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Leveraging the potential of charred archaeological seeds for reconstructing the history of date palm

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ABSTRACT

The analysis of seeds from archaeobotanical assemblages is essential for understanding the history of crop cultivation. However, the majority of these seeds are typically found charred, a condition that not only degrades DNA, which hinders genetic studies, but also distorts their morphological features, which may bias comparisons with uncharred modern samples. While the effects of charring on several other crop seeds or fruits are well-documented, date palm seeds remain largely unexamined, limiting our ability to use charred seeds effectively to document the agrobiodiversity dynamic of this crop.

In this study, we assessed the morphological changes induced by the charring of 1375 *Phoenix* seeds under varied conditions, including charring temperatures of 200–600 °C, exposure durations from 10 to 120 min, and oxidizing/reducing conditions. By comparing charred samples with a modern reference collection of 6991 seeds, we evaluated the extent to which charring affects the ability to discriminate between groups of interest, particularly between wild and domesticated specimens.

Our study identified a significant shrinkage in *Phoenix* seeds, up to 25%, as a result of charring, with the extent of deformation influenced by the conditions of exposure. The shrinkage displayed an isometric pattern, keeping the proportions between seed dimensions consistent, thereby validating size ratios as a dependable metric for studying *Phoenix* agrobiodiversity even when dealing with charred material. Moreover, seed outlines stay predominantly unchanged, further endorsing their utility in morphometric studies. Using our results to examine 13 charred seeds from Shahi Tump and Miri Qalat, two Protohistoric settlements (5th-3rd millennia BCE) located in the Kech-Makran district of southwestern Pakistan, we deduced a predominance of wild resource utilization over the cultivation of date palms.

This research sheds light on the impact of charring on seed morphology and underscores its potential in differentiating between species and groups. It moreover confirms the value of charred seeds as a crucial resource for unraveling the complex history of crop cultivation, offering a detailed framework for future studies in this domain.

1. Introduction

Over the course of the last century, the study of the size and shape of seeds from archaeobotanical assemblages has yielded substantial contributions to the field of crop history (Stummer, 1911; Evin et al., 2022; Fuks et al., 2024). 'Traditional morphometrics' has long been proved useful to distinguish between wild and domesticated types (Stummer, 1911) using scalar measurements, their ratios, and synthetic indices (e.g., length and width, elongation, and circularity, respectively). 'Modern morphometrics' has further advanced our understanding of crop evolution, especially of perennial fruits (Evin et al., 2022; Fuks et al., 2024). Modern (or geometric) morphometrics has a geometrical and a more comprehensive approach of shape, i.e., what remain invariant under isotropic rescaling, translations, and rotations (Bookstein, 1992; Kendall, 1989; Kuhl and Giardina, 1982; Small, 1996). Notably, this method has brought to light the prevalence of elongated shapes among

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domesticates and the diversification of morphotypes arising from human-induced selection for larger fruits and subsequent cultivation practices (Bonhomme et al., 2020; Fuller et al., 2012; Fuller and Stevens, 2018; Terral et al., 2010, 2021). It has enabled a finer assessment of within-species agrobiodiversity facilitating the tracking of its evolution over space and time as seen in olive (Terral et al., 2010), date (Kaczmarek et al., 2024), or wheat (Roushannafas and McKerracher, 2023).

The majority of seeds recovered in archaeological context are charred, due to exposure to fire, usually during cooking activities, or intentional preservation methods involving charring (Fantone, 2016; Miksicek, 1987). The charring process compromises the preservation of macroremains (Wright, 2003). It degrades DNA, significantly hindering genetic analyses, and consequently, seed morphometrics becomes the primary method for studying charred seeds. However, even preserved, seeds may exhibit distortions, challenging morphometric inferences that rely on models trained on modern uncharred material (Smith and Jones, 1990).

Taphonomic biases resulting from charring have been extensively studied across various plant species using experimental charring settings. The variability in charring outcomes, influenced by diverse conditions and seed attributes, is evident in studies where some seeds, like chenopod nutlets, exhibit enlargement due to perisperm swelling, but more commonly, others, such as olives and sunflowers, experience shrinkage (Braadbaart and Wright, 2007; Terral et al., 2004; Wright, 2003). Elevated temperatures, longer exposure durations, and oxidative conditions exacerbate distortions (Bouby et al., 2018; Smith and Jones, 1990; Wright, 2003). To circumvent the shrinkage issue, and since an increase in length without a proportional increase in width is a recognized hallmark of domestication, researchers have employed dimensional ratios (Fuller and Stevens, 2018; Stummer, 1911). However, distortions caused by charring may not be uniform across the various dimensions (e.g., in grape, Smith and Jones, 1990). Studies utilizing geometric morphometrics revealed that seed shape remains largely unaltered by the charring process (e.g., in cereals, Bonhomme et al., 2017 and in grape, Bouby et al., 2018).

While the study of seed morphometrics has provided insights into crop evolution, the specific effects of charring on date palm seed morphology have received limited attention. This oversight is significant, considering the date palm's pivotal role in the agrosystems of north Africa and west Asia, and where charred date seeds are recurrent in archaeobotanical assemblages. The date palm (*Phoenix dactylifera* L.) is a perennial, dioecious plant belonging to the Arecaceae family and the *Phoenix* genus, which includes an additional 12–13 recognized species distributed across south Europe, Africa, and Asia (Barrow, 1998; Gros-Balthazard et al., 2021a). Its sugar-rich fruits, known as dates, is characterized by a single, somewhat oblong, one-seeded berry, encompassing distinct components including a waxy epicarp (skin), a fleshy mesocarp, and a thin parchment-like endocarp encasing the seed, which itself constitutes a sclerotic endosperm formed by a cellulose deposit along the inner cell walls.

Through the study of date seed dimensions and shape, our understanding of the date palm's origins and evolutionary trajectory has been significantly enhanced. Early observations by Zohary and Spiegel-Roy (1975) indicated that domestication led to the enlargement of both fruit and seed, with subsequent analyses revealing distinctive characteristics of cultivated date palm seeds, such as elongation, acute apices, and greater diversity compared to wild *Phoenix* species (Gros-Balthazard et al., 2016; Terral et al., 2012). This research has facilitated the identification of relict wild populations in Oman, supported by genetic evidence (Gros-Balthazard et al., 2017). Moreover, the application of seed morphometrics to archaeological datasets has revealed a decrease in wild morphotypes over time, accompanied by an increase in length and elongation, indicative of intensified date palm cultivation linked to human selection and vegetative propagation practices (Fuller and Stevens, 2018; Kaczmarek et al., 2024; Terral et al., 2012).

While most morphometric investigations have focused on desiccated seeds, some studies have combined charred and uncharred materials to assess seed measurement. Beech and Shepherd (2001) notably documented an unexpected trend where the earliest seeds were the largest, suggesting that this observation might be due to differences between charred and uncharred specimens. Fuller (2018) applied a +20% correction factor for charred sample dimensions, but this method risks bias due to both the variability in charring effects (e.g., Braadbaart and Wright, 2007) and the potential non-uniform shrinkage across all dimensions (e.g., Bouby et al., 2018).

In this study, we address the significant gap in research regarding the effects of charring on *Phoenix* seeds, a limitation that hinders our comprehension of the evolution of date palm agrobiodiversity. To this end, we conduct an experiment to quantify the impact of charring on these seeds and address the following key questions: 1) How seed dimensions and shape are affected by charring, and is the deformation isometric? 2) How do charring conditions like temperature, duration, and oxygen availability affect deformation? 3) How does the initial seed morphology influence the distortion caused by charring? 4) What is the impact of charring on the discrimination between groups of interest? Our objective is to determine the effectiveness of traditional size measurements and geometric morphometrics in analyzing charred archaeological seeds and to establish a methodology for guiding future research in this field. A series of carbonization experiments was carried out, encompassing diverse parameters and applied to a selection of 1375 seeds drawn from nine distinct accessions exhibiting different morphotypes, including two species (*Phoenix canariensis* and *P. dactylifera*) and eight date palm cultivars.

