

This is a repository copy of *Chemical evidence for the persistence of wine production and trade in Early Medieval Islamic Sicily*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/171530/>

Version: Accepted Version

---

**Article:**

Drieu, Léa [orcid.org/0000-0002-7324-4925](https://orcid.org/0000-0002-7324-4925), Orecchioni, Paola, Capelli, Claudio et al. (7 more authors) (2021) Chemical evidence for the persistence of wine production and trade in Early Medieval Islamic Sicily. *Proceedings of the National Academy of Sciences USA*. e2017983118. ISSN: 1091-6490

<https://doi.org/10.1073/pnas.2017983118>

---

**Reuse**

This article is distributed under the terms of the Creative Commons Attribution-NoDerivs (CC BY-ND) licence. This licence allows for redistribution, commercial and non-commercial, as long as it is passed along unchanged and in whole, with credit to the original authors. More information and the full terms of the licence here: <https://creativecommons.org/licenses/>

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

# Chemical evidence for the persistence of wine production and trade in Early Medieval Islamic Sicily

Léa Drieu<sup>1\*</sup>, Paola Orecchioni<sup>2</sup>, Claudio Capelli<sup>3</sup>, Antonino Meo<sup>2</sup>, Jasmine Lundy<sup>1</sup>, Viva Sacco<sup>4</sup>, Lucia Arcifa<sup>5</sup>, Alessandra Molinari<sup>2</sup>, Martin Carver<sup>1</sup>, Oliver E. Craig<sup>1</sup>

<sup>1</sup> Department of Archaeology, BioArCh, University of York, York YO10 5DD, United Kingdom

<sup>2</sup> Dipartimento di Storia, Patrimonio Culturale, Formazione e Società, Università degli Studi di Roma Tor Vergata, Rome, Italy

<sup>3</sup> Dipartimento di Scienze della Terra, dell'Ambiente e della Vita, DiSTAV, Università degli Studi di Genova, Genova, Italy

<sup>4</sup> École française de Rome, 00186 Rome, Italy

<sup>5</sup> Università di Catania, Facoltà di Scienze della Formazione, Catania, Italy

\*Corresponding author: Archaeology, University of York, BioArCh, Environment building, Wentworth Way, York, YO10 5NG, United Kingdom, +441904 328806, lea.drieu@york.ac.uk

**Classification:** Anthropology, Chemistry.

## Keywords

Transport amphorae, wine, organic residue analysis, Late Antiquity and Early Middle Ages Sicily, provenance and trade

## Abstract

Although wine was unquestionably one of the most important commodities traded in the Mediterranean during the Roman Empire, less is known about wine commerce after its fall, and whether the trade continued in regions under Islamic control. To investigate, here we undertook systematic analysis of grapevine products in archaeological ceramics, encompassing the chemical analysis of 109 transport amphorae from the 5<sup>th</sup> to the 11<sup>th</sup> centuries, as well as numerous control samples. By quantifying tartaric acid in relation to malic acid, for the first time, we were able to distinguish grapevine from other fruit-based products with a high degree of confidence. Using these new quantitative criteria, we show beyond doubt that wine continued to be traded through Sicily during the Islamic period. Wine was supplied locally within Sicily but also exported from Palermo to ports under Christian control. Such direct evidence supports the notion that Sicilian merchants continued to capitalise on profitable Mediterranean trade networks during the Islamic period, including the trade in products prohibited by the Islamic *hadiths*, and that the relationship between wine and the rise of Islam was far from straightforward.

## Significance statement

As a high-value luxury commodity, wine has been transported across the Mediterranean since the Bronze-Age. The wine trade was potentially disrupted during political and religious change brought about by Islamisation in the Early Medieval period; wine consumption is prohibited in Islamic scripture. Utilising a novel quantitative criterion based on the relative amounts of two fruit acids in transport amphorae, we show that wine was exported from Sicily beyond the arrival of Islam in the 9<sup>th</sup> century, including to Christian regions of the Central Mediterranean. This finding is significant for understanding how regime change affected trade in the Middle Ages. We also outline a robust analytical approach for detecting wine in archaeological ceramics that will be useful elucidating viniculture more broadly.

## Introduction

Sicily was described by the 10<sup>th</sup> century Palestinian geographer al-Muqaddasī as 'the profitable island' and new archaeological research is enhancing the evidence for its commercial prosperity, especially in the 10<sup>th</sup>-11<sup>th</sup> century (1–3). There is increasing evidence that trade remained active in the centuries following the fall of the western Roman empire, as Sicily emerged as a key commercial centre. Transport amphorae produced in Sicily during the Islamic period are found throughout the Central Mediterranean (e.g., refs 4–6) and a wide variety of goods were likely to have been traded with Sicilian merchants at this time, including edible commodities, such as salted fish, vegetable oils, dairy products, fruits, spices and sugar (4, 7–9). But it is not clear whether the major political and economic upheaval during the Byzantine-Islamic transition had an impact on the traded commodities themselves.

Wine was certainly one of the major high value goods traded in the Roman and Byzantine periods (10–12). Some scholars consider that its production and trade dramatically decreased after the Islamic conquest of the island due to hadithic prohibitions (13, 14). The well-documented existence of viticulture during the Islamic period (13, 15) may instead have been oriented towards table grapes, raisins and vinegar, which are widely used in Islamic cuisine (e.g., refs 16, 17). In contrast, the

continuation of wine production in Islamic Sicily is also suggested by some sources (15), although the extent of production is hard to determine. A tax on wine is reported when the island was under the Fatimid rule (18), which suggests that it continued to be traded and of economic significance, but the volume and destination of this commerce is largely undetermined.

Indeed, the equation between the transportation of wine and the rise of Islam is likely to be far from simple and most likely fluctuated between the 7<sup>th</sup> and the 13<sup>th</sup> century. Perhaps our best source of evidence comes from transport amphorae which can often be provenanced by their form and composition to specific origins to reveal potential trade routes (2). In the 6<sup>th</sup> and 7<sup>th</sup> centuries commodities carried in Late Roman type 5-7 amphorae, produced in the Eastern Mediterranean, were reaching destinations in the Aegean, Adriatic and Tyrrhenian seas. Some of these are thought to have carried wine (2). At the beginning of the 8<sup>th</sup> century the Emir of the Theban region was ordering wine from Apollonopolis to supply other destinations in Egypt, including Fustat, and his cook was receiving a consignment of wine according to a document in the Christian monastery of Baouît (2). In the 10<sup>th</sup> and 11<sup>th</sup> centuries, an important new amphora production centre rose at Palermo, whilst at the height of Islamic control, supplying commerce to North Africa and the Tyrrhenian Sea area, notably Sardinia (6). The Norman conquest of Sicily in 1061 AD is thought to mark a revival of viniculture (14) and wine is again considered a major Sicilian export after this date (4). In the 12<sup>th</sup> and 13<sup>th</sup> centuries, new types of amphorae handled bulk supply in the Aegean (e.g. Calchis) but Sicily loses its primacy as an exporter and becomes a net importer, in the face of diverse and rising centres of production on the Italian peninsula (2).

