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ORIGINAL PAPER

Beyond staple crops: exploring the use of 'invisible' plant ingredients in Minoan cuisine through starch grain analysis on ceramic vessels

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Abstract
Systematic archaeobotanical research in the Bronze Age Aegean has greatly expanded our knowledge regarding staple crops and aspects such as palaeoecology, human diet and food production. However, some plant foodstuffs remain 'invisible' to conventional archaeobotanical methods. This study explores the use of plant ingredients in Minoan cuisine through the analysis of starch grains from cooking or cooking related vessels from two Minoan sites, Sissi and Malia. By combining available macrobotanical, textual and ethnobotanical data with newly acquired microbotanical evidence from cooking vessels, this study expands the list of plant species cooked and consumed in Minoan cuisine and enables a further exploration of food-related practices. In particular, we were able to document starch grains from staple crops (Triticeae), underground storage organs, tiger nut (*Cyperus esculentus*) and cumin (*Cuminum cyminum*). The identification of previously unattested plant ingredients of Minoan cuisine broadens the horizon of food consumption practices and contributes to the discussion regarding the economic and social meaning of food consumption in Minoan communities during Final Palatial and Post-Palatial periods.

Keywords Minoan pottery · Cooking vessels · Starch grains · Food condiments · *Cyperus esculentus* · *Cuminum cyminum*

Introduction

Systematic bioarchaeological research in the Bronze Age (BA) Aegean has greatly expanded our knowledge regarding palaeoecology, human diet and food production. In particular, intensive archaeobotanical research in Bronze Age Cretan (Minoan) contexts has provided a wide list of plant species used for a variety of purposes, including food consumption, fodder and dyeing (e.g. Livarda and Kotzamani 2013; Sarpaki 2012; Sarpaki and Bending 2004; Sarpaki and Skoula 2012). However, our understanding of past plant use is hampered by the specific conditions required for the preservation of macroscopic plant remains (in the BA Aegean, mostly charred). In the BA Aegean, Linear B tablets offer a unique source of information regarding the availability of plants, beyond food staples, and their use during the Late Bronze Age. Found at the palatial site of Knossos in Crete and within the Mycenaean palaces on the Greek Mainland, Linear B tablets deal with several aspects of administrative practices closely related to the palatial life, revealing economic strategies regulated by the palaces as well as the role of the palace in the definition of the value of different food staples (Killen 2004). As administrative documents dealing with economic matters, these tablets mention different commodities, such as wheat, barley, figs, olives, olive oil, wine and honey (Halstead 1992; Killen 2004; Palmer 1992, 1999; Ventris and Chadwick 1973), as well as coriander, cumin, sesame, fennel, mint and parsley (Andreadaki-Vlasaki 2008; Sarpaki 2001). These plants are referred to as condiments, aromatic plants and dyes in the administrative texts, giving additional economic but also social meaning to their consumption (Halstead 1992; Isaakidou 2007; Sarpaki 2001). In parallel, ethnobotanical research in Crete has shown that a large variety of wild greens, fruits and underground storage

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organs (USOs—rhizomes, roots, bulbs, tubers, etc.) that are indigenous to the island are used by present-day populations for food in traditional recipes, dying or medicinal practices (Livarda and Kotzamani 2013; Sarpaki and Skoula 2012; Skoula et al. 2009; Warren 2008, 2014). Condiments, leafy greens, USOs and fruits are underrepresented in BA archaeobotanical assemblages compared to crop staples (Livarda and Kotzamani 2013), possibly because they were handled differently and stored for shorter periods before their consumption (Sarpaki 2000: 117–119), thus reducing their chances of being preserved in the macrobotanical record. These plant food categories are thus virtually invisible to conventional archaeobotanical methods in the BA Aegean and can be identified only through the application of alternative analytical methods on the residues from food-related artefacts, such as chemical (Brogan and Koh 2008; Tzedakis and Martlew 1999) and microbotanical analyses (García-Granero et al. 2021).

Textual, residual and ethnobotanical evidence thus suggest that a wide range of plants potentially used as food in Minoan cuisine remain invisible to archaeologists (Sarpaki 2001; Killen 2004; Warren 2003, 2008). This study integrates all currently available evidence for the consumption of plant foods from Minoan Crete (macrobotanical remains, Linear B tablets and ethnobotanical research) with newly acquired starch evidence from cooking vessels from two Minoan settlements, Sissi and Malia/Area Pi. The analysis of cooking vessels offers direct evidence of the foodstuffs processed in them, since during the cooking process food residues are trapped in the pores of the vessel (García-Granero et al. 2021; Saul et al. 2012). In particular, starch analysis has the potential to shed light on the processing and consumption of macrobotanically invisible plant foodstuffs, such as USOs and spices. In addition, starch analysis allows us to explore the missing link between plant ingredients (recovered in the macrobotanical assemblage) and actual plant preparation and consumption as documented by Minoan ceramic vessels.

Materials and methods

Selection and preparation of modern comparative samples

Multiple datasets were taken into account to form the list of modern comparative plant species for this study, including the following:

- Archaeobotanical evidence from Minoan contexts in Crete (Livarda and Kotzamani 2013), including the two study sites, Sissi and Malia/Area Pi (Alexandra Livarda personal communication; Bouchard-Perron 2017; Sarpaki 2007)
- Textual information from Linear B tablets (Sarpaki 2001)
- Ethnographic data regarding the consumption of edible wild plants species in Crete, particularly in relation to USOs (Kavvadas 1950; Anaya Sarpaki personal communication; first author's ethnographic data)
- Historical sources (Megaloudi 2005)

Preparation of modern comparative samples included crushing the seeds/grains or bulbs, tubers, stems and fruits of each plant species with a porcelain mortar and pestle and sieving through a 250-µm mesh. The modern comparative collection was prepared at the Donald Baden-Powell Microscope Laboratory (School of Archaeology, University of Oxford, UK) and the Wiener Laboratory (American School of Classical Studies in Athens, Greece). A total of 41 plant species were included in the modern comparative collection for this study (Table S1), representing different plant food categories (cereals, pulses, nuts, vegetables and condiments).

Case studies and selection of archaeological samples

The archaeological samples selected for starch analysis come from cooking or cooking related vessels from two Minoan sites in northern Crete: Malia and Sissi (Fig. 1). Samples from Malia (thereafter ORAMA), a palace centre, come from recent excavations (2005–2016) conducted under the auspices of the French School at Athens and directed by Maia Pomadère at the residential district Pi. This research project aims to explore urban development around palaces in Crete during the Neopalatial period (1700–1430 BC; for a summary of the chronology, see Table 1) (Langohr and Alberti 2018; Pomadère et al. 2012; Sarpaki 2007). The samples from Sissi (thereafter ORASI) analysed in this study come from recent excavations (2007–2011 and 2015–2019) conducted under the auspices of the Belgian School of Athens and directed by Jan Driessen. In particular, the samples were collected from both domestic and public/ceremonial buildings dating to the Neopalatial, Final Palatial and Post-Palatial periods (1700–1200 BC). Both coastal settlements are well-known for their continuous occupation (2600–1200 BC) and the different types of buildings and artefacts that characterise a palatial and non-palatial site, providing a very good chronological representation of the material culture of the region (Driessen 2018). Studies in the production and consumption of material culture at each site and comparative analysis present substantial similarities between them, as well as notable differences (Langohr 2017a, b; Langohr and Alberti 2018).