Following the experiments, we conducted a case study analyzing 13 archaeological charred seeds from the Kech-Makran district, southwest Pakistan. The seeds were sourced from two archaeological sites, Miri Qalat and Shahi Tump, which were occupied from the 5th to the 3rd millennia BCE (Tengberg, 1998, 1999). The sparse findings of *Phoenix* seeds in these sites, underscores a dual discrepancy: relative scarcity compared to regional sites from the same historical period and a marked deviation from the intensive date palm cultivation characterizing these sites in the contemporary period. It posed questions on seed conservation over time or the historical significance of date palms during this period (Tengberg, 1998). Our analysis seeks to 1) ascertain the species of these seeds, potentially belonging to either *Phoenix dactylifera* or *Phoenix sylvestris*, and 2) if identified as date palms, determine whether they were harvested from the wild or cultivated.

2. Material & methods

2.1. Charring experiment

2.1.1. Material for the charring experiment

We conducted the charring experiments using 1375 *Phoenix* seeds obtained from nine different accessions/varieties (Fig. 1; Figure A.1). The selection of accession aimed to encompass the wide diversity of seed shapes evidenced in *Phoenix* (Gros-Balthazard et al., 2016; Terral et al., 2012). To represent the rounded morphotypes, we included one wild relative species, *Phoenix canariensis*. To encompass the full range of morphotypes found in cultivated date palms, we included eight varieties, representing varying seed sizes, from small to large, with diverse shapes and diverse apices, ranging from rounded to pointed (Fig. 1).

2.1.2. Protocol of the charring experiment

All samples were subjected to charring under controlled conditions in a laboratory muffle furnace (Figure A.2). We varied three key parameters known to create various outcomes of seed distortion: temperature, duration of heat exposure and oxygen availability, later referred to as oxidizing/reducing conditions (Table 1; Wright, 2003; Smith and Jones, 1990; Ucchesu et al., 2016; Bouby et al., 2018). For reducing conditions (absence of oxygen), individual seeds were wrapped in

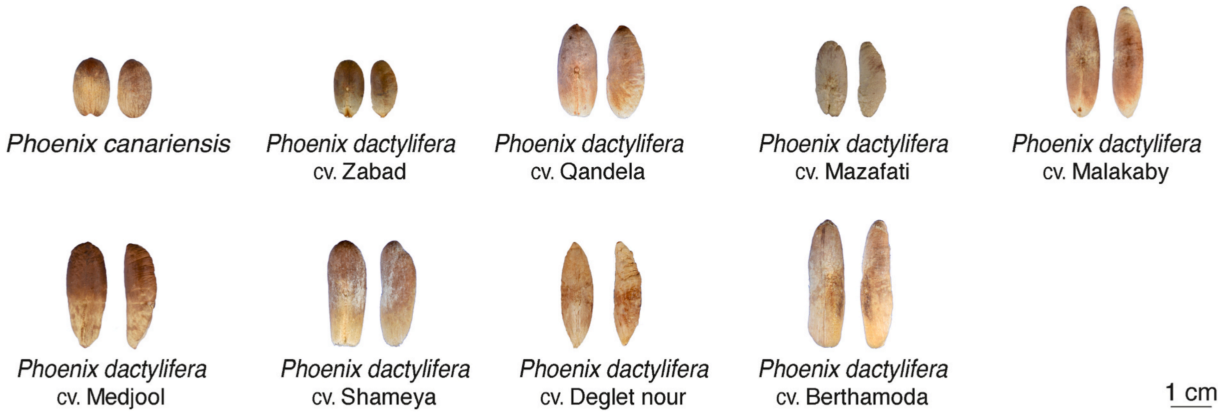

Fig. 1. Sampling of *Phoenix* accessions for the charring experiment. Although twenty seeds per accession were used for each set of charring conditions, the figure presents the dorsal and lateral views of just one example seed from each accession.

Table 1
Overview of charring experiment conditions (Ox: Oxidizing, Red: Reducing; X: Executed Combinations).

Temperature (°C)			250			350			450			550			
Duration of heating (min)			15	45	90	15	45	90	15	45	90	15	45	90	
		Condition													# seeds
		Ox	Exp 01	Exp 02	Exp 03	Exp 04	Exp 05	Exp 06							
		Red	Exp 07	Exp 08	Exp 09	Exp 10	Exp 11	Exp 12	Exp 13	Exp 14	Exp 15	Exp 16	Exp 17	Exp 18	
ID	**Cultivars/ Species**														
3482_DEG49	Deglet nour	Ox	x	x	x	x	x	x							360
		Red	x	x	x	x	x	x	x	x	x	x	x	x	
3481_CAN66	*Phoenix canariensis*	Ox	x	x	x	x	x	x							360
		Red	x	x	x	x	x	x	x	x	x	x	x	x	
3476_BER1	Berthamoda	Ox					x								60
		Red		x										x	
3477_SHA1	Shameya	Ox					x								60
		Red		x										x	
3478_QAN1	Qandela	Ox					x								60
		Red		x										x	
3479_MAL1	Malakaby	Ox					x								60
		Red		x										x	
134-136_ZAB	Zabad	Ox					x								60
		Red		x										x	
3480_MED16	Medjool	Ox					x								60
		Red		x										x	
3483_MAZ2	Mazafati	Ox					x								60
		Red		x										x	

aluminum foil, while oxidizing conditions were established by exposing the seeds to the air. By exploring the effects of these different variables, we aimed to encompass the diverse range of conditions that could be encountered in real-life charring processes.

Each seed was photographed before and after charring to monitor individual changes, using a Nikon D7200 camera equipped with a macro lens (60 mm). To remove any potential residual moisture that could influence the carbonization experiment (Wright, 2003), the seeds were dried in an oven at a low temperature (50 °C) for three days prior to the experiment.

We conducted three sequential experiments, with each subsequent experiment building upon the results of the previous one. The pilot experiment aimed at determining the parameters necessary for preserving seed integrity, considering that seed morphometric analyses are typically conducted on well-preserved seeds with smooth shapes and intact tips. We designed a series of experiments involving batches of five date seeds from the Deglet noor cultivar (cv.) (Table A.1). These seeds were subjected to carbonization under different experimental conditions, with temperatures varying from 200 to 600 °C and durations ranging from 10 to 120 min, in both oxidizing and reducing environments. Throughout the experiment, we gradually increased the duration exposure and temperatures, but refrained from reaching the maximum values in instances where seeds were destroyed beforehand. A total of 235 seeds was therefore included in this pilot experiment.

The subsequent experiment aimed at investigating the varying effects on seed morphology by applying distinct combinations of temperature, heating duration and oxygen availability. We used 720 seeds in total, from two accessions with dissimilar seed shapes, namely *Phoenix canariensis* (rounded seeds) and *Phoenix dactylifera* cv. Deglet noor (elongated seeds) (Fig. 1). This experiment involved a total of 18 combinations of charring conditions (Table 1). For each sample and experiment, we carbonized 20 seeds, a quantity previously shown to provide a representative depiction of individual seed shape and size in *Phoenix* seed assemblages (Gros-Balthazard et al., 2016; Terral et al., 2012).

The last experiment explored three charring conditions identified in the previous one as resulting in minimal, medium, and maximal seed deformation and referred to as mild, moderate and severe conditions, respectively (Table 1). We used a broader selection of accessions, incorporating a more diverse array of seed morphotypes to assess whether and how the initial seed morphology might influence the charring outcomes, or conversely, whether it has little impact. Therefore, in addition to the two accessions used previously, we added 7 accessions, 20 seeds each, totaling 9 accessions and 540 seeds.

2.1.3. Traditional and geometric seed morphometric methods

Two orthogonal views, using dorsal and lateral sides of the seeds were photographed to approximate their complete 3D shape. Dimensional measurements included length, width, thickness, and the dorsal view surface area, and were conducted using ImageJ v. 1.54f (Schneider et al., 2012). Despite prior findings of correlation among some of these variables (Gros-Balthazard et al., 2016), all were included in the present study to examine their differential changes under charring. Ratios among the three first dimensions were further calculated. In some cases, charred seeds were found in a deteriorated state after carbonization, impeding post-charring measurements. In these rare instances (2 cases for 1140 carbonized seeds), missing data were replaced with the average measurements from the respective accession under the specific conditions.