Deciphering the wine trade from the distribution of amphorae and the few documents available is however far from straightforward without knowing their contents. In the absence of visible residues, marks or labels, chemical analysis of organic compounds absorbed into the walls of amphorae offers the only direct approach for assessing changes in the commodities traded during this period. Although some studies have begun to explore the contents of amphorae exchanged in Sicily in the Early Middle Ages (19–21), no large-scale investigation has been carried out to date. Furthermore, the identification of wine through chemical analysis remains controversial (e.g., ref 22) and particularly prone to false positive identification (23). In the absence of other archaeological or historical data to confirm interpretations, application of a robust methodology including quantification of target molecules and the use of appropriate controls is essential, particularly to distinguish wine from other fruit-based products. In the context of Islamic Sicily, this is especially pertinent, as a range of fruits, their juices and syrups, are known to have been exported (9, 15, 19). For this reason, previous reports of wine in Islamic amphorae (19–21) need to be interpreted cautiously. In one of the largest studies of its kind, here we present the analysis of more than 100 amphorae produced or imported in Sicily between the 5<sup>th</sup> and the 11<sup>th</sup> century AD. We propose a novel quantitative criterion for the identification of grapevine products using the relative concentration of tartaric acid to malic acid as a proxy, validated on more than 80 control samples.

## Results and Discussion

One hundred and nine amphorae produced or imported in Sicily from the Late Roman period to the Early Middle Ages were selected from the assemblages of 17 Italian and North African sites (Table 1, Fig. 1, and SI Appendix, Fig. S1). Knowledge of provenance (i.e. place of production), identified based on the typological characteristics and the petrographic composition of ceramic pastes (4, 6, 24) (SI Appendix, Table S1 and Fig. S1) and place of discard allowed us to distinguish four groups (Table 1). These are i) amphorae that were found close to the centre of production (local trade), ii) those

produced in Sicily and exported within the island (Sicilian trade), iii) those produced in Sicily and exported outside the island (overseas export), and iv) those produced elsewhere and imported into the island (import). To facilitate comparison over time, the samples were divided into three chronological groups: the Late Roman and Byzantine periods (5<sup>th</sup> to 7<sup>th</sup> century), the transition from the Byzantine to the Islamic period (8<sup>th</sup> to 9<sup>th</sup> century), and the Islamic period (10<sup>th</sup> to 11<sup>th</sup> century). Notably, only a limited number of samples were available from the 8<sup>th</sup> to 9<sup>th</sup> centuries, reflecting the scarcity of ceramic assemblages in this period (4, 25).

Of the entire sample set, only two containers show visible residues on the inner surfaces (SI Appendix, Table S1) that indicate sealing with plant exudates (resin, pitch, etc.), a feature commonly used to putatively identify wine amphorae in classical antiquity (e.g., ref 26). To facilitate the robust identification of wine, we undertook comparative analysis of control samples from similar contexts that would not have been expected to have come into contact with grapevine products, satisfying the stringent criteria outlined by Drieu et al. (23). In this case, we used cooking pots from the same contexts and, where available, wall and floor tiles and sediments (Table 1). The results were compared with control samples from replica potsherds impregnated with wine and degraded for one year through burial under controlled conditions, and samples of archaeological pottery with known contents (SI Appendix, Table S2).

#### *Criteria for the identification of wine*

Sixty-nine amphorae (63%) yielded tartaric acid (TA), in varying amounts (Fig. 2, SI Appendix, Fig. S2 and Table S3). Additional small organic acids were identified in most of the amphorae and controls, including malic (82% of samples), succinic (54%), fumaric (15%), maleic (10%), malonic (7%) and oxalic (5%) acids. TA was also detected in many control samples (cooking pots, sediments, and tiles) but only at low concentration ( $< 0.7 \mu\text{g g}^{-1}$ ) in all but two domestic cooking vessels ( $3.2$  and  $1.4 \mu\text{g g}^{-1}$ ; Fig. 2 and SI Appendix, Fig. S2). Overall, the transport amphorae had significantly higher TA concentrations than the control sample set (Mann-Whitney test:  $W = 5602$ ;  $p < 0.01$ ), implying a difference in use (Fig. 2).

However, the detection of TA alone is insufficient to provide definitive evidence for the presence of wine, as this compound is present in many other fruits (23, 27, 28). In grapes, the proportion of TA increases with ripening while the proportion of malic acid decreases correspondingly (29, 30). Although the absolute amounts of both acids are dependent on the growing conditions (temperature, hydrological state, exposure to sunlight, etc.; 30–32), we are able to exploit their relative concentrations to distinguish grapevine products. A comparison of TA and MA for the identification of wine and other fruit products in an archaeological context has been noted before (33, 34), but neither quantitative data nor interpretative ranges have been reported. Consideration of authentic reference products from the literature shows that the median % tartaric acid (%TA), expressed as the amount of TA divided by the sum of TA and malic acid, is significantly higher in ripe grape and grape-products compared to other fruits (Mann-Whitney U test;  $W = 136452$ ,  $p\text{-value} < 0.01$ ), with the exception of tamarind (Fig. 3A and SI Appendix, Table S4). Fruits other than grape and tamarind have a median %TA of 7% compared to 63% for ripe grape products. The lower limit (5<sup>th</sup> percentile) of the %TA range for ripe grape products is 35%, and over 90% of the published data for fruits and berries ( $N = 163$ ; excluding unripe grape, pomegranate and tamarind) have %TA below this value.

To test the robustness of this criterion, 18<sup>th</sup> and 20<sup>th</sup> century Georgian *qvevri*, traditionally used for wine production, were analysed. These vessels yielded %TA within the range of grapevine products (i.e. %TA  $> 35\%$ ; Fig. 3C and SI Appendix, Table S2). Similarly, the %TA obtained from experimental pots soaked in wine and buried for one year under different environmental conditions also remains within the range of grapevine products, despite some alteration in the ratio when compared to the

non-degraded control (Fig. 3B). It cannot be excluded that degradation of fruit products, other than grapes, may lead to an increase in %TA. However, foodcrusts containing *Viburnum* berries found on the surface of Russian hunter-gatherer pottery (23, 36), show a %TA below the range for grapevine products (Fig. 3C), giving confidence to the use of this criterion on archaeological samples of unknown content.

Among all the transport amphorae studied, twenty-one show %TA > 35%, which corresponds to the range of grapevine products (Fig. 3C). Interestingly, all of them yielded > 0.3  $\mu\text{g g}^{-1}$  of tartaric acid, i.e. greater than all the tiles and the majority (79%) of cooking pots. The use of these amphorae to transport wine is therefore highly likely given the context and prior historical knowledge, although the storage or transport of vinegar, grape syrup, pomegranate or tamarind cannot be excluded. Indeed, many of these products are mentioned in the cuisine and pharmacopoeia of the Late Antique and Early Medieval Mediterranean (e.g., refs 13, 16, 17, 36, 37) but are overwhelmingly considered less likely to be commercial commodity transported in amphorae. Hereafter, we therefore consider transport amphorae with %TA > 35% to have contained wine. It is important to note, that the same rationale cannot be applied to cooking pots or amphorae produced and discarded locally (i.e. potential storage amphorae), as we cannot be sure that wine rather than other grapevine products (vinegar, grape syrup, etc.) were processed in these vessels.

Almost all of the cooking pots and 88 amphorae show %TA  $\leq$  35 %, with varying yields of TA (Fig. 3C). The TA in these samples may be derived from unripe grape products or other fruits (e.g. black currants, blackberries, mulberries, raspberries, cherries, some types of pomegranate). It is important to note that for amphorae with %TA  $\leq$  35%, we are not able to exclude wine if it were mixed with other products containing malic acid (e.g. honey, other fruits, etc.) as was common in the Roman period (e.g. addition of honey to sweeten wine; 38). Similarly, the reuse of amphorae (e.g. for transporting wine and then other fruit juices) would reduce the %TA value leading to false negative identifications. However, subsequent re-use for transporting olive oil would not be expected to substantially alter the %TA value. The use of fruits likely explains the presence of tartaric and malic acids, sometimes in substantial amounts, in Sicilian cooking pots, in keeping with Islamic recipes available from this period (e.g., refs 17, 39). Small amounts of TA and malic acid (respectively around 0.1 and 1  $\mu\text{g g}^{-1}$ ) are present in both wall and floor ceramic tiles, always with %TA < 25% (Fig. 3C), most likely indicating contamination from the burial environment. Amphorae and cooking pots that yielded less TA and malic acid than found in these control samples therefore cannot reasonably be interpreted as containers of wine or fruit products.