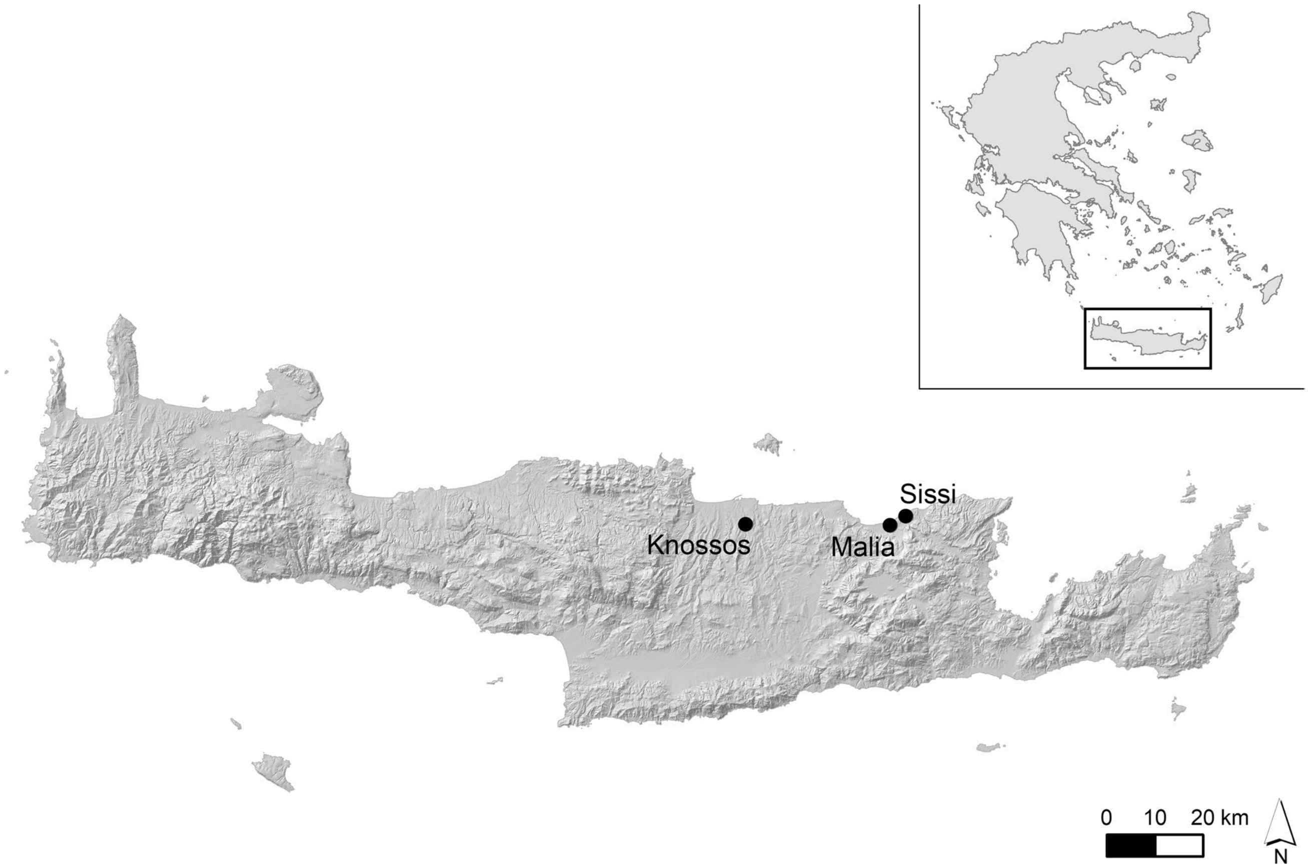

Fig. 1 Map of Crete showing the location of the study sites and other sites mentioned in the text. Courtesy of Sylviane Dederix

Table 1 Chronological horizons of the case studies (after Driessen and MacDonald 1997, 23)

Period	Phase	Abbreviation	Absolute date (BC)	N of samples
Protopalatial	Middle Minoan IIA	MM IIA	1800–1750	2
Protopalatial	Middle Minoan IIB	MM IIB	1750–1700	
Neopalatial	Middle Minoan IIIA	MM IIIA	1700–1640	12
Neopalatial	Middle Minoan IIIB	MM IIIB	1640–1600	27
Neopalatial	Late Minoan IA	LM IA	1600–1510	40
Neopalatial	Late Minoan IB	LM IB	1510–1430	-
Final Palatial	Late Minoan II	LM II	1430–1390	-
Final Palatial	Late Minoan IIIA1	LM IIIA1	1390–1360	15
	Late Minoan IIIA2	LM IIIA2	1360–1330	-
Post-Palatial	Late Minoan IIIB	LM IIIB	1330–1190	5
Total				101

A total of 101 starch samples (including ceramic vessels and sediment control samples) were analysed in this study (Table 1): 74 vessels and eight sediment control samples from Sissi and 15 vessels and four sediment control samples from Malia-Building Pi. The typological repertoire of vessels analysed included 29 dishes (large, very thin-walled curved plates), 22 tripod cooking pots (tcp), 14 jars, eight trays, five kalathoi, three bowls, three basins, two portable hearths, a larnax, a pyxis, a brazier and a smoker. Samples were selected based on the exploration of their unknown function and/or their potential use in the cooking preparation based on the vessel's typology, in correlation to their contextual information which indicates domestic activities, food preparation and consumption practices. The selection of the samples and the recovery of the microbotanical remains followed specific protocols that take into account the vessels' erosion and taphonomy, contamination parameters, as well as typological variation and archaeological contexts (Tsafou forthcoming).

Field sampling and recovery of microbotanical remains

To minimise the possibility of contamination during the collection of the samples in the field, direct bare-handed contact with the artefact's used surface was avoided. Moreover, a specific protocol for the collection, post-excavation treatment and storage of the pottery sherds were followed (Tsafou forthcoming). After retrieval, each artefact was wrapped in aluminium foil and bagged in a sealed plastic bag. The bag containing the artefact together with a label tag was placed into a second bag. Moreover, a small zip-lock plastic bag with approximately 25 g of sediment was collected from the context related to the sampled artefact as a control sample.

The recovery of microbotanical remains from potsherds took place in a controlled environment—a closed room with no airstream at the Sissi and Malia storerooms. Microremains recovery and extraction followed the protocols described in García-Granero et al. (2017) and Horrocks (2005). In particular, residue recovery consisted of a two-step process. The first layer of the sediment was removed from the used surface of the vessel by brushing (dry sample) and kept for future reference. The second step consisted on carefully brushing of the interior surface of the vessel with deionised water and the collection of the sediment (wet sample) into 50-ml centrifuge plastic tubes (García-Granero et al. 2017; Hart 2011). The utensils used to collect the samples were thoroughly washed between samples to avoid cross-contamination.

Starch extraction

Processing and analysis of the wet and control samples took place at the Donald Baden-Powell Microscope Laboratory, University of Oxford. Firstly, 5% sodium hexametaphosphate ($Na_6[(PO_3)_6]$) was used to disaggregate clays. During this process, the tubes containing the wet samples were topped up with sodium hexametaphosphate, shook and left overnight. The tubes were then centrifuged at 4000 revolutions per minute (rpm) for 3', decanted and topped up with distilled water. This procedure was repeated until the supernatant was completely clear. Samples were subsequently dried into the oven at < 40 °C. Next, the starch residues were isolated by adding 5 ml of sodium polytungstate ($Na_6[H_2W_{12}O_{40}]$) at a specific gravity of 1.8 g/cm^3 and centrifuging the tubes at 1500 rpm for 3'. Glass pipettes were then used to recover the floating fraction containing the starch residue into new labelled tubes. The starch isolation process was repeated to ensure all starch residue was recovered. Tubes were then topped up with distilled water, centrifuged at 4000 rpm for 3' and decanted a total of four times. The starch residues were finally transferred to glass vials and dried for storage. When drying the samples in the oven, the temperature was always kept below 40 ºC to prevent starch gelatinisation (Gott et al. 2006). In order to control any potential environmental contamination during laboratory work, microscopy slides were left on the lab bench and inside the fume for 5' and 30'. Further laboratory control samples included the glycerine used to prepare the starch slides, the nail polish used to fix the cover to the slide and the tubes used to collect and process the wet samples.