All subsequent analyses were performed with R v. 4.1.3 (R Core Team, 2024). Seed shapes were quantified using outline analysis and the elliptic Fourier transform (EFT) method (Kuhl and Giardina, 1982) using the package Momocs v. 1.4.0 (Bonhomme et al., 2014). A total of 130 equidistant points along the curvilinear abscissa were sampled on the seed (x, y) outline coordinates, using the seed's base as the homologous first point for outline analyses. These outlines were subsequently decomposed into a natural harmonic sum of trigonometric functions, known as harmonics, each represented by four coefficients (two for the x coordinates, two for the y coordinates). For standardization purposes, the harmonic H_0 was excluded, and the outline was centered and scaled based on its normalized centroid size to focus solely only on shape attributes which is form minus its size component. The information contributed by higher rank harmonics decreases while noise increases. Therefore, an optimal subset of seven harmonics per view was selected for accurate characterization of the seed's outline on both sides, following Kaczmarek et al. (2024). For subsequent statistical analyses, we thus used four Fourier coefficients for each of these seven selected harmonics, across each view (dorsal and lateral), resulting in a total of 64 coefficients per seed, later treated as quantitative variables.

2.1.4. Statistical analyses of charring experiments

To analyze the impact of charring on size, we computed the reduction induced by charring for each accession, size variable and set of charring condition. We investigated if the deformation magnitude was influenced by charring conditions or initial shape (represented by the length-to-width ratio, also called elongation) using multivariate analyses of variance (MANOVA) with the *adonis* function in the package *vegan* using 1000 permutations. Whether higher temperatures and exposure duration lead to higher seed shrinkage was tested with linear models using the *lm* function from the package *stats*. Whether oxidizing environment leads to higher seed shrinkage was tested with a one-sided Wilcoxon test with the *wilcox.test* function from the same package. The association between the seed morphotype (both seed length and seed elongation quantified by the length-to-width ratio) and the post-charring dimensional reduction was determined using Spearman's rank correlation coefficient using the *cor.test* function from the package *stats*.

We evaluated whether the deformation induced by charring is isometric, i.e., whether the proportional relationships among seed dimensions (length, width, and thickness) remain consistent before and after the charring process. This was achieved by formulating a linear model for each pair of dimensions using the *lm* function from the package *stats*, with an additional focus on the equation's slope expected to be 1 in case of isometry.

To assess the impact of charring on our ability to distinguish between the nine samples, we conducted two separate linear discriminant analyses (LDAs) using the *lda* function from the MASS package: one analysis focused on seed size, and the other on seed size ratios. The LDA models were trained on the uncarbonized seed data, allowing for the classification of the charred seeds into predefined groups. The accuracy of the model, determined before charring, and the accuracy of predictions made post-charring were calculated based on the proportion of seeds correctly allocated to their actual variety.

We further evaluated the discriminatory power of seed size measurements and their ratios among various groups and assess the effects of simulated charring on a large reference dataset. To simulate charring, we introduced a random reduction in size, ranging from 5 to 25%, to the seed measurements of each accession, reflecting the changes observed in our experimental charring (see Results). The reference dataset to which we applied simulated charring consists of data from previous studies and comprise 352 accessions from 6 species (Table B.1; Gros-Balthazard et al., 2016, 2017; Kaczmarek et al., 2024; Terral et al., 2012). For each accession, we used 20 seeds when available to capture the intra-individual diversity (Gros-Balthazard et al., 2016; Terral et al., 2012), but for 11 accessions, we could not access 20 seeds and they are thus represented by 7–19 seeds, totaling 6991 seeds. The date palm reference dataset includes cultivated ($n = 221$), feral ($n = 30$) and wild individuals ($n = 66$). Cultivated accessions derive from managed varieties, while feral accessions represent date palms that have escaped cultivation and now grow outside managed gardens. Wild accessions, identified as relict ancestral populations, are known solely from the mountains of Oman (Gros-Balthazard et al., 2017). The wild relative dataset comprises five wild relative species of the date palm: 3 *Phoenix caespitosa* (60 seeds), 7 *Phoenix canariensis* (107 seeds), 13 *Phoenix reclinata* (241 seeds), 38 *Phoenix sylvestris* (760 seeds), 6 *Phoenix theophrasti* (120 seeds). We applied separate LDA aiming to maximize the separation between various groups, namely species, status (wild relative species, cultivated date palm, feral date palm, wild date palm), and domestication status (cultivated and feral date palm versus wild date palm and wild relative species).

The LDA models were trained on the unaltered reference data, then allowing for the classification of the simulated-charred seeds into the predefined groups. To ensure the robustness in the model's predictive capability despite uneven sample size among groups, we used permutational LDAs. The method is described elsewhere (Bonhomme et al., 2021; Evin et al., 2013) and consists of resampling equal sample sizes from the various groups of the training dataset, ensuring unbiased class accuracies. To obtain balanced sample sizes, we sampled without replacement 80% of the sample size of the smallest class. For each cofactor of interest, 100 resampled datasets were generated, from which class accuracies (i.e., proportion of seeds predicted in their class of origin) were determined. Subsequently, these models were employed to predict the group for the simulated-charred seeds. As a result, each received 100 separate predictions, each derived from a distinct LDA model trained on different datasets. We aggregated the classification results using a majority voting approach: for each seed, across all repetitions, we tallied the frequency of its allocation to each class and assigned it to the class receiving the most votes.

Lastly, we assessed the effect of charring on seed shapes based on our carbonization experiment dataset. We derived the average contour of 20 seeds originating from the same individual or species by employing inverse EFT (Rohlf and Archie, 1984). We compared the average seed outlines pre- and post-charring through a visual inspection of their alignment and conducted a LDA on the Fourier coefficients to evaluate and compare the discrimination between pre- and post-charring conditions.

2.2. Case study: morphometric analysis of charred archaeological Phoenix seeds

2.2.1. Archaeological material

Six and seven non-fragmented charred seeds were recovered from the archaeological sites of Miri Qalat and Shahi Tump, respectively (Table 2). The origin of these seeds, whether from wild or domesticated *Phoenix*, is unclear, making them a valuable archaeological case study for our charring experiments based on modern materials.

Miri Qalat and Shahi Tump are two stratified mounds located near the modern town of Turbat in the Kech Valley, in the southwestern part of the Pakistani province of Baluchistan. They were investigated by the *French Archaeological Mission to Makran* directed by Roland Besenval (CNRS) as part of a comprehensive program comprising regional surveys (1987-89), followed by the large-scale excavations of Miri Qalat (1990-96) and Shahi Tump (1997–2003). A chronological framework identified four main protohistoric periods, I-IV (Besenval, 1997). The earliest known occupation dates to the mid-late 5th mill. BCE, representing a local aceramic Neolithic tradition. Periods II and III (4th and early 3rd mill. BCE) are marked by rich ceramic and metallurgic traditions within a larger cultural context centered on the Indo-Iranian borderlands. Period IV marks the end of the protohistoric period and is characterized by the presence of a material culture associated with the Indus Valley civilization whose heartland was situated in the eponymous river valley several hundred km to the east. Miri Qalat as well as a few other Indus settlements in the Makran region, such as Sutkagen-Dor and Sotka Koh, thus bear witness to the western extension of the Indus civilization during the second half of the 3rd mill. BCE. After a hiatus during the 2nd and early 1st mill. BCE, the region was reoccupied from early historical times until present day (periods V-VIII).