#### *The Sicilian wine trade through time*

Having established this robust criterion for the identification of wine in amphorae, we now turn to comparison of their use through time (Fig. 4A). First, wine was identified in all periods regardless of the political regime in power. The low number of samples available from the 8<sup>th</sup> and 9<sup>th</sup> centuries precludes identification of a specific pattern, but even during this turbulent period, it is clear that wine was also traded within Sicily. By far the most surprising result is that wine was also used in the 10<sup>th</sup> and 11<sup>th</sup> centuries, when Sicily was under full Islamic control. A group of Sicilian-made amphorae, representing 15% of the total analysed from this period is clearly distinguished with a %TA > 35% (Fig. 4A).

During the Islamic period, petrographic analysis shows that Palermo was the main production centre for amphorae found in Sicily and Palermitan amphorae are also found throughout the Central Mediterranean (e.g., refs 5, 6, 24). Five of the amphorae that contained grapevine products during the Islamic period were produced and discarded in Palermo (Fig. 4B). This finding is interesting since

Palermo was under full Islamic control and our results may indicate that these vessels were used for local transport or storage of wine vinegar or grape syrup rather than wine; the former were widely used in medieval Islamic cuisine, as a preservative, or for medicinal purposes (e.g., refs 17, 36, 37, 40). However, wine cannot be excluded and equally may have been produced for consumption by the Jewish and Christian communities still present in Sicily at this time (13, 41, 42), or by some members of the Muslim community, as discernible from Islamic medieval poems (13, 41). No traces of wine were found in amphorae exported to inland Sicily, but, surprisingly, grapevine products were identified in several Palermitan amphorae exported overseas to Christian mainland Italy and Sardinia (Fig. 4B). Therefore, by using a combination of analytical approaches aimed at provenance and use on a large corpus of amphorae, we can begin to reveal the extent of a Sicilian wine trade network that appears to encompass the city of Palermo itself, and also the Central Mediterranean. Of course, it is difficult to estimate the volumes of wine trade, not least as wine and grapevine products may also have been stored or transported in perishable organic containers, such as barrels or skins, which do not survive in the archaeological record (43).

It is important to note that wine was not the only product transported in the amphorae manufactured and imported into Sicily between the 5<sup>th</sup> and 11<sup>th</sup> centuries. Degraded lipids from various fats and oils were identified in 75% of the amphorae analysed, including the majority of that also contained wine, suggesting extensive reuse of these containers, as has been previously suggested (e.g., ref 44). Significant lipid degradation, and the potential for extensive mixing, precludes further identification in the majority of cases, with profiles dominated by saturated fatty acids. Two amphorae from the 5<sup>th</sup> to 7<sup>th</sup> centuries and three from the 10<sup>th</sup> to 11<sup>th</sup> centuries contained more distinctive fatty acid profiles with a high relative abundance of oleic acid ( $C_{18:1}$ ) and palmitic acid ( $C_{16:0}$ ) compared to stearic acid ( $C_{18:0}$ ;  $C_{18:1}/C_{18:0} \geq 1.5$  and  $C_{16:0}/C_{18:0} \geq 2$ ; SI Appendix, Table S1) and are broadly attributed to vegetable oils (45). We undertook individual carbon stable isotope measurements of fatty acids of all of the amphorae and based on this evidence we were able to exclude marine products, which have fatty acid  $\delta^{13}C$  greater than -27‰ (46), in all but one amphora from the 5<sup>th</sup> century and two amphorae from the 10<sup>th</sup> to 11<sup>th</sup> centuries (SI Appendix, Fig. S3 and Table S3). Therefore, fermented fish sauces and pastes, such as garum, liquamen or salsamenta, do not seem to have been a major trade commodity during this period.

Finally, the presence of diterpenes and their degradation products derived from Pinaceae resin and pitch (47) were far less abundant in Islamic amphorae (5% of samples) compared to Late Roman and Byzantine periods (60%). Resin linings and sealants are thought to aid waterproofing or help preserve the contents and were frequently applied to Mediterranean amphorae during the Classical and Late Roman periods (e.g., refs 48–50). The presence of undetermined fats or oils in the majority of amphorae could be due to an alternative waterproofing method, as has previously been suggested for amphorae of the same period (19, 21). It is not clear whether this change in practice is unique to the Islamic period or whether it is specific to Sicilian production.

## Conclusion

Using a novel quantitative approach for distinguishing ripe grape products from other fruits, here we provide compelling evidence that the production and trade in Sicilian wine continued into the Islamic period and therefore were not substantially affected by the political and religious changes in Sicily between Late Antiquity and the Early Middle Ages. These results do not necessarily imply that Islamic prohibitions (51) were not strictly observed on the island, as wine may have been produced and traded for the benefit of non-Muslim communities in Sicily and elsewhere. We found evidence that wine was exported from Palermo under Kalbid rule to the Christian regions of the Mediterranean,

demonstrating continuity of the wine trade, at least, since the Byzantine period when the great Sicilian estates supplied Rome with wine via the port of Palermo (52). The volumes of wine traded are difficult to discern using this approach as a range of other commodities were also transported to and from Sicily at this time in similar containers, including vegetable oils, and the organic residue analysis shows evidence of re-use. Nevertheless, there is little direct evidence to suggest that the Mediterranean wine trade decreased under Islamic control as has often been assumed, rather Islamic merchants benefited from new markets satisfying the Christian demand for Sicilian wine, a trade that must have been approved by the Kalbid emir. Finally, we note that only by using our more robust quantitative criterion we can distinguish grapevine products and other fruits. Indeed, 69% of Sicilian amphorae and 70% of the cooking pots we tested contained tartaric acid but only a small fraction of these could be accurately assigned to wine, avoiding false positive identifications. We recommend that this new quantitative criterion should now be used to identify the presence of grapevine products in archaeological pottery, particularly in contexts where wine production is disputed (e.g. to study the origins of viniculture).

## Material and Methods

### *Degradation of authentic wine in pottery*

Three replica pots were filled with different wine obtained from commercial producers for two days (SI Appendix, Table S2). One potsherd from each pot was directly analysed after being emptied and dried. Other potsherds were buried for 12 months in different environments in order to evaluate the degradation of wine molecules in different climatic conditions and soil pH: the archaeological site of Casale San Pietro in Castronovo di Sicilia (Lat 37.68, Long 13.63; September 2018 – September 2019), a field in the south of France (Eze, Alpes-Maritimes; Lat 43.73, Long 7.36; November 2018 – November 2019), and at the YEAR Centre at the University of York (United Kingdom; Lat 53.94, Long -1.06; November 2018 – November 2019).