Microscopic analysis and starch identification

The starch residue from modern and archaeological samples was mounted on a glass microscopy slide with 50% glycerine and covered with a slide cover, which was fixed to the first slide by applying a drop of nail polish to each corner of the cover. Starch samples were scanned at × 200 to × 500 magnification with a Leitz Dialux 20 equipped with a Leica MC170 HD microcamera and a Zeiss Axioplan equipped with an Infinity 3 microcamera (Oxford) and a Leitz Laborlux 12Pol S equipped with a Jenoptik ProgRes C10 Plus microcamera (Athens). Starch grains were described and photographed under transmitted plain and cross-polarised light. A table of descriptors was used for the description of the starch grains and the definition of the starch morphotypes (Table S2). Taxonomical identification of plant remains relied on the comparison of the starch grain morphotypes of the archaeological samples with the starch comparative collection. The maximum length of all modern and archaeological starch grains was measured with the software ImageJ 10.2, and morphometric data were expressed as boxplots for visualisation using the R package 'ggplot2'. Minimum count size for starch grain morphometric data (N_{min}) was calculated according to the formula proposed by Ball et al. (2016) for phytolith morphometrics to assess if the number of starch grains measured for each taxon (N_m) accurately represents the taxon. We aimed at measuring the length of a minimum of 50 starch grains per sample based on the N_{min} values from modern *Triticum* and *Hordeum* spp. presented in García-Granero et al. (2021: Table 4), which was not possible for some of the modern taxa where starch grains were rare or very rare due to the shortage of reference material at the time of processing.

For modern samples, random areas of the slide were scanned until a representative amount of starch grains had been identified, photographed, described and measured. For archaeological samples, the whole area of the slide was scanned, and the percentage of starch residues analysed per sample was standardised (10%), allowing for a quantitative analysis of the results (García-Granero et al. 2017). For certain archaeological samples where the presence of minerals did not allow for the identification of starch grains, a second slide was prepared, and thus the analysed fraction represented 20% of the starch residue (samples ORASI 10, 17, 22, 60 and ORAMA 28).

Results

Modern comparative collection

Starch grains were identified in 33 out of the 41 plant species that form the comparative collection, with variable frequency (Table 2; Fig. 2). A total of 14 morphotypes were identified, described and measured (Fig. 3, Table 2), which were diagnostic at different taxonomic levels (family, subfamily, tribe or species). Only one taxon is shown per taxonomical category in Table 2 to avoid unnecessary repetition (raw data can be found in Table S4). N_{min} was lower than N_m in 66% of all the analysed taxa (Table S4) and 71% of the taxa shown in Table 2, therefore, showing that for most of the analysed taxa N_m is sufficiently large to accurately represent the taxon. Taxonomically diagnostic morphotypes include the following:

1. Two morphotypes (Types a and b) frequently encountered in the caryopses of all observed taxa within the Triticeae tribe (Yang and Perry 2013). Type a grains (Fig. 3a) are medium/large, round/oval in two-dimensional shape and discoidal in 3D, with central, linear hila, whereas Type b grains (Fig. 3b) are very small/small, round/oval in two-dimensional shape, spherical in 3D, with no lamellae and central, small vacuole hila.
2. One morphotype (Fig. 3c) frequently occurring in the seeds of all observed taxa within the Faboideae subfamily, consisting of medium/large grains, crescent/oval in two-dimensional shape, kidney-shaped/ovoid in 3D, with lamellae and central, linear hila.
3. One morphotype (Fig. 3d) frequently observed in the caryopses of all observed taxa within the Panicoideae subfamily, consisting of very small to medium grains, polyhedral in 3D, with flat facets, no lamellae and central hila with either a small vacuole or a linear fissure.
4. Two morphotypes found in *Cyperus esculentus* tubers. Type a grains (Fig. 3e), which appear frequently, are medium-sized, subround/ovoid in two-dimensional shape, discoidal in 3D, with a characteristic central depression, with no lamellae and central, large vacuole hila, whereas Type b grains (Fig. 3f), which are rare, are medium-sized, ovoid in 3D, with no lamellae and central, Y-shaped hila.
5. Two morphotypes found in the seeds of the observed taxa within the Apiaceae family. Type a grains (Fig. 3g), which appear frequently in all the analysed taxa, are very small to small, subrounded/polygonal in two-dimensional shape, polyhedral/irregular in 3D, with no lamellae and central, small vacuole hila, whereas Type b grains (Fig. 3h), which are found very rarely in *Cuminum cyminum*, are very small to medium, rounded/subrounded in two-dimensional shape, polyhedral/irregular in 3D, with no lamellae and no visible hila.
6. One morphotype (Fig. 3i) frequently observed in *Avena sativa* caryopses, consisting of very small to medium grains, rounded in two-dimensional shape, ovoid in 3D, with no lamellae and no visible hila.
7. One morphotype (Fig. 3j) rarely found in *Prunus dulcis* seeds, consisting of very small/small grains, rounded/subrounded in two-dimensional shape, spherical in 3D, with no lamellae and central, small vacuole hila.
8. One morphotype (Fig. 3k) rarely found in *Leopoldia comosa* bulbs, consisting of small to large grains, ovoid/subrounded in two-dimensional shape, ovoid/globose in 3D, with lamellae and central, small vacuole or linear hila.
9. One morphotype (Fig. 3l) frequently found in *Quercus ilex* acorns, consisting of very small to medium grains, oval in two-dimensional shape, globose in 3D, with no lamellae and central, large vacuole hila.
10. One morphotype (Fig. 3m) frequently found in *Pinus pinea* seeds (pine nuts), consisting of very small/small grains, subround/oval in two-dimensional shape, discoidal in 3D, with no lamellae and no visible hila.
11. One morphotype (Fig. 3n) very rarely found in *Pistacia terebinthus* fruits, consisting of very small/small grains, round/subround in two-dimensional shape, discoidal in 3D, with no lamellae and central, large vacuole hila.

Lastly, in two plant species (*Anethum graveolens* and *Foeniculum vulgare*), starch grains were very rare and the characterisation of the morphotype was not possible. Moreover, no starch grains were observed in *Pistacia lentiscus*, *Nigella sativa*, *Lepidium sativum*, *Ficus carica*, *Allium cepa*, *Allium sativum*, *Vitis vinifera*, *Colocasia esculenta*, *Scolymus hispanicus* and *Ceratonia siliqua*. The absence of starch grains in these species, and especially those known for their starch content such as *Colocasia esculenta*, could be related to the starch extraction process followed in this study and does not imply the complete absence of starch grains in these plant species.

Table 2 Description of the starch morphotypes identified in the modern comparative collection