Most of the Makran region (*Gedrosia* in ancient Greek sources) consists of barren desert lands with a series of east-west oriented low mountain chains enclosing narrow alluvial valleys, such as the one where the intermittent Kech river flows before joining the larger Dasht river that reaches the Arabian Sea. Anthracological analyses undertaken at Miri Qalat and Shahi Tump shows an environment dominated during the protohistoric period by gallery-forests growing along the Kech river as well as xeromorphic subtropical wood- and shrublands on drier soils (Tengberg and Thiébault, 2003). The studies of faunal and seed/fruit remains show that subsistence economies were based since the late 5th mill. BCE on agro-pastoral activities with the herding of sheep, goats and cattle taking place alongside the cultivation of wheat, barley and pulses (Desse et al., 2008; Tengberg, 1999). Besides annual grain crops, the consumption of fruits from taxa such as jujube (*Ziziphus* sp.), dwarf palm (*Nannorrhops ritchieana* (Griff.) Aitch.) and date palm (*Phoenix* spp.) is attested by the presence of charred endocarp and seed remains.

Seeds attributed to *Phoenix* are relatively scarce on both sites. At Miri Qalat, where almost 186,200 seed and fruits remains (mostly cereals) have been determined taxonomically, only 27 date seeds were attested among which the majority (22) were found in contexts belonging to the most recent levels dated to the second half of the 3rd mill. BCE (Tengberg 1999). The archaeobotanical record from Shahi Tump has only been partly studied and produced occasional date seeds from contexts dated to the 3rd mill. BCE.

Table 2
Archaeological material from Miri Qalat (MQ) and Shahi Tump (ST).

ID	Site	Sample Number	Trench - Unit	Radiocarbon date
MQ_D1	MQ	14	IV-24	5005 ± 35 BP
MQ_D2	MQ	502	X-11	NA
MQ_D3	MQ	434	II-1017	NA
MQ_D4	MQ	564	IX-107	4645 ± 35 BP
MQ_D5	MQ	12	III-78	NA
MQ_D6	MQ	10	III-67	NA
ST_D1	ST	455	II-698	NA
ST_D2	ST	550	II-889	NA
ST_D3	ST	957	II-1017	4890 ± 30 BP
ST_D4	ST	919	II-974	NA
ST_D5	ST	919	II-974	NA
ST_D6	ST	924	II-985	NA
ST_D7	ST	914	II-988	NA
ST_D8	ST	914	II-988	NA
ST_D9	ST	122	II-206	4670 ± 40 BP

The low numbers of *Phoenix* seeds as well as their unusually small size compared to contemporaneous finds in eastern Arabia raised the question of their status as wild or cultivated fruits and generally of the role of date palm cultivation in the Makran region during the Protohistoric period. They may belong either to *Phoenix dactylifera* or *Phoenix sylvestris*, the latter being closely related to the date palm (Barrow, 1998; Gros-Balthazard et al., 2021). Presently, *Phoenix sylvestris* is found in India and Pakistan, to the east of the Makran region, though historical records suggest its range might have been more extensive (Gros-Balthazard et al., 2021). The original distribution of the date palm is still a matter of debate (reviewed by Gros-Balthazard and Flowers, 2021), with some researchers proposing an original habitat that encompasses this broad region (Fuller and Stevens, 2019). Our aim is to ascertain not only the species of these seeds but also whether they originated from wild or cultivated/domesticated plants if identified as *Phoenix dactylifera*.

Four seeds identified as belonging to the *Phoenix* genus, two from each site, were chosen for direct radio-carbon dating at the Poznan Radiocarbon Laboratory, Poland.

2.2.2. Statistical analyses of archaeological material using size and shape descriptors

Seed shape and seed size of the archaeological seeds were derived using the same method as described for the seeds of the charring experiment.

To explore the diversity of seed shapes across both the modern reference dataset (described above; Table B.1) and archaeological seeds, we performed a Principal Component Analysis (PCA) using the *prcomp* function on the full matrix of Fourier coefficients. The modern reference dataset formed the foundation for our model, which was then applied to the archaeological seeds through the *predict* function.

Subsequently, we aimed to predict the species and status (wild or cultivated) of the archaeological seeds. This was achieved through multiple LDAs, with models constructed based on the EFT data of the reference dataset. The classification of the archaeological seeds was then predicted using these LDA models. To address the disparities in sample sizes among the different classes of discriminant factors (cofactors), we employed the same method as described before to balance the sample sizes between groups of interest.

3. Results

3.1. Impact of charring on the morphology of Phoenix seeds

3.1.1. Charring conditions preserving seed integrity

To establish the threshold conditions under which seeds are not destroyed during charring, we conducted a series of experiments, each involving batches of five date seeds from the Deglet noor cultivar (Table A.1).

Depending on the specific conditions applied, the charring process yields a range of outcomes, spanning from seeds that are only lightly torrefied to seeds with destroyed tips, ultimately resulting in seeds reduced to ash (Figure A.2BC). Seeds exposed to oxidizing conditions exhibited a greater impact compared to those charred under reducing conditions (Table A.1). Indeed, under oxidizing conditions, no intact seeds were observed at temperatures of 400 °C and above. In contrast, even under the harshest tested reducing condition (600 °C for 120 min), 4 out of 5 seeds were recovered intact.

3.1.2. Impact of charring on seed dimensions

Building upon the insights of the pilot experiment, we conducted a second study wherein we varied heat exposure from 15 to 90 min and temperatures from 250 to 550 °C under reducing conditions, and from 250 to 350 °C under oxidizing conditions, on two accessions of different morphotypes (Table 1).

Comparing seeds before and after charring, we observed a consistent reduction in dimensions (Figs. 2–3; Table B.2). A significant positive correlation between pre- and post-charred measurements was evidenced across all four size variables, indicating systematic alterations in their dimensions (Figure A.3). On average, and across all experiments, we observed that the length, width, and thickness exhibited reductions of 9.3 ± 5.3%, 9.6 ± 6.8 %, and 8.6 ± 7.1 %, respectively, while the square root of the surface area of the dorsal view experienced a decrease of 10.1 ± 5.7 % (Fig. 3).

Our study reveals that the extent of deformation differs significantly across charring conditions (permutational MANOVA, p-value $<10^{-3}$; Fig. 3). Both higher temperatures and longer charring exposure resulted in greater seed size shrinkage (linear models, p-values $<10^{-15}$). For instance, at 250 °C, the length is reduced by 10.1% at most, while at 550 °C, the shrinkage ranges between 12.3% (15 min, reducing conditions) and 23.8% (90 min, reducing conditions). The same pattern is observed for the other seed dimensions, namely width, thickness and surface. Investigating the effect of the availability of oxygen, we found that an oxidative environment exacerbates the shrinkage (one-sided Wilcoxon test across all experiments, $W = 133904$, p-value $= 6.7 \times 10^{-6}$). For example, while seeds charred at 350 °C for 90 min in a reducing medium exhibited a length reduction of 7.5 ± 1.5%, the same conditions in an oxidative medium led to a reduction of 9.6 ± 1.7%. Our data notably suggest that temperature is the prevailing factor affecting seed deformation, as evidenced by the fact that at 550 °C, even a brief exposure of 15 min results in more than 10% length reduction, surpassing the maximum reduction observed at 250 °C under any duration.

3.1.3. Effect of the initial seed morphology on the distortion induced by charring

Although the size shrinkage trajectory is identical for both tested accessions, we found a significant difference in deformation among them across all experiments (permutational MANOVA, p-value $<10^{-3}$). For example, at 350 °C, we noted a more pronounced reduction in seed length for *Phoenix canariensis* in contrast to the Deglet noor date palm (9.1 ± 1.2% versus 7.0 ± 2.0%, respectively). Whether this divergence stems from a random effect of the experiment or from the distinct initial seed shapes (rounded versus elongated) remains uncertain and was thus investigated in the next set of experiments, encompassing a broader range of seed shapes.