### *Experimental approach*

Following the most recent publications in terms of identification of grapevine products (23, 53), two successive extractions were used. Approximately 2 g of ceramics were drilled into the inner walls of the potsherds, after removal of the outer surface (1-2 mm) to remove contamination from the surrounding sediments and from the handling. Ten  $\mu\text{g}$  of an internal standard ( $n\text{-C}_{34}$ ) was added to 1 g of the powder, which was then extracted 3 times with DCM/MeOH (2:1, v/v) in an ultrasonic bath. The successive extracts, that contained lipids and resin acids (terpenes), were combined and evaporated under a nitrogen flow. The powder remaining after extraction with DCM/MeOH was treated with a boron trifluoride-butanol/hexane mixture (1:2, v/v) for 2 hours at 80°C to extract and butylate small organic acids, in particular malic and tartaric acids. The samples were centrifuged, and the supernatants were neutralised with a saturated sodium carbonate solution. The samples were then extracted 3 times with DCM and washed twice with distilled water before being evaporated under a stream of nitrogen. All samples were derivatized with BSTFA ( $N,O$ -Bis(trimethylsilyl)trifluoroacetamide, 1% trimethylchlorosilane). After evaporation under nitrogen flow, 10  $\mu\text{g}$  of an internal standard ( $n\text{-C}_{36}$ ) was added and the samples were dissolved in hexane before injection in gas chromatography-mass spectrometry (GC/MS). The untreated powder (about 1 g) was sonicated for 15 min in 4 mL of methanol, before adding 80  $\mu\text{L}$  of sulphuric acid and heating at 70°C for 4h (54). The methylated lipids were extracted three times in hexane before analysis in GC/MS. Samples with sufficient lipids ( $> 10 \mu\text{g g}^{-1}$ ) were injected in gas chromatography-combustion-isotope ratio mass spectrometry (GC-C-IRMS), to study the stable carbon isotope composition of palmitic and stearic acids and to verify the presence of marine fats.



## Instrumentation

The analyses were performed on an Agilent 7890A chromatograph, equipped with a DB5-HT column (30 m x 0.25 mm i.d., 0.1 µm film thickness, Agilent J&W), via splitless injection. The temperature program was as follows: the oven was maintained at 50°C for 2 min, then the temperature was raised to 325°C at 10°C min<sup>-1</sup>, and held for 15 min. The mass spectrometer used was an Agilent 5977B, used in electron ionization mode (EI, 70 eV), with mass spectra acquisition between *m/z* 50 and 1000. The presence of tartaric acid was identified from the mass spectrum of trimethylsilylated tartaric acid dibutyl ester (*m/z* 147, 276 and 391) (53). In some samples, a peak of trimethylsilylated tartaric acid methyl butyl ester (*m/z* 147, 234, 276 and 349), resulting from the reaction with residual methanol from the DCM/MeOH extraction, was also considered for quantification. Other small acids were also identified from the mass spectrum of their trimethylsilylated dibutyl ester: malic (*m/z* 145, 161, 173, 217 and 303), succinic (*m/z* 101, 157), fumaric and maleic (*m/z* 99, 117, 155, 173), malonic (*m/z* 87, 105, 143) and oxalic (*m/z* 57, 87, 130) acids. GC-C-IRMS analyses were performed using a Hewlett Packard 7890B series gas chromatograph (Agilent Technologies) with an Isoprime GC5 interface coupled to an Isoprime 100 isotope ratio mass spectrometer. The carrier gas (helium) was used at a constant flow rate of 3 mL/min. The samples were analysed in a DB-5MS fused silica column (60m x 0.25mm x 0.25 µm; J&W Scientific), after injection of 1 µL of sample via a splitless injector at 300°C. The eluted compounds were ionized by electronic impact (70°C). The <sup>13</sup>C/<sup>12</sup>C ratio of each peak was calculated from measurements of the ion intensities of *m/z* 44, 45 and 46. The calculations were carried out by comparison with measurements of a standard reference gas (CO<sub>2</sub>), and the results are expressed compared to the international standard Vienna Pee Dee belemnite (VPDB), in *m/z* (‰).

## Acknowledgment

This research was undertaken as part of the ERC Advanced Grant SICTRANSIT (The Archaeology of Regime Change: Sicily in Transition, ERC-ADG-2015 No 693600). The samples were selected and acquired for the SICTRANSIT project by A. Molinari and P. Orecchioni. We are grateful to A. Alfano, A. Canu, V. Carsana, F. Giacoppo, E. Lesnes, M. Randazzo, G.T. Ricciardi, M.S. Rizzo, and C. Tohuiri for providing them. We also thank J. Niemann and N. Wales for providing the Georgian *qvevri* samples and to M. Bondetti for the Zamostje 2 samples. We would like to acknowledge A. Little and A. Langley from the YEAR Centre (University of York), M. Von Terssch, N. Manié, J. Morales and F. Adamo for their contribution to degradation experiments, and H. Talbot for her help in the analysis and maintenance of the instruments. Finally, we are thankful for the comments of the two reviewers who contributed to improving the quality of this article.

## References

1. D. Booms, P. Higgs, *Sicily: culture and conquest* (British Museum Press, 2016).
2. A. Molinari, Le anfore medievali come proxy per la storia degli scambi mediterranei tra VIII e XIII secolo? *Archeologia Medievale* **XLV**, 293–306 (2018).
3. C. Wickham, The Mediterranean around 800: on the brink of the second trade cycle. *Dumbarton Oaks Papers* **58**, 161–174 (2004).
4. F. Ardizzone Lo Bue, *Anfore in Sicilia VIII-XII sec. dC* (Torri Del Vento Edizioni, 2012).

- 330 5. A. Meo, Anfore, uomini e reti di scambio sul mare pisano (VIII-XII secolo). *Archeologia*  
331 *medievale* **XLV**, 219–238 (2018).
- 332 6. V. Sacco, Produzione e circolazione delle anfore palermitane tra la fine del IX e il XII secolo.  
333 *Archeologia medievale* **XLV**, 175–191 (2018).
- 334 7. H. Bresc, “Le marchand, le marché et le Palais dans la Sicile des X-XII siècles” in *Mercati e*  
335 *Mercanti Nell’Alto-Medioevo: L’area Euroasiatica e l’area Mediterranea. Atti Della XL*  
336 *Settimana Di Studio Del Centro Italiano Di Studi Sull’Alto Medioevo (Il 23-29 Aprile 1992)*,  
337 (Fondazione CISAM, 1993), pp. 285–321.
- 338 8. A. Nef, “La Sicile dans la documentation de la Geniza cairote (fin Xe-Xiiiè siècle) : les réseaux  
339 attestés et leur nature” in *Espaces et Réseaux En Méditerranée VIe -XVIe Siècle*, Bibliothèque  
340 de la Méditerranée., D. Coulon, C. Picard, D. Valérian, Eds. (Editions Bouchène, 2007), pp. 273–  
341 292.
- 342 9. S. Simonsohn, “Merchants, Artisans and Others” in *Between Scylla and Charybdis*, Brill’s Series  
343 in Jewish Studies (Brill, 2011), pp. 77–93.
- 344 10. D. Malfitana, E. Botte, C. Franco, M. G. Morgano, A. L. Palazzo, Roman Sicily Project (RSP):  
345 Ceramics and Trade: a Multidisciplinary Approach to the Study of Material Culture  
346 Assemblages. First Overview: the Transport Amphorae Evidence. *Facta: a journal of Roman*  
347 *material culture studies* **2**, 127–192 (2008).
- 348 11. D. Malfitana, G. Cacciaguerra, C. Franco, A. Di Mauro, G. Fragalà, “Merci e scambi tra il Nord e  
349 il Sud dell’Italia: dati ed osservazioni da alcuni contesti della Sicilia romana, tardoantica e  
350 bizantina. Il contributo del «Roman Sicily Project: Ceramics and Trade»” in *Archeologia Classica*  
351 *in Sicilia e Nel Mediterraneo. Didattica e Ricerca Nell’esperienza Mista CNR e Università. Il*  
352 *Contributo Delle Giovani Generazioni. Un Triennio Di Ricerche e Di Tesi Universitarie*, Ricerche  
353 di Archeologia Classica e Post Classica in Sicilia, D. Malfitana, G. Cacciaguerra, Eds. (Ist Beni  
354 Archeologici, 2014), pp. 303–332.
- 355 12. E. Vaccaro, “Patterning the Late Antique Economies of Inland Sicily in a Mediterranean  
356 Context” in *Local Economies? Production and Exchange of Inland Regions in Late Antiquity*, L.  
357 Lavan, Ed. (Brill, 2015), pp. 259–313.
- 358 13. V. D’Alessandro, “Vite e vino nella Sicilia medievale” in *Città e Campagne Nella Sicilia*  
359 *Medievale*, Biblioteca di storia agraria medievale (CLU EB, 2010), pp. 33–52.
- 360 14. R. M. Dentici Buccellato, “Produzione, commercio e consumo del vino nella Sicilia medievale”  
361 in *Il Vino Nell’economia e Nella Società Italiana Medioevale e Moderna, Convegno Di Studi*  
362 *Greve in Chianti, 21-24 Maggio 1987 Firenze* (Accademia economico-agraria dei georgofili,  
363 1988), pp. 157–168.
- 364 15. S. Davis-Secord, “Sicily in the Dār al-Islām” in *Where Three Worlds Met: Sicily in the Early*  
365 *Medieval Mediterranean* (Cornell University Press, 2017), pp. 111–173.
- 366 16. N. Alonso Martinez, Agriculture and food from the Roman to the Islamic Period in the North-  
367 East of the Iberian peninsula: archaeobotanical studies in the city of Lleida (Catalonia, Spain).  
368 *Vegetation History and Archaeobotany* **14**, 341–361 (2005).
- 369 17. P. Lewicka, *Food and Foodways of Medieval Cairenes. Aspects of Life in an Islamic Metropolis of*  
370 *the Eastern Mediterranean, Islamic History and Civilization: Studies and Texts* (Brill, 2011).