Taxa	Frequency	Size	Extinction cross	Shape		Facet	Texture	Lamellae	Hilum			Length (μm)			
				2D	3D				Position	Type	Fissure	N_m	Range	Mean (StD)	N_{min}
Avena sativa	xxx	VS/S/M	R	R	OV		S	N				50	2.36–11.75	5.33 ± 1.74	40
*Carum carvi** (Apiaceae Type a)	xxx	VS/S	R	SR/PL	SPH/PL	FL	R/WR	N	C	SV		27	1.64–5.09	3.40 ± 0.84	48
*Cuminum cyminum** (Apiaceae Type b)	x	VS/S/M	R	R/SR	HEM/SR		RD	N				18	2.89–13.4	7.88 ± 2.32	24
Cyperus esculentus Type a	xxx	S/M	R	SB/OV	DI		S	N	C	LV		24	6.78–15.34	10.94 ± 2.05	11
Cyperus esculentus Type b	xx	S	R	OV	OV		S	N	C		Y	22	4.05–8.85	6.87 ± 1.47	20
*Lens culinaris** (Faboideae)	xxx	M/L	R	CR/OV	KI/OV		S	Y	C		L	52	11.07–38.44	23.56 ± 6.31	7
Leopoldia comosa	xx	S/M/L	R	OV/SR	OV/GL		S	Y	C	SV	L	60	5.46–30.92	16.18 ± 6.43	16
Pinus pinea	xxx	VS/S	R	SR/OV	DI		S	N				55	1.49–5.38	3.62 ± 0.87	44
Pistacia terebinthus	x	VS/S	R	R/SR	HEM		RD	N	C	LV		11	3.79–7.76	5.83 ± 1.23	24
Prunus dulcis	xx	VS/S	R	R/SR	SPH		RD	N	C	SV		24	1.52–5.07	3.29 ± 0.85	51
Quercus ilex	xxx	VS/S/M	R	OV	GL		S	N	C	L	L	62	3.61–21.51	13.44 ± 3.21	12
*Setaria viridis** (Panicoideae)	xxx	S/M	R	PL	PL	FL	WR	N	C	SV	Y	50	5.59–13.09	8.46 ± 1.81	17
*Triticum aestivum** (Triticeae Type a)	xxx	M/L	R	R/OV	DI		S	N	C		L	50	11.33–31.95	21.36 ± 4.83	7
*Triticum aestivum** (Triticeae Type b)	xxx	VS/S	R	R/OV	SPH		S	N	C	SV		50	1.79–8.52	4.98 ± 1.45	38

*Species taken as representative of the taxonomic category. Frequency: x = very rare, xx = rare, xxx = frequent. Size: VS = very small (< 5 μm), S = small (5–10 μm). *M*, medium (10–20 μm); *L*, large (20–50 μm). Extinction cross: R = regular. Shape 2D: SR = subround, R = round, OV = ovate, PL = polygonal, CR = crescent. Shape 3D: HEM = hemispherical, SPH = spherical, OV = ovoid, GL = globose, PL = polyhedral, DI = discoidal. Facet: FL = flat. Texture: WR = wrinkle, S = smooth, R = rough, RD = ridged. Lamellae: Y = yes, N = no. Hilum position: C = centric. Hilum type: LV = large vacuole, SV = small vacuole. Hilum fissure: L = linear, Y = y-shaped (see Table S2 for the full list of descriptors). N_m = number of measured starch grains (raw data can be found in Table S4). N_{min} = minimum number of starch grains that need to me measured to accurately represent the taxon (according to the formula proposed by Ball et al. 2016)

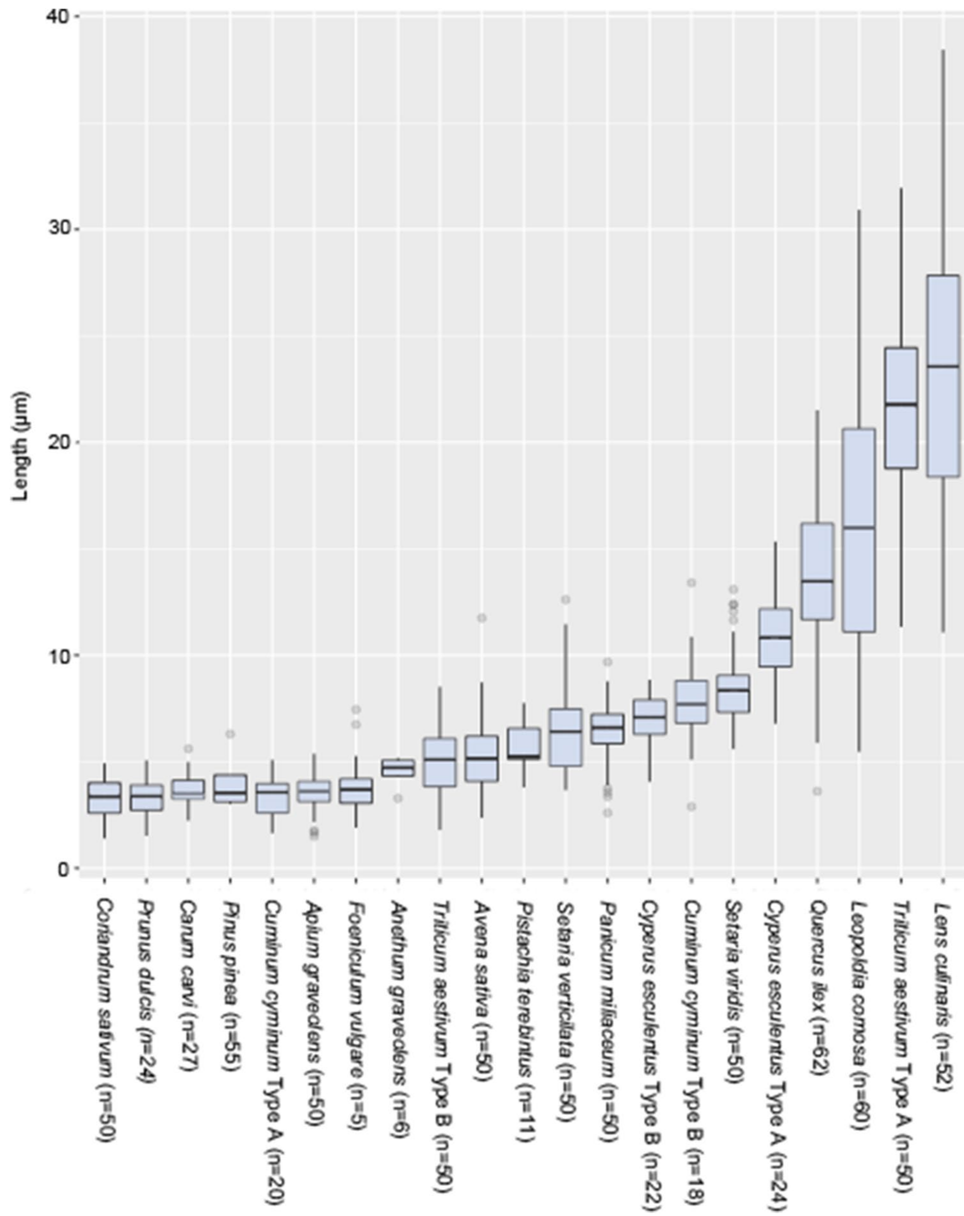

Fig. 2 Boxplots showing the maximum length of starch grains from all the taxa within the modern comparative reference collection where starch grains were encountered

Laboratory control samples

No starch grains were observed in the control samples from the laboratory bench and the fume nor from the glycerine, the nail polish or the tubes.

Archaeological samples

A total of 235 starch grains were observed in 66% of the analysed samples. Starch concentration (Table S3) is relatively low compared to published starch analyses from charred food crust recovered from cooking vessels (e.g. Saul et al. 2012) but comparable to a previous starch study in ceramic vessels from a Minoan context (García-Granero et al. 2021) and higher than in grinding stones recovered from Minoan contexts (Procopiou et al. 2002). Starch grains were grouped in 25 morphotypes, which were measured (Table S5) and further arranged in eight taxonomical categories (Fig. 4, Table 3):

1) 49 small/medium polyhedral grains resembling taxa within the Panicoideae subfamily (Type 1, Fig. 4a).
2) 27 small to large rounded and discoidal/ovoid grains characteristic of the Triticeae tribe, including both types identified in the comparative collection (Types 2 and