While retaining the two initial accessions, we incorporated seven additional date palm varieties (Fig. 1), but streamlined our experimental focus by conducting fewer experiments, selecting three distinct sets of charring conditions that induced mild, moderate and severe impact on the seeds according to the previous set of experiments (Fig. 3; Table 1; Table B.2). Comparing seed dimensions pre- and post-charring across all experiments, we again observed consistent size reductions attributed to charring across the four size variables and for all morphotypes (Fig. 4). The reduction in length spans from 3.1 ± 0.8% to 7.4 ± 1.5% under the mild conditions, to 17.0 ± 0.9% to 18.9 ± 1.7% under the severe conditions. Our analysis revealed no monotonic relationship between the reduction in dimension post-charring and either the initial average seed length (Spearman's rank correlation, $S = 1.38 \times 10^{10}$, p-value $= 0.074$) or the morphotype's elongation, quantified by the length-to-width ratio ($S = 1.38 \times 10^{10}$, p-value $= 0.051$) (Fig. 4).

3.1.4. Effect of charring on group differentiation based on seed size and size ratios

A linear discriminant analysis (LDA) was used to assess size as a distinguishing factor among 9 individuals and to verify if seeds maintain their distinct size traits allowing for differentiation post-charring. Initially, seeds were accurately classified to their respective individuals at a rate of 94.7% (Figure A.4A). Post-charring, classification

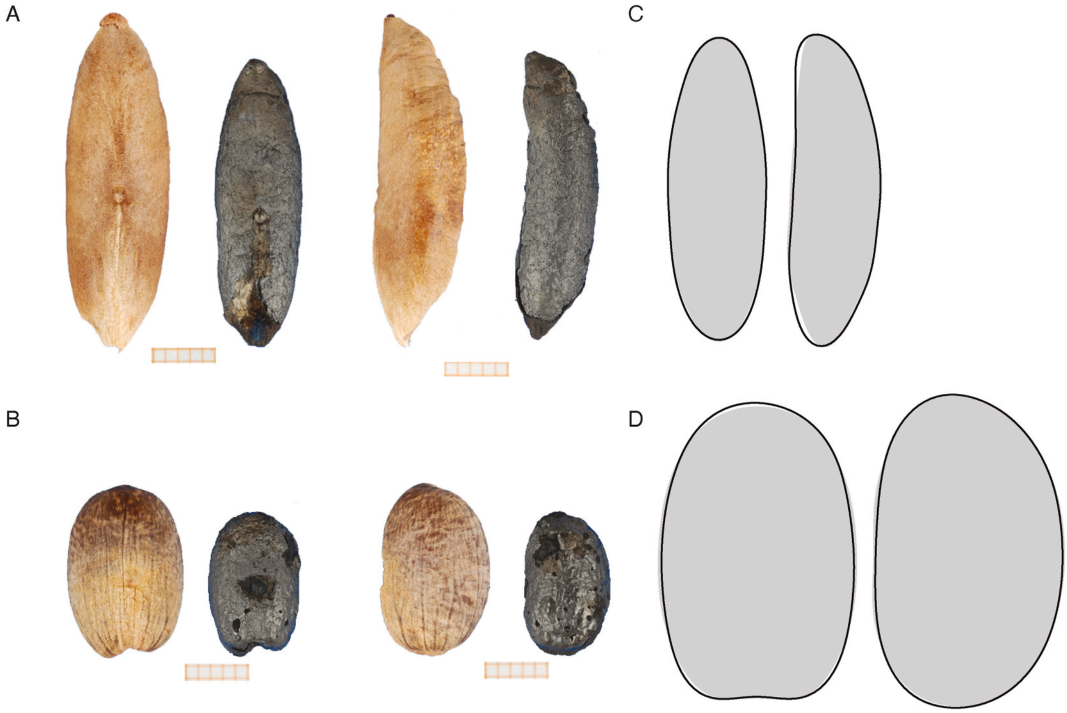

Fig. 2. Example of seed deformation due to charring at 450 °C, during 90 min in reducing condition. Example with one seed for both *P. dactylifera* cv. Deglet noor (top) and *P. canariensis* (bottom). A and B. Pictures of seeds before and after charring in dorsal and lateral side. C and D. Seed outline reconstruction based on 20 seeds before (black outline) and after (grey shape) charring.

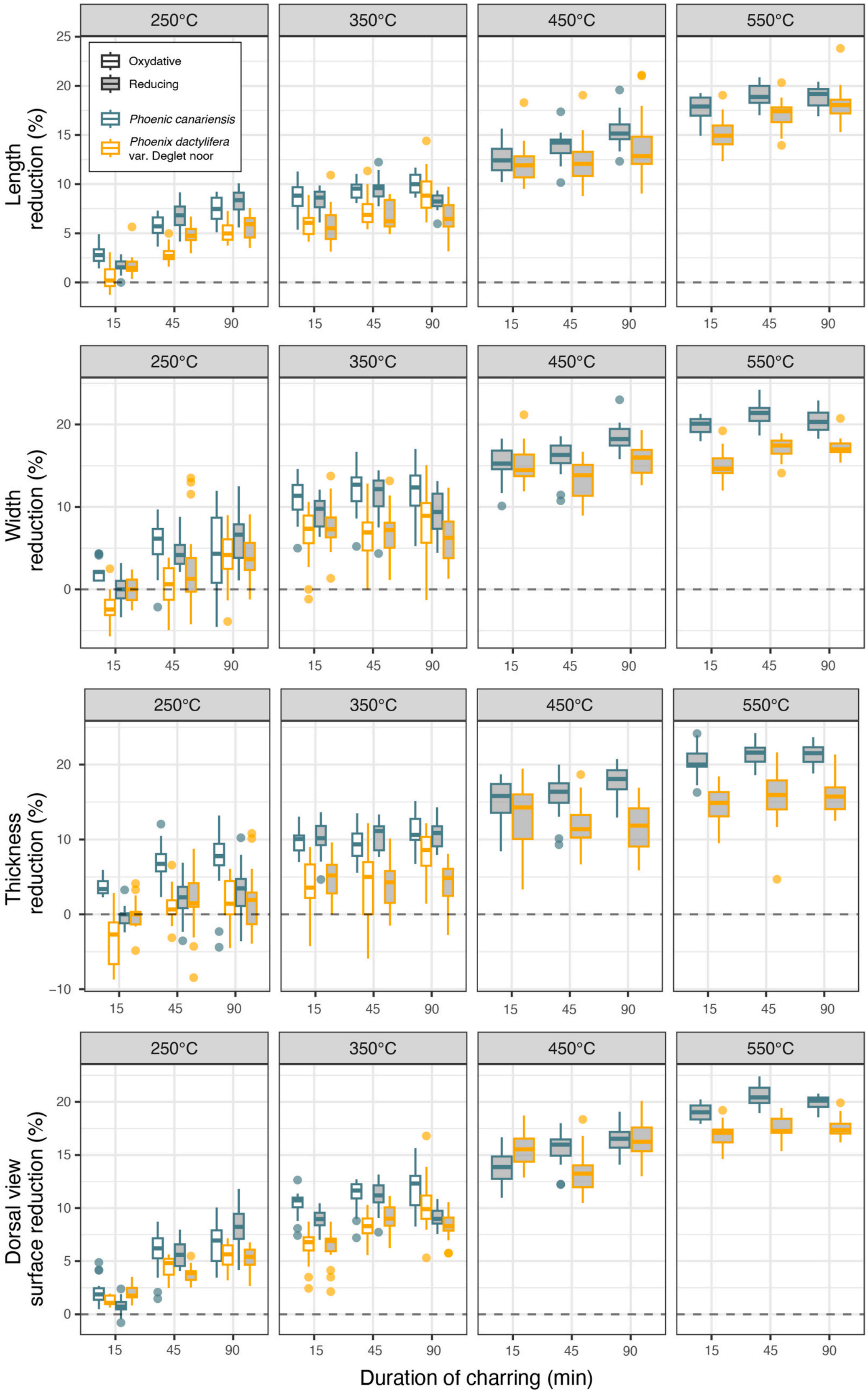

Fig. 3. Reduction in *Phoenix* seed dimension due to charring. The length, width, thickness and square root of the dorsal view were measured before and after charring. The reduction was assessed in two accessions (*Phoenix canariensis* and *Phoenix dactylifera* cv. Deglet noor) in 18 experiments with varying temperature, duration of exposure and availability of oxygen, totaling 720 seeds.