- 371 18. A. Metcalfe, "Fatimid rule in Sicily" in *The Muslims of Medieval Italy* (Edinburgh University  
372 Press, 2009), pp. 44–69.
- 373 19. D. Bramoullé, C. Richarté-Manfredi, V. Sacco, N. Garnier, Le mobilier céramique dans la  
374 Méditerranée des xe-xiie siècles : Données archéologiques et sources judéo-arabes. *Annales*  
375 *islamologiques*, 191–221 (2017).
- 376 20. F. Pisciotta, N. Garnier, "Nuovi dati sulle anfore di fine X-XI secolo dal relitto 'A' di Lido  
377 Signorino (Marsala)" in *Studi in Memoria Di Fabiola Ardizzone 3: Ceramica*, Quaderni Digitali di  
378 Archeologica Postclassica (Antipodes, 2018), pp. 169–186.
- 379 21. C. Richarté-Manfredi, C. Capelli, N. Garnier, Analyses archéométriques et nouvelles  
380 contributions à l'étude des récipients de transport des épaves islamiques de Provence (fin IXe-  
381 Xe s.). *Archeologia Medievale XLV*, 239–250 (2018).
- 382 22. B. Stern, C. Heron, T. Tellefsen, M. Serpico, New investigations into the Uluburun resin cargo.  
383 *Journal of Archaeological Science* **35**, 2188–2203 (2008)
- 384 23. L. Drieu, *et al.*, Is it possible to identify ancient wine production using biomolecular  
385 approaches? *STAR: Science & Technology of Archaeological Research* **6**, 16–29 (2020)
- 386 24. P. Orecchioni, C. Capelli, Considerazioni di sintesi sulle analisi petrografiche di alcuni  
387 contenitori anforici di VIII-XII secolo. *Archeologia Medievale XLV*, 251–268, (2018).
- 388 25. L. Arcifa, Contenitori da trasporto nella Sicilia bizantina (VIII-X secolo) : produzioni e  
389 circolazione, con Appendice di Veronica Testolini. *Archeologia Medievale XLV*, 123–148 (2018).
- 390 26. S. Gallimore, Amphora Production in the Roman World. A View from the Papyri. *The Bulletin of*  
391 *the American Society of Papyrologists* **47**, 155–184 (2010).
- 392 27. H. Barnard, A. N. Dooley, G. Areshian, B. Gasparyan, K. F. Faull, Chemical evidence for wine  
393 production around 4000 BCE in the Late Chalcolithic Near Eastern highlands. *Journal of*  
394 *Archaeological Science* **38**, 977–984 (2011).
- 395 28. V. L. Singleton, "An enologist's commentary on ancient wines" in *The Origins and Ancient*  
396 *History of Wine. Food and Nutrition in History and Antropology*, P. E. McGovern, S. J. Fleming,  
397 S. H. Katz, Eds. (Gordon and Breach, 1996), pp. 67–77.
- 398 29. H. P. Ruffner, Metabolism of tartaric and malic acids in Vitis: A review - Part B. *Vitis* **21**, 247–  
399 259 (1982).
- 400 30. H. Volschenk, H. J. J. Van Vuuren, M. Viljoen-Bloom, Malic acid in wine: Origin, function and  
401 metabolism during vinification *South African Journal for Enology and Viticulture* **27**, 123–136  
402 (2006).
- 403 31. W. M. Kiewer, L. Howarth, M. Omori, Concentrations of tartaric acid and malic acids and their  
404 salts in Vitis vinifera grapes. *American Journal of Enology and Viticulture* **18**, 42–54 (1967).
- 405 32. P. Ribéreau-Gayon, Y. Glories, A. Maujean, D. Dubourdieu, *Handbook of Enology. Vol. 2, The*  
406 *chemistry of wine stabilization and treatment* (John Wiley, Chichester, 2006).
- 407 33. S. Jaeggi, A. Whittmann, N. Garnier, D. Frère, "Biberon or not biberon ? Les analyses  
408 biochimiques de contenus et la question de la fonction de vases gallo-romains communément