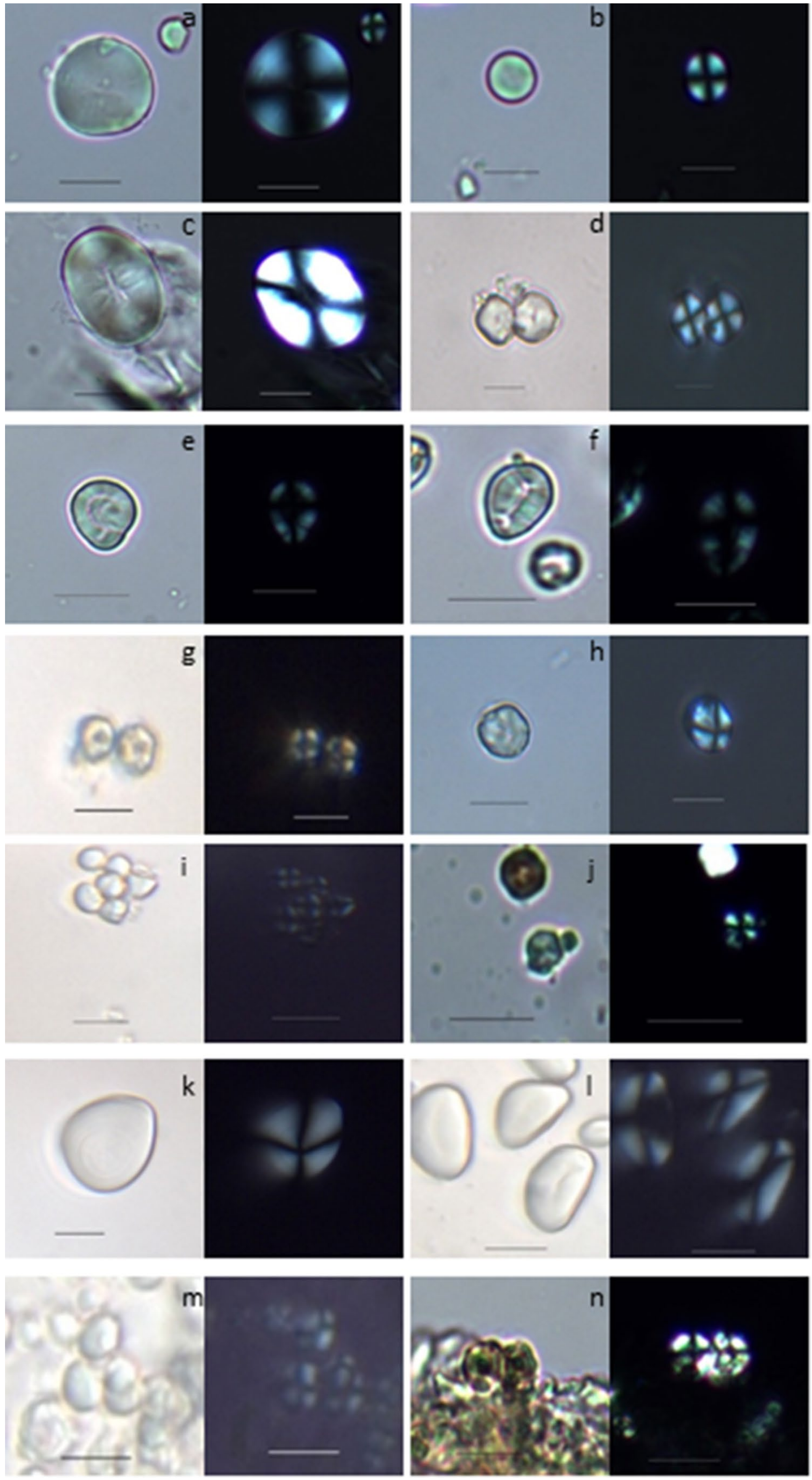

Fig. 3 Starch morphotypes observed from the modern comparative collection: **a** *Triticum aestivum* (Triticeae Type a), **b** *Triticum aestivum* (Triticeae Type b), **c** *Lens culinaris* (Faboideae), **d** *Setaria viridis* (Panicoideae), **e** *Cyperus esculentus* (Type a), **f** *Cyperus esculentus* (Type b), **g** *Coriandrum sativum* (Apiaceae Type a), **h** *Cuminum cyminum* (Apiaceae Type b), **i** *Avena sativa*, **j** *Prunus dulcis*, **k** *Leopoldia comosa*, **l** *Quercus ilex*, **m** *Pinus pinea*, **n** *Pistacia terebinthus*. Scale bar, 10 µm

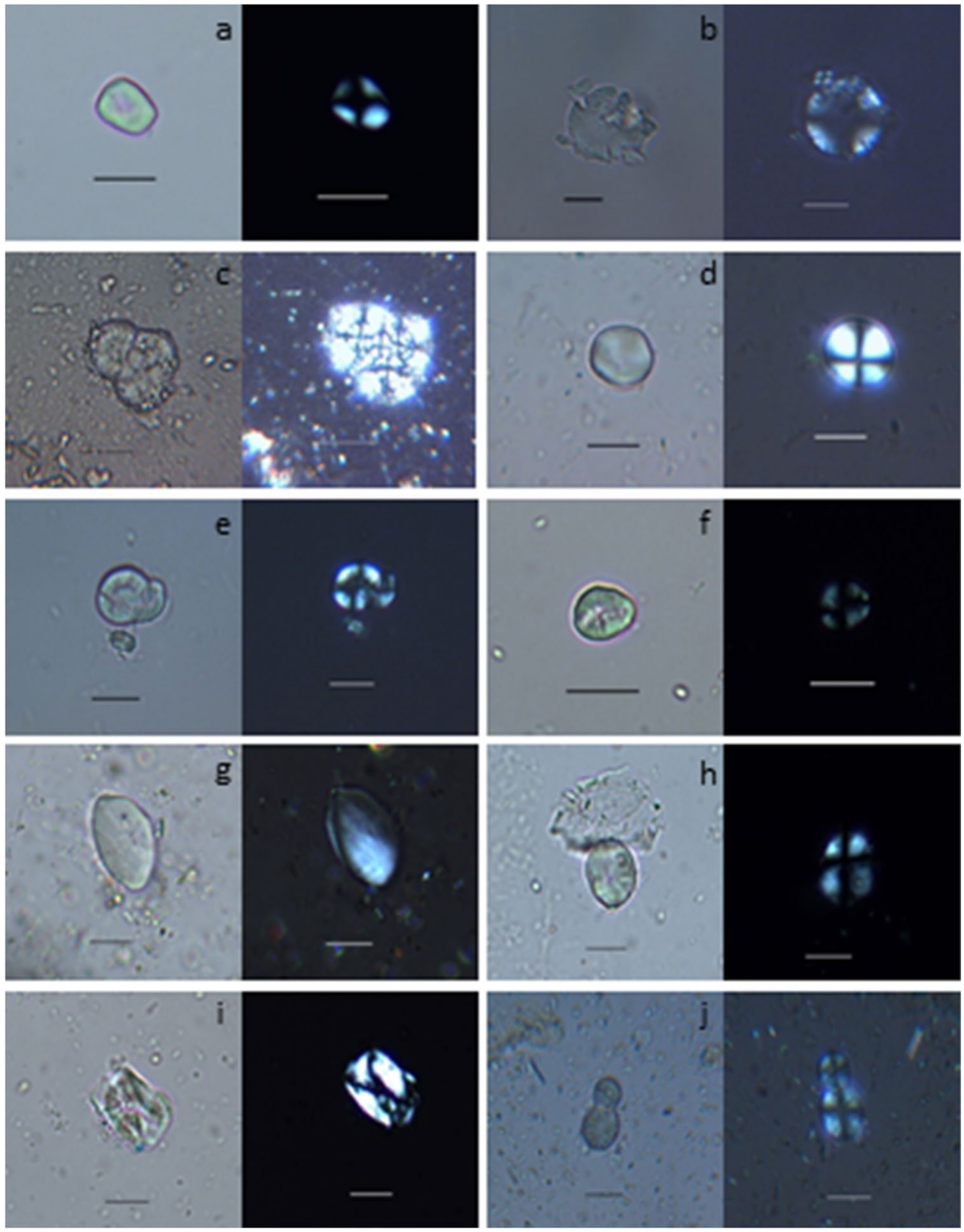

Fig. 4 Starch morphotypes observed in samples from Sissi and Malia: **a** Panicoideae (Type 1), **b** Triticeae Types a and b (Types 2 and 3), **c** cf. Triticeae (Type 15), **d** cumin-type (Type 13), **e** *Cyperus esculentus* Type 7 (Type a), **f** *Cyperus esculentus* Type 6 (Type b), **g** unidentified USO (Type 4), **h** Unidentified plant taxa (Type 14), **i** damaged unidentified grains, **j** possible starch grains (Types 21 and 22). Scale bar, 10 µm

3, Fig. 4b), as well as 18 medium ovoid grains showing certain resemblance to Type A Triticeae starches, categorised as cf. Triticeae (Type 15, Fig. 4c).