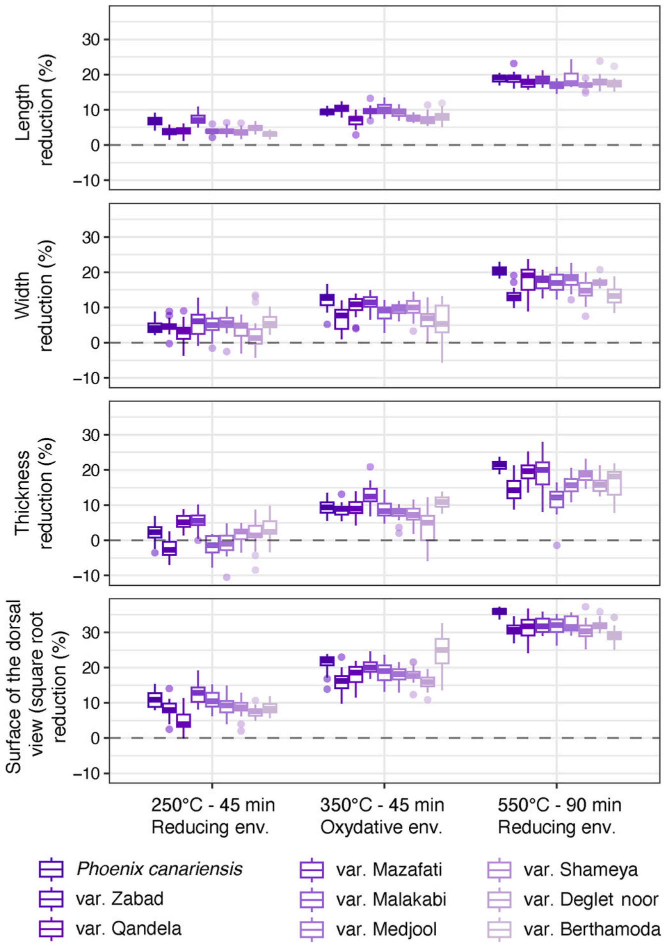

Fig. 4. Reduction in each size dimension across the nine accessions and under 3 sets of conditions. Accessions are ordered from left to right by length-to-width ratio, from high ratio (rounded seed) to small ratio (elongated seed): *Phoenix canariensis*, *Phoenix dactylifera* cv. Zabad, cv. Qandela, cv. Mazafati, cv. Malakabi, cv. Shameya, cv. Deglet noor, cv. Berthamoda. (one-column image).

effectiveness reduced to 73.9% in mild conditions, 70.0% in moderate conditions, and 30.6% under severe conditions. Using size ratios instead of absolute size measurements, the classification accuracy was 71.5% on average, 53.3% for the mild conditions, 69.4% for the moderate and 50.6% for the severe ones (Figure A.4B).

We then aimed at evaluating the discriminative potential of seed size measurements and their ratios in distinguishing among *Phoenix* species and among groups (wild, feral, cultivated date palms and wild relative species). We used a reference dataset (Table B.1; Table B.3) comprising nearly 7000 seeds from the six species. This assessment was conducted on seeds in their original state and following random reduction of the seed dimensions by 5–25% in order to simulate the effect of charring. The results suggest that seed size measurements are not effective discriminators of species, as substantial overlap occurs among them (Figure A.5A). Nonetheless, date palms were notable for their larger size metrics; they were the only species with seeds retaining a length above 2.4 cm even after simulated charring. Furthermore, only date palms exhibited a length-to-width ratio greater than 2.5, a length-to-thickness ratio greater than 2.9, and a width-to-thickness ratio exceeding 1.3, even post-simulation. Concerning the differentiation of the four *Phoenix* groups, the results mirrored those observed at the species level, with a significant overlap in both size measurements and ratios (Figure A.5B). The only exception was observed in cultivated date palms, which uniquely (even after charring) demonstrated a length exceeding 2.8 cm, a length-to-width ratio greater than 3.6, a width-to-thickness ratio above 1.4, and a length-to-thickness ratio above 3.9. These specific size metrics may serve as distinctive markers for cultivated date palms. We note that there is no specificity among species or groups for the smaller values of any of those measures nor their ratios which could provide indication if charred seeds happened to be of one species or of a specific wild or cultivated status.

We applied LDAs to our reference dataset (Table B.1; Table B.3) to evaluate the discriminative accuracy of seed size and size ratios in identifying species and domestication status. To discriminate species, size alone proved limited, with an accuracy of 70.8%, aligned with the previously noted overlaps. This accuracy dropped to 51.4% following simulated charring. Size ratios also turned out to present limited interest for differentiating species with accuracies of 55.4% and 56.7% before and after simulated charring. To discriminate different categories (wild, feral, cultivated date palms and wild relative species), size-based discrimination was modest, averaging 63.7% accuracy before simulated charring and falling to 50.3% thereafter. Size ratios scored low as well, with accuracies of 50.9% and 51.1% pre- and post-charring, respectively. In contrast, when attempting to distinguish between domesticated date palms (including both cultivated and feral accessions) and wild *Phoenix* species (encompassing wild date palm and wild relative species) based on size measurements, we achieved a notable accuracy of 85.4% for uncharred seeds. However, this accuracy decreased to 78.1% following simulated charring. Importantly, while this average accuracy appears satisfactory, it obscures a significant detail: accuracy for correctly identifying domesticated seeds was much lower compared to wild seeds in both uncharred and simulated-charred conditions (77.1%/93.6% and 58.7%/97.5%, respectively), suggesting that domesticated seeds are more frequently misclassified as wild, a trend that logically follows from the size-reducing effect of charring on seed dimensions. Finally, size ratios provided consistent high discrimination rates, achieving accuracies of 81.0% for uncharred seeds (73.9% for domesticated and 88.2% for wild) and 81.1% for simulated-charred seeds (74.0% for domesticated and 88.3% for wild).

3.1.5. Assessment of the isometric deformation patterns resulting from charring

We explored if the deformation induced by charring adhered to isometry, i.e., whether changes in the seed dimensions (length, width, and thickness) occurred at consistent and proportional rates relative to each other. Perfect isometry would result in a slope of 1 and an intercept of 0 in a linear regression analysis.

Upon analyzing all experiments and all nine accessions collectively, pronounced correlations in the reduction patterns of these dimensions became evident, suggesting near isometric deformation induced by charring (Fig. 5). Specifically, the length-to-width reduction ratio was nearly isometric at 0.98, suggesting that the length is decreasing slightly more than the width (linear regression, $R^2 = 0.72$, p-value $<10^{-15}$). In contrast, the length-to-thickness reduction ratio slightly exceeded isometry at 1.1, but still displayed a marked association ($R^2 = 0.71$, p-value $<10^{-15}$). The width-to-thickness reduction ratio, at 0.88, highlighted a distinct deformation pattern with the shrinking slightly more than the thickness, yet the relationship was still robust, evidenced by an $R^2 = 0.63$ (p-value $<10^{-15}$).

3.1.6. Evaluation of seed shape alteration induced by charring

Our findings suggest a near-isometric seed shrinkage induced by charring, implying minimal shape deformation, but seed shape extends beyond ratios of dimensions (Fig. 1) and we consequently further investigated the effects of charring on seed shape outlines (Table B.4).