- 409        appelés « biberons »” in *SFECAG, Actes Du Congrès de Nyon (14 - 17 Mai 2015)*, (SFECAG,  
410        2015), pp. 561–576.
- 411    34.    N. Garnier, “Identifier les traces de vin archéologique : des structures de production aux vases  
412        à boire. Un bilan des méthodologies et des apports de l’analyse chimique organique” in  
413        *SFECAG, Actes Du Congrès de Nyon (14 - 17 Mai 2015)*, (SFECAG, 2015), pp. 299–314.
- 414    35.    M. Bondetti, *et al.*, Fruits, fish and the introduction of pottery in the Eastern European plain:  
415        Lipid residue analysis of ceramic vessels from Zamostje 2. *Quaternary International* **541**, 104–  
416        114 (2020).
- 417    36.    E. Lev, Drugs held and sold by pharmacists of the Jewish community of medieval (11–14th  
418        centuries) Cairo according to lists of materia medica found at the Taylor–Schechter Genizah  
419        collection, Cambridge. *Journal of Ethnopharmacology* **110**, 275–293 (2007).
- 420    37.    P. A. Norrie, “The history of wine as a medicine” in *Wine: A Scientific Exploration*, M. Sandler, R.  
421        Pinder, Eds. (CRC Press, 2003), pp. 21–55.
- 422    38.    P. V. Stanley, Gradation and quality of wines in the greek and roman worlds. *Journal of Wine*  
423        *Research* **10**, 105–114 (1999).
- 424    39.    L. Zaouali, *Medieval Cuisine of the Islamic World: A Concise History with 174 Recipes* (University  
425        of California Press, 2009).
- 426    40.    M. Vaquero Piñeiro, “Vigne e vino nella penisola Iberica” in *La Civiltà Del Vino. Fonti, Temi e*  
427        *Produzioni Vitivinicole Dal Medioevo al Novecento. Atti Del Convegno (Monticelli Brusati,*  
428        *Antica Fratta, 5-6 Ottobre 2001)*, G. Archetti, Ed. (Centro Culturale Artistico di Franciacorta e  
429        del Sebino, 2003), pp. 67–90.
- 430    41.    P. Branca, “Il vino nella cultura arabo-musulmana. Un genere letterario... e qualcosa di più” in  
431        *La Civiltà Del Vino. Fonti, Temi e Produzioni Vitivinicole Dal Medioevo al Novecento. Atti Del*  
432        *Convegno (Monticelli Brusati, Antica Fratta, 5-6 Ottobre 2001)*, G. Archetti, Ed. (Centro  
433        Culturale Artistico di Franciacorta e del Sebino, 2003), pp. 165–191.
- 434    42.    A. Metcalfe, “Before the Normans: Identity and Societal Formation in Muslim Sicily” in *Sicily:*  
435        *Heritage of the World*, D. Booms, P. Higgs, Eds. (British Museum Research Publications, 2019),  
436        pp. 102–119.
- 437    43.    A. Bevan, Mediterranean containerization. *Current Anthropology* **55**, 387–418 (2014).
- 438    44.    A. Pecci, Analisi dei residui organici e anfore medievali. *Archeologia Medievale* **XLV**, 275–280  
439        (2018).
- 440    45.    M. S. Copley, H. A. Bland, P. Rose, M. Horton, R. P. Evershed, Gas chromatographic, mass  
441        spectrometric and stable carbon isotopic investigations of organic residues of plant oils and  
442        animal fats employed as illuminants in archaeological lamps from Egypt. *Analyst* **130**, 860–871  
443        (2005).
- 444    46.    L. J. Cramp, R. P. Evershed, “Reading the residues: the use of chromatographic and mass  
445        spectrometric techniques for reconstructing the role of kitchen and other domestic vessels in  
446        Roman Antiquity” in *Ceramics, Cuisine and Culture: The Archaeology and Science of Kitchen*  
447        *Pottery in the Ancient Mediterranean World*, M. Spataro, A. Villing, Eds. (Oxbow, 2015), pp.  
448        125–140.

47. M. P. Colombini, F. Modugno, E. Ribechini, Direct exposure electron ionization mass spectrometry and gas chromatography/mass spectrometry techniques to study organic coatings on archaeological amphorae. *J. Mass Spectrom.* **40**, 675–687 (2005).
48. M. Bonifay, “Que transportaient donc les amphores africaines?” in *Supplying Rome and the Empire. The Proceedings of an International Seminar Held at Siena-Certosa Di Pontignano on May 2-4, 2004, On Rome, The Provinces, Production and Distribution*, Journal of Roman archaeology, Supplementary series, E. Papi, M. Bonifay, Eds. (2007).
49. A. Pecci, *et al.*, Use and reuse of amphorae. Wine residues in Dressel 2–4 amphorae from Oplontis Villa B (Torre Annunziata, Italy). *Journal of Archaeological Science: Reports* **12**, 515–521 (2017).
50. M. Woodworth, *et al.*, “The content of African Keay 25/Africana 3 amphorae: initial results of the CORONAM Project” in *ArchaeoAnalytics: Chromatography and DNA Analysis in Archaeology*, C. Oliveira, R. Morais, Á. Morillo Cerdán, Eds. (Município de Esposende, 2015), pp. 41–57.
51. J. E. Campo, “Dietary rules”, in *The Oxford Encyclopedia of the Modern Islamic World, Vol. I*, J. L. Esposito, Ed. (Oxford University Press, 1995).
52. V. Prigent, “Palermo in the Eastern Roman Empire” in *A Companion to Medieval Palermo. The History of a Mediterranean City from 600 to 1500*, A. Nef, Ed. (Brill, 2013), pp. 11–38.
53. N. Garnier, S. M. Valamoti, Prehistoric wine-making at Dikili Tash (Northern Greece): Integrating residue analysis and archaeobotany. *Journal of Archaeological Science* **74**, 195–206 (2016).
54. O. E. Craig, *et al.*, Earliest evidence for the use of pottery. *Nature* **496**, 351–354 (2013).

## Figure legends

**Table 1: Overview of the archaeological samples examined in this study.** \* The origin of the pots, identified based on typological characteristics and the composition of ceramic pastes, is indicated in parentheses. More detailed information on amphora type and dates is available in Supplementary Information (SI Appendix, Table S1 and Fig. S1).

**Fig. 1: Map of all the sites studied and details on the Sicilian trade routes during the Islamic period.** The sites are shown by period: 5<sup>th</sup> to 7<sup>th</sup> century (blue circles); 8<sup>th</sup> to 9<sup>th</sup> century (green circles), and 10<sup>th</sup> to 11<sup>th</sup> century (orange circles): Castello Brina (1), Via Cavalca (2), Via Sapienza (3), Largo delle Monache Cappuccine (4), Stazione Università, Piazza Bovio (5), Santa Maria degli Angeli, detta della Gancia (6), Castello San Pietro (7), Palazzo Bonagia (8), San Miceli (9), Mazara del Vallo (10), Casale San Pietro (11), Valle dei Templi, Quartiere Ellenistico (12), Piazza Armerina, Islamic village (13), Piazza Armerina, Excavation Gentili (14), Rocchicella di Mineo-Paliké (15), Catacombe di Siracusa (16), Althiburos (17). Black diamonds indicate the main towns and ports in the central Mediterranean between the 10<sup>th</sup> and 11<sup>th</sup> centuries, and the lines show the main direct (solid) and indirect (dashed) Sicilian maritime trade routes, according to the distribution of Palermo's pottery production and historical documents (6, 8).

**Fig. 2: Extraction yields of tartaric acid in transport amphorae and control samples.** a) Transport amphorae; b) Cooking pots; c) Tiles; d) Sediments. The number of samples analysed is shown in italics.

**Fig. 3: Results of tartaric (TA) and malic (MA) acids analysis in Early Medieval amphorae and control samples.** (A) Box plots of %TA, expressed as the % contribution of TA to the sum of TA and MA, in various fruits and fruit products (data from the literature, detailed in SI Appendix, Table S4). The number of samples considered is shown in italics. (B) %TA in experimental pots used to contain wine (filled circles) and degraded in different environmental contexts for 1 year (open circles). (C) %TA in archaeological samples, plotted versus the amount of tartaric acid extracted ( $\mu\text{g g}^{-1}$ , logarithmic scale) in amphorae (blue filled circles), cooking pots (blue open circles), tiles (black circles), Georgian *qvevri* (pink circles), and Viburnum foodcrusts (Zamostje, Russia; Bondetti et al., 2020; yellow circles). The vertical dashed line indicates the %TA value of 35%. Archaeological samples yielding  $< 0.05 \mu\text{g g}^{-1}$  of TA are not shown in this figure but are reported in SI Appendix, Table S3.