3) Eight small spherical grains comparable to the Apiaceae Type b grains identified in *Cuminum cyminum*, categorised as cumin-type (Types 9 and 13, Fig. 4d).
4) 21 grains characteristic of *Cyperus esculentus*, including both types identified in the comparative collection (Types 6 and 7, Fig. 4e–f).
5) Six grains with highly eccentric hila, often found in USOs, which were further categorised in four different types: two large, ovoid and discoidal grains (Type 4, Fig. 4g); two small, ovoid grains (Type 23); one ovoid-piriform (pear-shaped) grain (Type 17) and one rounded-piriform grain (Type 18).
6) Six medium grains of variable shape (spherical, hemispherical and ovoid) from unidentified plant taxa (Types 14, 16, 19, 24, 25, Fig. 4h), not observed in the comparative collection or published literature.
7) Seven starch grains were too damaged to be taxonomically identified (Type DU, Fig. 4i).
8) 93 particles of unknown nature, possibly starch grains (Types 21 and 22, Fig. 4j).

Archaeological starch grains from most identified taxa (Triticeae, Panicoideae, *Cyperus esculentus* and cumin-type)

Table 3 Description of the starch morphotypes identified in the archaeological samples of Sissi and Malia

Type	N_o	Size	Extinction cross	Shape		Facet	Texture	Lamellae	Hilum			Length (µm)				Taxonomy
				2D	3D				Position	Type	Fissure	N_m	Range	Mean (StD)	N_{min}	
3	16	M/L	R	R	DI		S	Y	C			14	11.39–28.88	21.74 ± 4.70	7	Triticeae Type a
2	11	S	R	R	OV		S	N	C	SV		10	3.58–9.56	6.42 ± 2.12	34	Triticeae Type b
15	18	M	R	OV	OV		R	N				4	21.81–31.04	27.84 ± 4.14	4	cf. Triticeae Type a (damaged aggregate)
1	49	M	R	PL	PL	FL	WR	N	E	SV		49	6.58–22.88	13.94 ± 3.64	12	Panicoideae
13	8	S	R	R	SPH		RD	N				8	5.17–11.83	9.70 ± 2.08	15	Apiaceae Type b (cumin-type)
7	16	M	R	SR	IR		R	N	C	LV		16	8.46–17.41	13.51 ± 2.84	10	*Cyperus esculentus* Type a
6	4	M	R	OV	OV		S	N	C		Y	4	6.40–9.77	8.02 ± 1.69	17	*Cyperus esculentus* Type b
4	1	L	R	OV	DI		S	N	HE			1	28.73			USO Type a
17	2	M	IR	OV	PI		S	Y				2	15.13–21.64	18.39 ± 4.60	9	USO Type b
18	1	M	IR	R	PI	FL	WR	N				1	16.86			USO Type c
23	2	S	R	OV	OV		S	N	C		L	2	10.56–11.10	10.83 ± 0.38	2	USO Type d
14	2	M/L	R	R	OV		R/S	N				2	17.71–19.33	18.52 ± 1.15	2	Unknown taxon Type a
16	1	M	IR	BL	HEM		S	N				1	16.56			Unknown taxon Type b
19	1	S	IR	TR	OV		S	N				1	21.33			Unknown taxon Type c
24	1	S	R	SR	SPH/GB		s	N	C	SV	C,SV	1	10.08			Unknown taxon Type d
25	1	M	M	IR	OV/OV		RD		C		L	1	14.94			Unknown taxon Type e
21	68	S	R	R	DI		S	N				27	2.32–26.52	12.23 ± 5.03	22	Possible starch Type a
22	25	S	R	R	DI		S	Y				11	9.07–19.40	12.50 ± 3.08	13	Possible starch Type b
DU	7															Damaged unidentifiable

Size: S = small (5–10 µm), M = medium (10–20 µm), L = large (20–50 µm). Extinction cross: R = regular, IR = irregular. Shape 2D: SR = subround, R = round, OV = ovate, PL = polygonal, TR = triangular, IR = irregular, BL = bell-shaped. Shape 3D: HEM = hemispherical, SPH = spherical, OV = ovoid, GL = globose, PL = polyhedral, IR = irregular, DI = discoidal, PI = piriform. Facet: FL = flat. Texture: WR = wrinkle, S = smooth, R = rough, RD = ridged. Lamellae: Y = yes, N = no. Hilum position: C = centric, E = eccentric, HE = highly eccentric. Hilum type: LV = large vacuole, SV = small vacuole. Hilum fissure: L = linear, Y = y-shaped (see Table S2 for the list full of descriptors). N_o = number of observed starch grains. N_m: number of measured starch grains (raw data can be found in Table S5). N_{min} = minimum number of starch grains that need to me measured to accurately represent the taxon (according to the formula proposed by Ball et al. 2016)

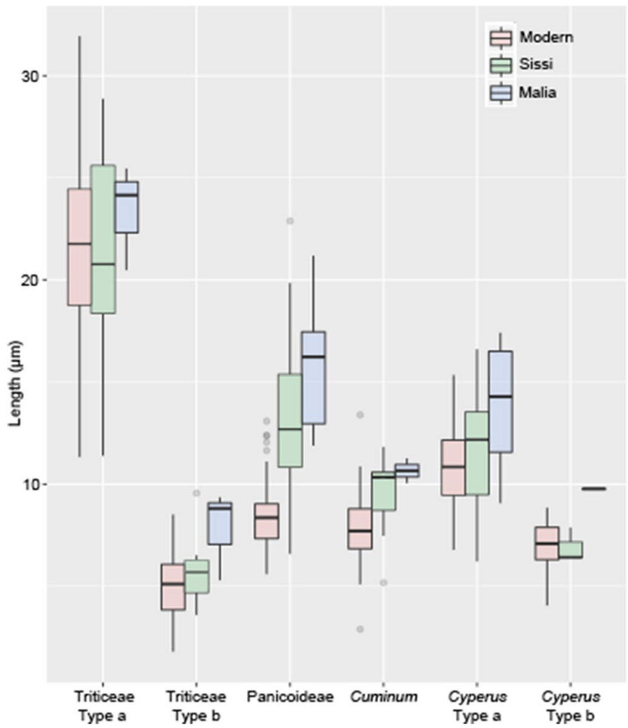

Fig. 5 Boxplots comparing the maximum length of starch grains from selected taxa within the modern comparative reference collection and archaeological samples from Sissi and Malia

are bigger than modern comparative material from the same taxa (Fig. 5). For the archaeological material, N_{min} was lower than N_m only where a substantial amount of starch grains from a particular taxon were recovered, specifically Triticeae Type a, Panicoideae and *Cyperus esculentus* Type a (Table 3).

Starch grains were not equally retrieved from all vessel types (Table 4). Most grains come from cooking dishes ($n = 49$), tripod cooking pots ($n = 30$), jars ($n = 20$) and trays ($n = 10$), whereas few grains ($n \leq 5$) were recovered in basins, bowls, kalathos, larnax, portable hearths and the pyxis, and no starch was observed in the samples from the smoker and the brazier. *Cyperus esculentus* starch grains were particularly abundant in cooking dishes, whereas other morphotypes were more widespread among different vessel types.

