x	
lauric acid TMS (FFA) C12:0						x		
pentadecanoic acid TMS (FFA) C15:0						x		
palmitelaidic acid TMS (FFA) C16:1						x		
oleic acid TMS (FFA) C18:1						x		
margaric acid TMS (FFA) C17:0						x		
Hydroxycinnamic acid TMS	x	x	x	x	x	x	x	
valeric acid (FAME) C5:0	x	x	x	x	x			
dodecenoic acid methyl ester (FAME) C12:1	x	x	x	x	x			
palmitic acid methyl ester (FAME) C16:0	x	x	x	x	x	x	x	
cinnamic acid	x	x	x	x	x	x	x	
olei acid methyl ester (FAME) C18:1	x	x	x	x		x	x	
stearic acid methyl ester (FAME) C18:0	x	x	x	x	x	x	x	
linalol oxyde TMS	x	x	x	x	x			
myristoleic acid methyl ester (FAME) C14:1	x	x	x	x	x			
linoleic acid TMS (FFA) C18:2	x	x	x	x	x			
pelargonic acid methyl ester (FAME) C9:0		x						
tridecanoic acid methyl ester (FAME) C13:0		x						
palmitelaidic acid methyl ester (FAME) C16:1							x	
bisnorabieta						x		
podocarpa						x		

Table A.2
Identification of metals from dolia samples.

	Sample 4	Sample 5	Sample 8	Sample 11	Sample 12
9 Be [1]	3.204	3.658	1.581	1.095	1.550
24 Mg [1]	345105.645	221159.882	348840.688	240013.514	165082.626
27 Al [2]	119545.126	126317.121	73134.739	32459.095	82389.351
39 K [2]	218752.959	51596.578	600.583	<6.119	14897.569
43 Ca [2]	355155.007	213987.714	342826.690	228924.203	167679.223
45 Sc [1]	<0.907	283.207	<0.907	<0.907	<0.907
51 V [2]	1753.884	2870.287	4796.577	24079.399	4143.401
52 Cr [2]	9091.312	3437.980	2559.762	3296.767	1852.560
55 Mn [1]	624.243	1065.597	872.469	292.788	304.402
56 Fe [2]	131567.227	124664.450	46290.440	26314.418	65823.676
59 Co [1]	25.066	31.207	10.827	17.420	24.812
60 Ni [2]	5426.686	2486.345	3700.368	2710.368	2017.242
63 Cu [2]	154251.110	91911.539	196824.478	136828.892	107514.993
66 Zn [2]	37691.004	28006.630	14105.644	44781.103	17139.002
72 Ge [2]	1174.026	<1.043	305.941	<1.043	<1.043
75 As [2]	21355.156	14212.292	1433.403	60709.257	25941.267
78 Se [2]	103.104	218.952	19.694	51.359	180.336
79 Br [1]	148228.230	114103.405	332262.182	235439.537	144378.238
89 Y [2]	183.891	149.407	79.299	204.570	89.646
95 Mo [1]	134.267	43.153	37.116	24.398	22.559
105 Pd [1]	33.150	8.818	14.138	8.275	5.463
107 Ag [1]	16046350.615	11518236.553	10666876.231	23846865.542	12543120.436
111 Cd [1]	31.530	50.162	21.497	17.676	41.563
118 Sn [1]	2657990.921	4081391.205	730.508	3207915.149	4186764.590
121 Sb [1]	96286.552	11574.390	9777.466	108434.037	102800.862
137 Ba [1]	5995.264	6371.049	4583.346	4474.593	6576.058
159 Tb [1]	4111.442	6073.442	12438.348	6584.151	5616.876
166 Er [1]	2.103	2.633	1.975	2.121	1.774
195 Pt [1]	996.775	10104.774	469.014	1074.988	273.687
205 Tl [1]	202.415	200.688	129.906	180.737	240.414
208 Pb	212354503.815	212242860.800	139740522.657	169003561.364	216569388.091
232 Th [1]	84.176	219.514	2.752	22.215	72.966
238 U [1]	13.679	13.900	68.124	232.710	109.379

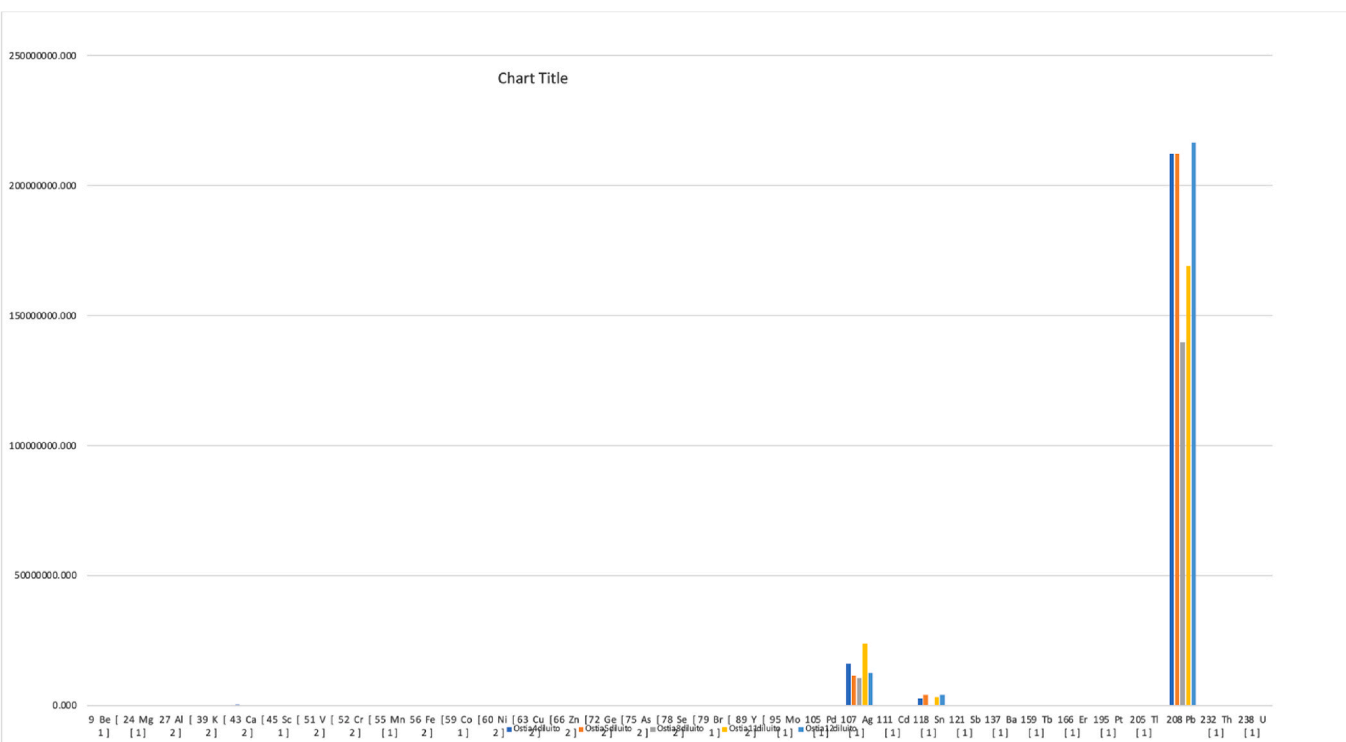

Fig. A.1. Graph showing types and amounts of metal present in dolium reinforcements at Ostia.

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