**Fig. 4: Results of tartaric (TA) and malic (MA) acids analysis in amphorae by chronological period.** (A) %TA plotted against the amount of TA extracted ( $\mu\text{g g}^{-1}$ , logarithmic scale) in transport amphorae from the 5<sup>th</sup>-7<sup>th</sup> century, 8<sup>th</sup>-9<sup>th</sup> century, and 10<sup>th</sup>-11<sup>th</sup> century. (B) Examples of typical Palermitan amphora forms (from Sacco, 2018). (C) %TA plotted against the amount of TA extracted ( $\mu\text{g g}^{-1}$ , logarithmic scale) in Palermitan amphorae from the 10<sup>th</sup>-11<sup>th</sup> centuries found in Palermo (green), Castronovo di Sicilia (orange), Mazara (light blue), Sardinia (yellow), Tuscany (pink), and Tunisia (dark blue). The type of trade is derived from the place where the amphorae were made, the location where they were found and their date. Samples yielding  $< 0.05 \mu\text{g g}^{-1}$  of TA are not shown in this figure but are reported in SI Appendix, Table S3. The number of samples yielding both malic and tartaric acids in relation to the total number of samples analysed is indicated in italics. The dotted grey line indicates the %TA value of 35%.

**Table 1: Overview of the archaeological samples examined in this study.**

Site	Region	Period group	Transport amphorae	Provenance group*	Control samples
Excavation Gentili (Piazza Armerina)	Sicily	5 <sup>th</sup> -7 <sup>th</sup>	3	nd	
Valle dei Templi, Quartiere Ellenistico (Agrigento)	Sicily	5 <sup>th</sup> -7 <sup>th</sup>	8	Imports ( <i>Tunisia</i> ) and Sicilian trade ( <i>nd</i> )	
San Miceli (Salemi)	Sicily	5 <sup>th</sup> -7 <sup>th</sup>	13	Imports ( <i>Tunisia</i> )	
Mazara del Vallo	Sicily	5 <sup>th</sup> -7 <sup>th</sup>	3	Imports ( <i>Tunisia</i> )	
		10 <sup>th</sup> -11 <sup>th</sup>	22	Imports ( <i>Tunisia</i> ), Sicilian trade ( <i>Palermo</i> ) and local trade	
Rocchicella di Mineo-Paliké (Mineo)	Sicily	8 <sup>th</sup> -9 <sup>th</sup>	3	Imports ( <i>Aegean</i> ) and Local trade	
Catacombe di Siracusa	Sicily	8 <sup>th</sup> -9 <sup>th</sup>	1	Imports ( <i>Aegean</i> )	
Casale San Pietro (Castronovo di Sicilia)	Sicily	8 <sup>th</sup> -9 <sup>th</sup>	2	Sicilian trade ( <i>nd</i> )	23 cooking pots 7 tiles 4 sediments
		10 <sup>th</sup> -11 <sup>th</sup>	7	Sicilian trade ( <i>Palermo</i> )	
Santa Maria degli Angeli, detta della Gancia (Palermo)	Sicily	10 <sup>th</sup> -11 <sup>th</sup>	5	Imports ( <i>nd</i> ) and local trade	18 cooking pots
Castello San Pietro (Palermo)	Sicily	10 <sup>th</sup> -11 <sup>th</sup>	5	Local trade	18 cooking pots
Palazzo Bonagia (Palermo)	Sicily	10 <sup>th</sup> -11 <sup>th</sup>	10	Local trade	15 cooking pots
Piazza Armerina, Islamic village	Sicily	10 <sup>th</sup> -11 <sup>th</sup>	1	Sicilian trade ( <i>nd</i> )	
Althiburos	Tunisia	10 <sup>th</sup> -11 <sup>th</sup>	1	Oversea export ( <i>Palermo</i> )	
Castello Brina (Sarzana)	Northern Italy	10 <sup>th</sup> -11 <sup>th</sup>	2	Oversea export ( <i>Palermo</i> )	
Stazione Università', Piazza Bovio (Naples)	Southern Italy	10 <sup>th</sup> -11 <sup>th</sup>	1	Oversea export ( <i>Palermo</i> )	
Via Cavalca (Pisa)	Northern Italy	10 <sup>th</sup> -11 <sup>th</sup>	4	Oversea export ( <i>Palermo</i> )	
Via Sapienza (Pisa)	Northern Italy	10 <sup>th</sup> -11 <sup>th</sup>	4	Oversea export ( <i>Palermo</i> )	
Largo delle Monache Cappuccine (Sassari)	Sardinia	10 <sup>th</sup> -11 <sup>th</sup>	13	Oversea export ( <i>Palermo</i> )	

\* The origin of the pots, identified based on the typological characteristics and the composition of ceramic pastes, is indicated in parentheses. More detailed information on amphora type and dates is available in Supplementary Information (Table S1 and Figure S1).