Discussion

The analysis of starch grains from Minoan cooking-related vessels evidenced the presence of different types of plant foodstuffs, including cereals, USOs and, potentially, spices and expands the extant information about the Minoan diet and enriches aspects of food preparation and consumption in BA Crete. The starch assemblage further included a number of unidentified grains that do not belong to agricultural staples (cereals and pulses) or to plant species included in the comparative collection. These starch grains could belong to plants consumed as complements to agricultural staples such as fruits, nuts, condiments and leafy greens, all categories that have been recovered from BA contexts in Crete (Livarda and Kotzamani 2013: Table 3) or are recorded in Linear B tablets (Sarpaki 2001), which were not included in the comparative collection. We are aware of the limitations of this study, where a relatively small number of modern

Table 4 Starch grains identified in ceramic samples from Sissi and Malia classified by sample type

Material sampled	N of samples	Triticeae	Panicoideae	Cumin-type	Cyperus esculentus	Oher USOs	Unknown taxa	Damaged unidentified	Possible starches	N of starch grains
Basin	3	1	0	0	0	0	0	0	0	1
Bowl	3	0	0	1	0	0	0	0	0	1
Brazier	1	0	0	0	0	0	0	0	0	0
Dish	29	6	21	1	17	0	2	1	0	48
Jar	14	8	6	1	1	1	2	1	0	20
Kalathos	5	1	2	0	0	0	0	0	0	3
Larnax	1	0	2	0	0	0	0	0	0	2
Portable hearth	2	2	0	1	0	0	0	0	0	3
Pyxis	1	5	0	0	0	0	0	0	0	5
Smoker	1	0	0	0	0	0	0	0	0	0
Tripod cooking pot	22	8	11	3	3	0	2	3	0	30
Tray	8	0	7	0	0	2	0	1	0	10
Sediment	11	14	0	1	0	3	0	1	93	112
Total	101	45	49	8	21	6	6	7	93	235

plant species was included. Moreover, N_{min} was not reached for the morphometric data of all the analysed modern taxa, which means we may not have accurately represented the variability within some of the studied taxa, particularly those where starch grains are rare or very rare. The results of this study, however, add valuable data to the study of past culinary practices in the eastern Mediterranean and beyond, expanding the extant information about the Minoan diet and enriching aspects of food preparation and consumption in BA Crete.

The identification of staple crops

Macrobotanical evidence shows that the main crops in Minoan Crete were emmer (*Triticum turgidum* ssp. *dicoccum*), free-threshing wheat (*Triticum turgidum/aestivum*), hulled barley (*Hordeum vulgare*) and a variety of pulses (*Lens culinaris*, *Vicia faba*, etc.) (Livarda and Kotzamani 2013). The presence of domestic cereals (Triticeae) in the starch assemblages from Sissi and Malia is, therefore, not surprising. Indeed, Triticeae starch grains were identified at both sites in different types of cooking vessels, suggesting that a variety of cooking techniques (boiling, stewing and roasting) were used to prepare cereal-based meals.

In striking contrast, the absence of pulses in the starch assemblage from both sites clearly diverges from the macrobotanical evidence. Pulses have been attested in Minoan contexts throughout the island, from small settlements to palaces (Livarda and Kotzamani 2013), including the two sites that were part of this study (Bouchard-Perron 2017; Livarda personal communication; Sarpaki 2007). Two alternative interpretations can explain the absence of pulse starch grains at Malia and Sissi. On the one hand, it could be related to the low preservation of pulse starch grains in Minoan vessels due to taphonomical processes. Interestingly, pulse starch grains were also absent from pottery vessels and sediment samples at nearby Knossos-Gypsades (García-Granero et al. 2021), which would seem to support this hypothesis. However, soil bacteria do not seem to favour pulse starch grains over other plant resources (Hutschenreuther et al. 2017). Moreover, the wide variety of starch morphotypes observed at Malia and Sissi shows that starch preservation at both sites is generally good (despite the relatively low overall starch concentration), therefore suggesting that taphonomical processes are unlikely to have caused the absence of pulse starch grains. Alternatively, this absence may be reflecting the social context of pulse consumption in Minoan urban centres and peripheral settlements. Despite their ubiquity in macrobotanical assemblages (including palatial sites), the (deliberate?) lack of references to pulses in administrative Minoan palatial records (Linear B tablets)—contrary to other staple crops such as wheat and barley (Halstead 1992; Palmer 1999: 465; Sarpaki 2001)—seems to suggest that pulses were treated/valued differently than cereals. Indeed, stable isotope analyses from the LM II storage deposits from the Unexplored Mansion at Knossos suggest that the production of pulses was household-based and not controlled by the palace, as seems to have been the case for cereal crops (Nitsch et al. 2019). The starch evidence from Sissi and Malia, as well as Knossos-Gypsades (García-Granero et al. 2021), further suggesting that pulses followed a different *culinary* pathway than cereals. Future starch grain research from storage and food-related artefacts at palatial and non-palatial sites will help enlightening pulse production and consumption practices in Minoan contexts.

The presence of Panicoideae starch grains in different types of vessels is also puzzling. There is a small evidence of millet crops (c.f. *Panicum* sp., putatively domestic *Panicum miliaceum*) and weeds (*Setaria* sp., presumably *Setaria verticillata/viridis*) in BA Crete, in particular during the Post-Palatial period—LMIIIB at Malia/Quartier Nu (Sarpaki 2007: 883) and LMIIIC at Kastelli/Chania (West Crete) (Sarpaki 2016: 421). Although the macrobotanical evidence suggests that small millets were a very minor crop in Minoan Crete, if at all cultivated, it is worth keeping in mind that charring conditions leading to potential preservation are more restrictive for small millets (e.g. Walsh 2017) than for large-seeded cereals (e.g. Boardman and Jones 1990). Considering that the overall preservation of macrobotanical remains in Minoan contexts is relatively low (Livarda and Kotzamani 2013), it is plausible that small millets are underrepresented in the Minoan archaeobotanical record. Microbotanical remains may be thus better suited to identify the consumption of small millets in Minoan Crete. Indeed, phytolith analyses from a small trench (3 × 2 m) excavated in 1997 in the Central Court at Knossos spanning the whole Neolithic occupation of the site (c. 7000–4800 cal. BC) showed the presence of millet-type phytoliths in the upper layers of the trench (Madella 2013). Although the absence of clear contextual information impeded a more nuanced interpretation of the phytolith assemblages, it should be noted that small millets were not recovered from the macrobotanical samples from the same contexts (Sarpaki 2013). Starch grains are also good indicators for the preparation/consumption of small millets in contexts where macrobotanical evidence is scant or virtually absent. One such case is Middle/Late Neolithic Stavroupoli (northern Greece), where starch evidence from cooking vessels showed the preparation of small millet weeds together with domestic crops (García-Granero et al. 2018).

The apparent contradiction between the macrobotanical and starch assemblages at Sissi and Malia can therefore be explained as a result of the different taphonomic pathways affecting the deposition and preservation of each type of plant remain. This said, it is worth noting that the Panicoideae starch grains recovered at Sissi and Malia are bigger than the *Panicum* and *Setaria* grains observed in our modern comparative collection and elsewhere (e.g. Yang et al. 2012). The comparatively big size of the archaeological starch grains does not necessarily exclude their identification as small millets. Recent research has shown that different processing techniques such as grinding and boiling enlarge the size of small millet starch grains (Li et al. 2020; Ma et al. 2019; Wang et al. 2017: Fig. 6). The relatively large size of most archaeological starch grains from Sissi and Malia compared to modern material could thus suggest that starch grains had been processed before their deposition, which is unsurprising considering that most analysed samples come from cooking vessels. Therefore, the Panicoideae starch grains observed at Sissi and Malia could represent the consumption of small millet crops and/or weeds. However, we must also consider the possibility that these starch grains (or, at least, part of them) could belong to a different taxon within the Panicoideae subfamily, including maize (*Zea mays*), a common source of modern starch contamination (Crowther et al. 2014). Although we took strict precautions to minimise the chance of environmental contamination and while starch grains were completely absent from all laboratory control samples, this possibility cannot be entirely discarded.