Using the inverse EFT method, we reconstructed the average seed outline for each accession, calculated from 20 seeds, both before and after charring. Based on visual observations, the alignment between outlines before and after charring is strikingly accurate (Fig. 2; Figures A.5-6; Table B.3). Notably, even under the harshest conditions of charring at 550 °C for a duration of 90 min, the accession-average seed

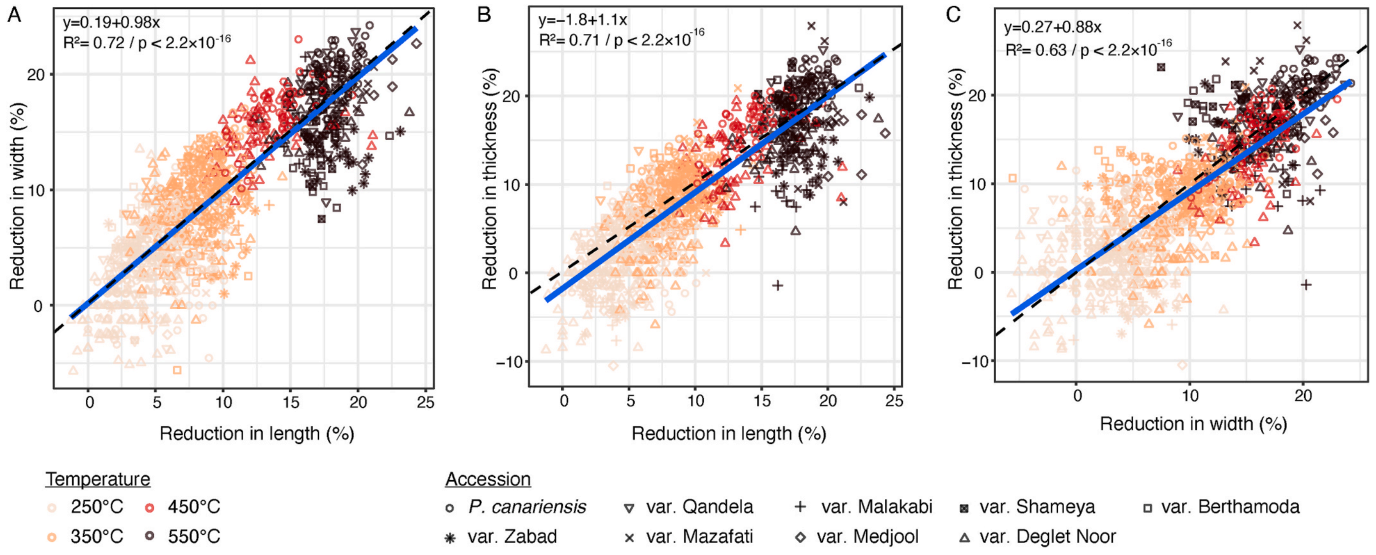

Fig. 5. Testing the isometry of the deformation of the seed due to the charring through correlations between variable reduction.

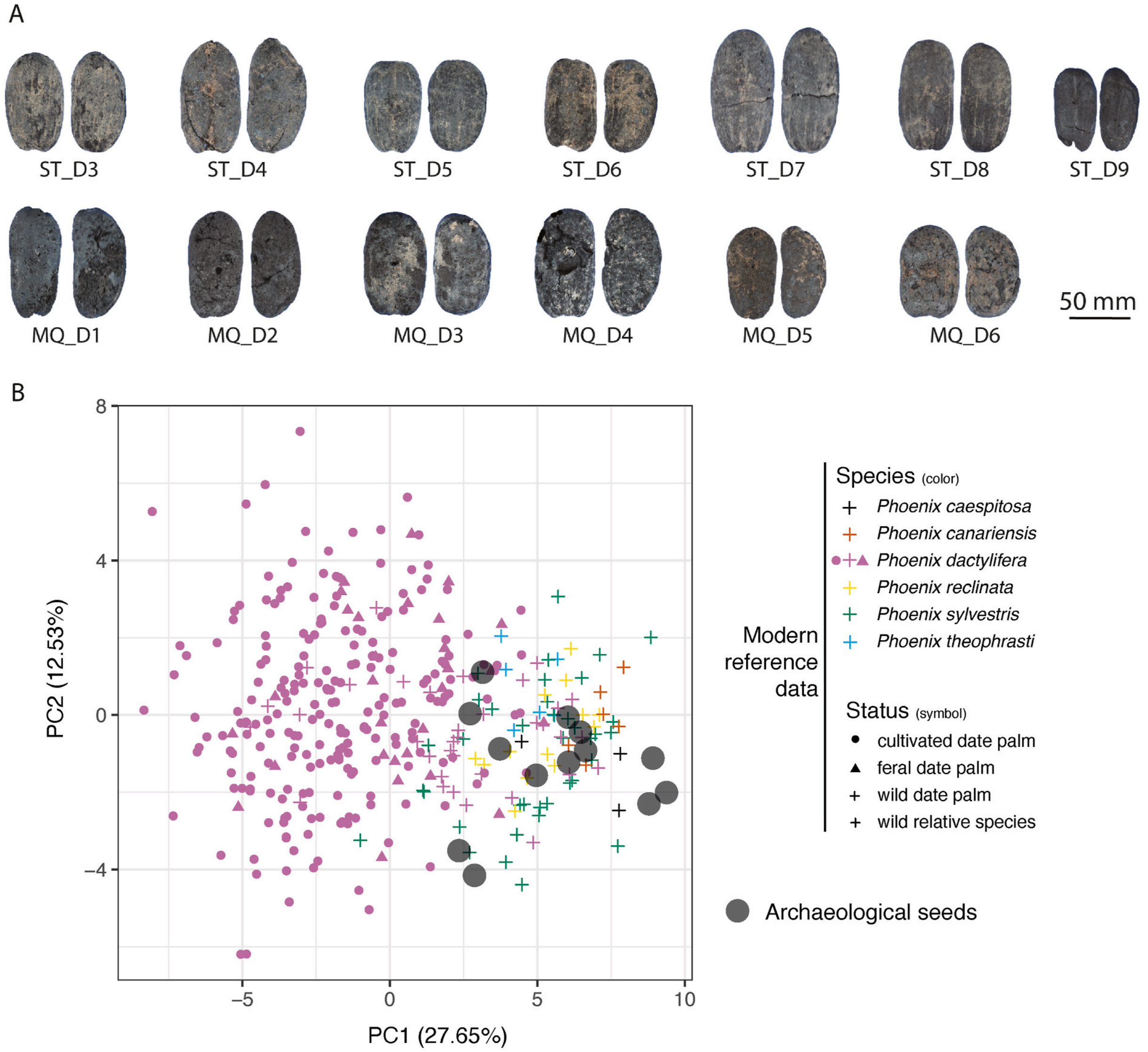

Fig. 6. Morphometric study of seeds recovered in Miri Qalat and Shahi Tump. A. Picture of the dorsal and lateral sides of each seed. B. Principal Component Analysis of modern reference sample (averaged seed coordinates) with projected archaeological seeds.

outline remains remarkably consistent (Figures A.5-6). A close examination of the outlines reveals only subtle distinctions between the uncharred and charred morphotypes, especially at the tip of the seeds (Fig. 2BD).

To determine whether seeds retain their unique attributes after charring, a LDA was conducted to differentiate the nine accessions using uncharred seeds as the training set defining the LDA model. Results demonstrate that pre-charring seeds were correctly classified to their corresponding accession with an accuracy of 98.9%. Following the charring process, the classification accuracy decreased to an average of 91.9% across the three experimental conditions (Figure A.4C). The rounded seeds of *P. canariensis* were always perfectly classified at 100%. In contrast, other accessions saw a reduction in classification accuracy. The decline was less marked under the mild and moderate charring conditions, which resulted in an average accuracy of 96.7% and 95.6%, respectively. The most severe charring conditions caused a more pronounced drop to 83.3%, a result that appears nevertheless quite reliable.

3.2. Case study: morphometric analyses of charred seeds from Miri Qalat and Shahi Tump

We studied 13 seeds from the sites of Miri Qalat and Shahi Tump, Pakistan (Fig. 6A). Four seeds underwent radiocarbon dating, yielding dates corresponding to the early 3rd mill. BCE (Table 2).

Our morphometric analysis targeted both seed size and shape of the archaeological charred seeds (Table A.2; Table B.5). This decision was based on the observation that, despite the general size decrease, higher measurements of length and measurement ratios might still offer insights into the seeds' domesticated status (Figure A.6BC). Additionally, the rationale for incorporating shape analysis stemmed from the minimal impact of charring on seed morphology, ensuring the preservation of vital morphological attributes for analysis.