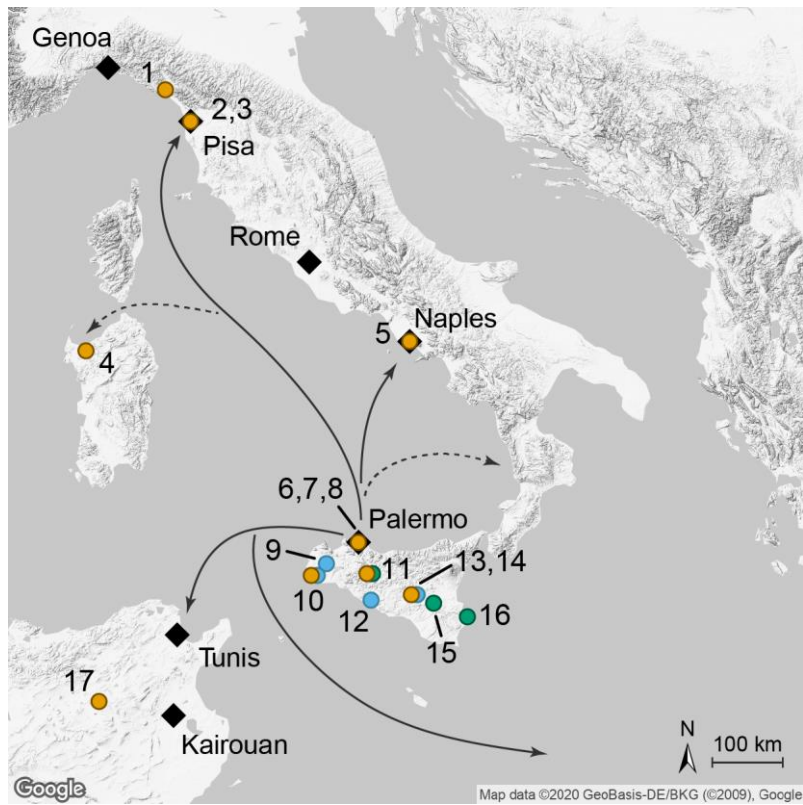


Figure 1



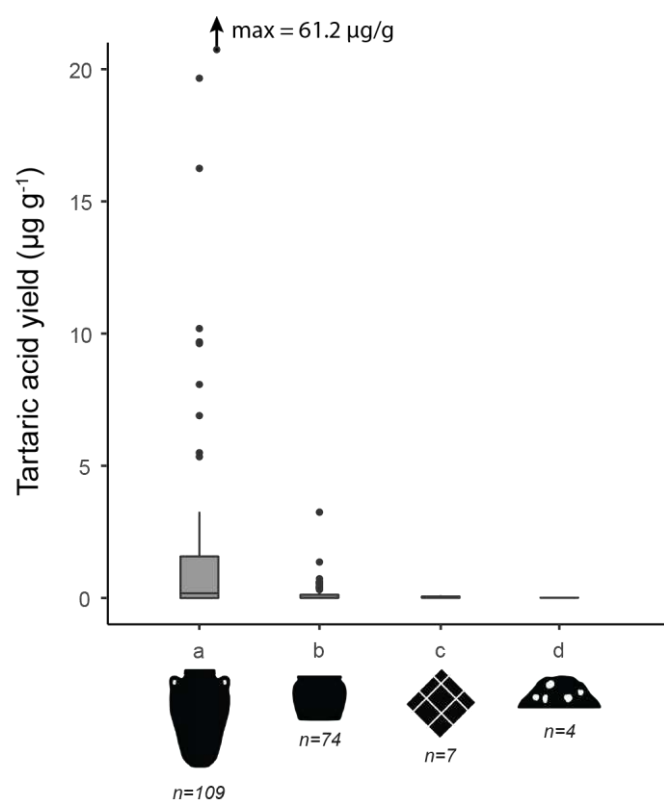


Figure 2

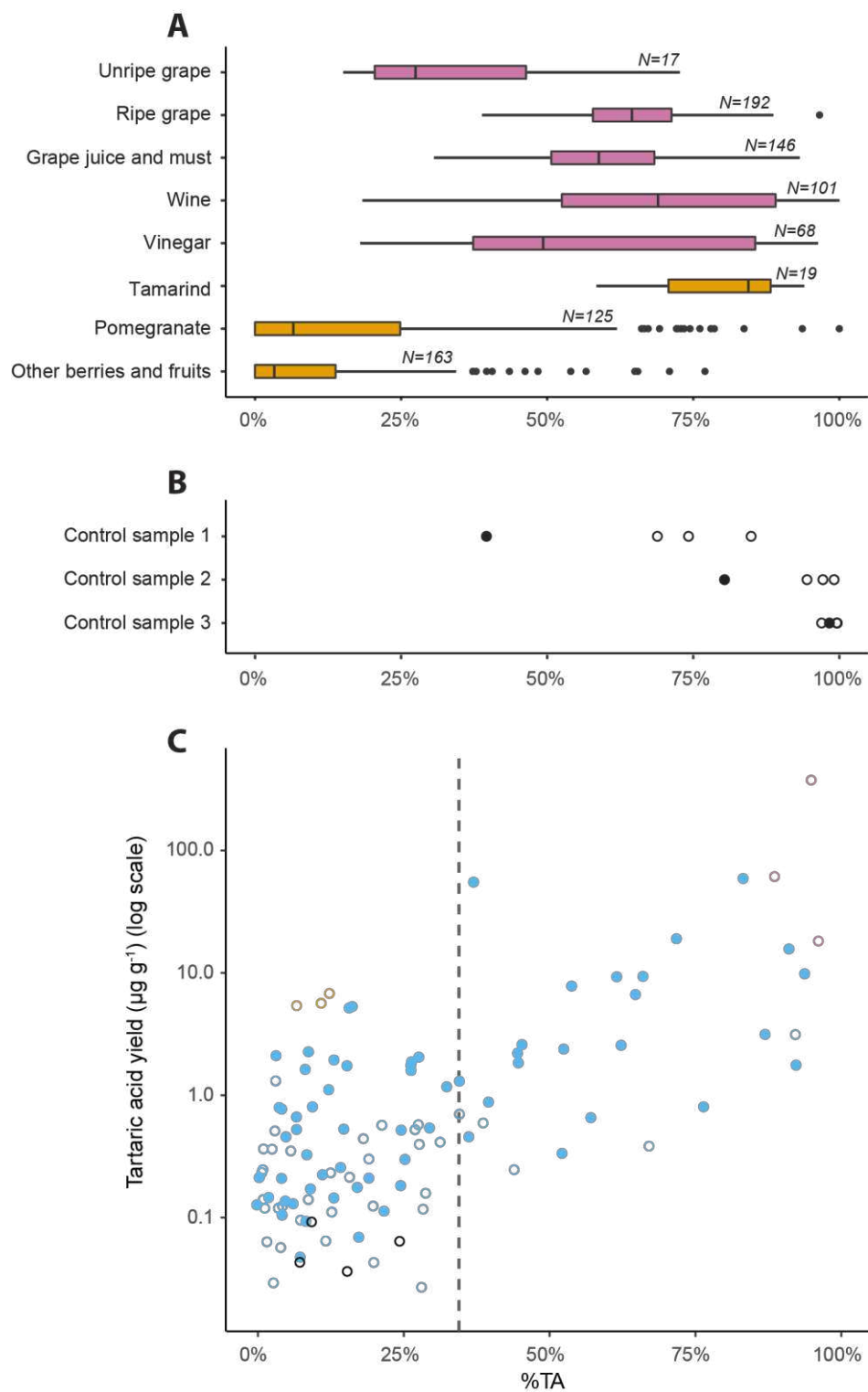


Figure 3

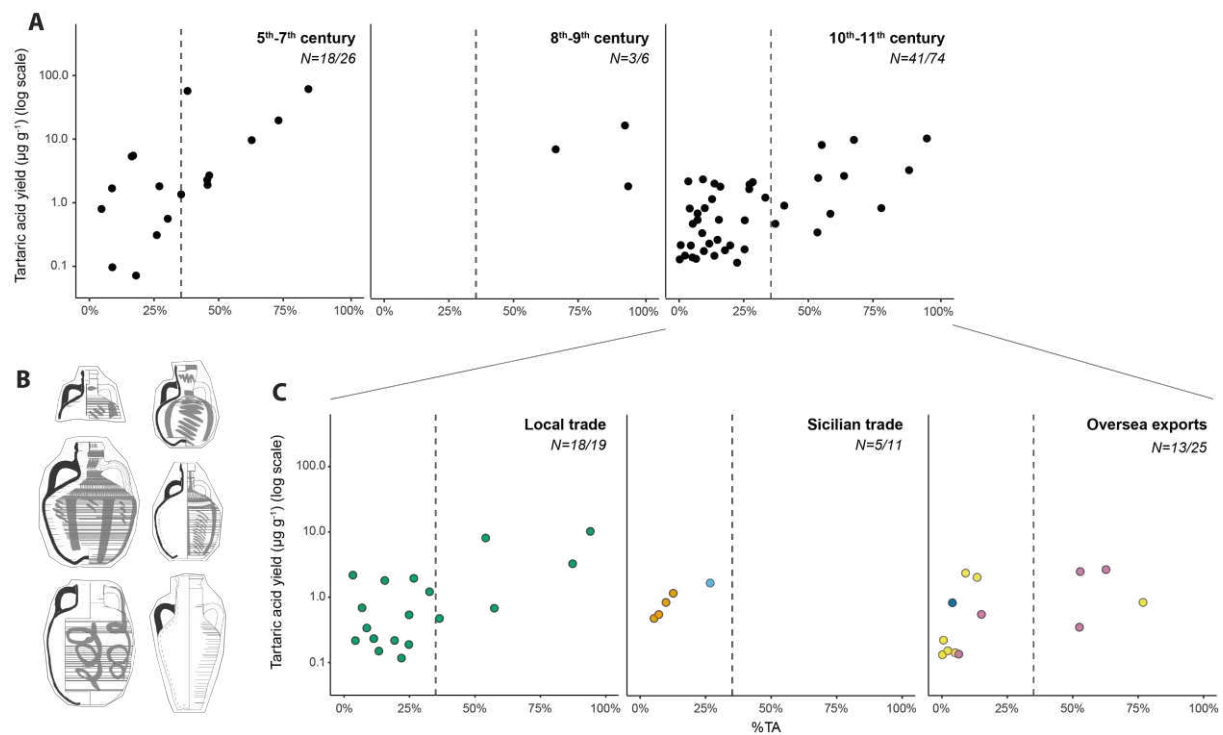


Figure 4