Overcoming the staple crops paradigm

Although herbs and condiments are mentioned in Linear B tablets, they have rarely been macrobotanically attested in BA Crete, with only two coriander seeds having been reported to date (Livarda and Kotzamani 2013: Fig. 12), including one case from Malia palace (Politis 1933: Fig. 4). The presence of cumin-type starch grains at Sissi is thus highly relevant, since it constitutes direct evidence for the use of condiments in Minoan cuisine and in different cooking techniques. It is worth highlighting that the larger concentration of cumin-type starch grains were observed in tripod cooking pots, suggesting that they represent the remnants of condiments added to stews. The low number of cumin-type starch grains observed ($n=8$) may lead to the interpretation that cumin was not commonly used in Minoan cuisine; however, we must take into account that this morphotype was very rarely observed in modern cumin seeds, and therefore, cumin may be underrepresented in the starch assemblage when compared to high starch-producing taxa (e.g. cereals).

References to cumin in Linear B tablets are scarce, and it is only mentioned in tablets from Mainland Greece (Mycenae), not from Knossos. According to these administrative texts, cumin, among other ‘exotic’ commodities, had a controlled acquisition and handling procedure (Ventris and Chadwick 1973). This potentially controlled consumption and culinary use as flavour enhancer and/or in aromatics as essence (Fox 2008) could enrich the discussion about the existence of elite food consumption in Minoan contexts (Isaakidou 2007). It remains unclear whether cumin was imported from the east to the Mycenaean mainland and then to Crete or if cumin seeds arrived to Crete directly from the east (Sarpaki 2001; Shelmerdine 1985). Indeed, archaeological evidence for the use of cumin has not been reported so far in the prehistoric Aegean (Sarpaki 2001) but has been attested in BA contexts in Egypt, Anatolia and the Levant during the 2nd mil. BC—see, for example, the evidence from Deir el Medineh, in the Tomb of Kha, and from the Tomb of Tutankhamun (Egypt), or from Tell ed-Der (Syria), (Sarpaki 2001; Saul et al. 2013 and references therein). Further pottery and contextual analysis, currently ongoing, will enlighten the context of consumption of this exotic commodity in the most common Minoan type of cooking vessel.

Beyond condiments, the widespread presence of USOs in cooking vessels from Sissi and Malia offers a new perspective, from a nutritional and economical point of view, to the foodstuffs consumed in Minoan cuisine. According to ethnobotanical evidence, the consumption of rhizomes, tubers, bulbs and roots is an important aspect of the Mediterranean diet which still survives in the Cretan food tradition until today—for example, Cretans collect wild *Leopoldia comosa* (syn. *Muscari comosum*) bulbs (common name βολβοί or ασκορδουλάκοι) from the mountains for human consumption (first author’s ethnographic work; Kavvadas 1950: 389). Despite the inclusion of several USOs in the comparative collection, it was not possible to identify plant species of six starch grains with morphological characteristics comparable to USOs. A more refined identification of these food resources, and thus a better understanding of the role of USOs in Minoan cuisine, will only be possible with the creation of an all-encompassing modern comparative collection of edible USOs in Mediterranean and Cretan flora (Kavvadas 1950; Sarpaki 1992a, b), which is beyond the scope of this study.

Based on the comparative collection created for this study, we were able to identify starch grains from tiger nuts (*Cyperus esculentus* tubers*)* in samples from Sissi and Malia. Archaeobotanical remains of *Cyperus* sp. have not been reported in the prehistoric Aegean, but the presence of this taxon among charred remains is not excluded (and, actually, its cultivation has been suggested in Akrotiri-Thera; Sarpaki 2001). Moreover, *C. esculentus* is mentioned in Linear B Tablets, called *ku-pa-ro* and described as of Cypriot origin (together with coriander, Melena 1974; Ventris and Chadwick 1973: 221), referring to its provenance and confirming the connection of the plant with the East. Furthermore, sedges (identified as potential *C. esculentus*) are depicted in two Minoan wall paintings in the BA Aegean: the Landscape painting in the Miniature frieze of the West House in Akrotiri-Thera (Morgan 1988, 19) and the Floral fresco from the Unexplored Mansion at Knossos (see discussion in Chapin 1997: 17).

According to ethnobotanical evidence around the world, *C. esculentus* has multiple uses, including fodder, crafts, medicine, perfumery and food (Simpson and Inglis 2001). It is a summer crop, and the edible parts of the plant, the tubers, contain more oil and starch than its weedy relatives (de Vries 1991: 29). Tiger nuts can be eaten raw as a vegetable, tasting sweet or nutty, boiled and/or roasted, as flour or as edible oil (de Vries 1991; Sarpaki 2001; Wilson 1988). In modern Greece, it is known as ground almond (αμύγδαλο εδάφους) or manna of heaven (μάννα του ουρανού) (Kavvadas 1950: 2207; Sarpaki 2001: 217–219) but is not currently cultivated or consumed. *C. esculentus* cultivation is documented in Egypt since 2400 BC, where abundant archaeobotanical data confirm its long history of cultivation (probably locally domesticated) and consumption during predynastic and dynastic periods (de Vries 1991; Negbi 1992; Sarpaki 2001).

The cooking and consumption of tiger nuts (*C. esculentus)* in prehistory are depicted in a wall painting of the Vizir Rekhmire's tomb, in Thebes, Egypt (18th Dynasty, fifteenth century BC). This example is very valuable not only because scenes of cooking are rare in Ancient Egyptian wall paintings but also because it has an inscribed recipe. The wall painting describes the preparation of a sweet pastry (a biscuit or cake) made with tiger nut flour and honey and cooked/fried with some kind of fat in a pan (de Garis Davies 1935, 1943; Wilson 1988; Negbi 1992; Manniche 1989: 42–43). The prepared tiger nut loaves, prepared as offerings for the gods on the name of the Vizir, have a ritual character and were consumed by priests or by the population of Thebes. The starch grains of *C. esculentus* observed at Sissi and Malia come mostly from cooking dishes, which are very similar to the pans depicted in Vizir Rekhmire's tomb. This evidence thus suggests that Minoan cooking dishes could have been used to process tiger nut dough (Table 4), which is a so far unknown culinary practice in Minoan cuisine. While very sporadic, the presence of *Cyperus esculentus* starch grains in other vessel types, such as tripod cooking pots and a jar, attests to the use of this plant species in the Minoan diet.

Conclusions

The present study illustrates the benefits of integrating several analytical methods and datasets (starch analysis, macrobotanical evidence, textual sources and pottery typological analysis) when analysing past culinary practices. The identification of previously unattested plant ingredients of Minoan cuisine broadens the horizon of food consumption practices, establishing a direct connection between archaeologically recognised plant species and the food prepared and consumed in utilitarian and cooking vessels. Moreover, this study contributes to the discussion regarding the economic and social meaning of food consumption in Minoan communities during Final Palatial and Post-Palatial periods, especially those food commodities mentioned in the palatial administrative texts of Knossos. Extensive and systematic sampling and analysis of cooking vessels in Minoan sites will help further unravelling Minoan culinary practices. Moreover, additional contextual, typological and traceological analyses of the cooking vessels analysed in this study, which are currently ongoing, will allow us to integrate the starch data in its wider context, in order to shed new light on the cooking methods and culinary processes employed by Minoan communities.

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