Seed size of the charred archaeological seeds are reported in Table A.2. Their length ranges from 7.14 to 9.91 mm with an average of 8.5 ± 0.8 mm. These values may correspond to various species and all statuses, including cultivated date palms, in our simulated-charred reference dataset and they are thus not useful for identification purposes.

The PCA, focused on seed shape, differentiates modern cultivated date palm seeds from those of wild date palms and wild relative *Phoenix* species (Fig. 6B). The archaeological seeds incorporated into the model tend to group with the wild accessions, aligning with expectations drawn from their rounded morphology.

Using only shape and excluding size metrics, the LDA model built on the modern reference and discriminating between domesticated (including feral and cultivated date palms) and wild (encompassing wild date palms and wild relative species) achieved an accuracy of 90.6%. Analysis of the archaeological seeds resulted in one seed (from Miri Qalat) being classified as domesticated, while the remaining twelve (92.3%) were categorized as wild (Table A.3). When the model focused on differentiating among wild date palm, domesticated date palm, and *P. sylvestris*, the accuracy was 84.8%. The results revealed that a single seed from Miri Qalat assigned to the domesticated group and five seeds (four from Miri Qalat and one from Shahi Tump) assigned to *P. sylvestris*, while seven seeds (one from Miri Qalat and six from Shahi Tump) were identified as wild date palm (Table A.3). These results make it challenging to conclusively determine whether the seeds are *P. sylvestris* or wild date palm due to the mixed classification.

4. Discussion

Our study delves into the effects of charring on the morphological characteristics of *Phoenix* seeds, providing insights crucial for archaeobotanical analysis. Through controlled charring experiments on over a thousand seeds from nine distinct accessions, we evaluated the implications for seed size and shape, and the potential for accurate group discrimination between species, as well as distinguishing between wild populations and cultivated types. Building on the insights gained from our charring experiments, we analyzed charred seeds from the early 3rd millennium BCE, found in the Kech-Makran region of Pakistan. This analysis enabled us to effectively interpret ancient fruit consumption practices and the exploitation of *Phoenix* species, highlighting the practical applications of our research in archaeological contexts.

4.1. Charring-induced distortions in Phoenix seeds: experimental insights versus archaeological realities

4.1.1. Phoenix seeds show remarkable thermal resilience under charring

Our study has revealed the exceptional thermal resilience of *Phoenix* seeds, particularly under reducing conditions where they exhibit remarkable durability. Despite exposure to 400 °C for 2 h, they largely maintain their morphological integrity, only showing slight deterioration at 500 °C, and remarkably, they mostly remain intact even at 600 °C. Conversely, under oxidizing conditions, their structural integrity begins to degrade at 300 °C, with complete failure observed beyond 400 °C. This level of heat tolerance exceeds that observed in other crops. Indeed, cereals were shown to be highly sensitive, being fully carbonized between 200 and 400 °C (Bonhomme et al., 2017; Guarino and Sciarrillo, 2004). Grape pips and pulses were rather found to be fully carbonized at 450 °C and 500 °C, respectively (Guarino and Sciarrillo, 2004; Smith and Jones, 1990). The outstanding resilience of date palm seeds may be attributed to their inherently lignified and larger structure.

In contexts such as domestic hearths or fireplaces, where temperatures can fluctuate significantly, from 300 °C to 600 °C to over 1000 °C in extreme conditions, the robustness of date palm seeds when exposed to heat suggests their potential to retain structural integrity. This finding is particularly valuable for archaeological research, indicating that a significant number of *Phoenix* seeds could survive charring, thereby remaining available for analysis.

4.1.2. Isometric size reduction and preserved shape in Phoenix seeds subject to charring

Charring leads to a significant reduction in seed dimensions, consistently reducing length, width, and thickness by up to 25%. This extent of shrinkage aligns with findings in other crops, such as olives, which experience a 9–10% reduction in size (Terral et al., 2004), and sunflowers, with size reductions up to 27% (Braadbaart and Wright, 2007).

Notably, date palm seeds demonstrated isometric shrinkage, preserving their original proportions across length, width, and thickness. This finding aligns with Mueller's (2017) observation of unchanged aspect ratios in erect knotweed's smooth morphs post-charring. Yet, it contrasts with tubercled morphs' significant aspect ratio decrease and other crops. Bouby et al. (2018) noted that grape seeds shrink more in length than breadth and thickness, making domesticated pips more rounded like wild seeds. Similarly, Berihuete-Azorín et al. (2019) found that spelt wheat grains widen post-charring, taking on a rounded and puffed shape. The variance in charring effects, as seen in other crops, underscores the importance of determining the presence and type of deformation, whether isometric or not, before conducting studies on charred seeds using size ratios.

The overall shape of the seed, as assessed using the EFT method, exhibits minimal alteration, with mean outlines reconstructed before and after charring aligning almost perfectly. Notably, date seed shapes demonstrate remarkable resilience to charring compared to grape pip outlines or cereal grains analyzed using the same method (Bonhomme et al., 2017; Bouby et al., 2018).

4.1.3. Variability in seed morphology responses to differing charring conditions

The variability in outcomes from charring experiments can be linked to the interplay between the specific conditions of charring and the unique properties of the crop seeds studied (Märkle and Rösch, 2008). Consistent with findings from earlier research, our experiments on date seeds confirm that higher temperatures, longer duration of exposure and oxidative condition lead to more pronounced distortions in seed morphology (Wright, 2003; Smith and Jones, 1990; Mueller, 2017; Bouby et al., 2018). Our findings underscore temperature as the primary influence on seed deformation, consistent with observations from charring experiments across various crops. (Berihuete-Azorín et al., 2019; Bouby et al., 2018).

Other studies have put forward the significant impact of seeds' physical and chemical properties on charring outcomes, highlighting seed moisture content as a crucial factor (Märkle and Rösch, 2008; Wright, 2003). While our study did not assess moisture content directly, due to standardizing the samples by drying, the inherent aridity of *Phoenix* seeds' native environments suggests minimal variability in their moisture levels. However, the occurrence of seeds found within fruits, a common discovery especially in contexts such as offerings in tombs (e.g., in Hili, United Arab Emirates, Méry and Tengberg, 2009) or in sites affected by fires (e.g., in Muweilah, United Arab Emirates, Tengberg, 2013), represents an important area for future research. This condition, indicative of distinct moisture dynamics, thermal insulation properties, and potentially other environmental factors, underscores the need for further investigation into how these contexts influence seed charring and preservation.

While our study explores a range of charring scenarios, it is important to acknowledge that the controlled conditions of a laboratory setting cannot perfectly replicate the diverse and fluctuating conditions encountered in real-world contexts such as cooking pits and campfires, as previously noted by Wright (2003). However, our comprehensive testing spans conditions ranging from those that have minimal impact on seeds to those that significantly affect them, thereby providing a thorough assessment. Given the consistent reduction in length, width, and thickness in an isometric manner, as well as minimal impact on seed outline observed across these varying conditions, we anticipate that even under variable conditions, similar outcomes (isometric shrinkage and no impact on shape) can be expected. This consistency in outcomes lays the groundwork for proposing a roadmap to study charred *Phoenix* seeds in archaeological contexts.

4.2. A roadmap to study charred archaeological Phoenix seeds

Based on our extensive charring experiment and subsequent analysis of group discrimination before and after charring, we can provide valuable recommendations for researchers undertaking the analysis of charred *Phoenix* seeds.

First, only intact *Phoenix* seeds should be selected for morphometric analyses. While statistical tests do not reveal a significant difference in the overall susceptibility of seeds to charring-related deformations, visual observations of pre- and post-charring outlines highlight that the narrow tips of seeds are particularly prone to damage. This can lead to accelerated disintegration, a pattern frequently observed in archaeobotanical assemblages where damage to seed tips is prevalent due to their susceptibility to charring and abrasion. The integrity of the seed tip is crucial for precise morphometric analysis, as pointed tips are a hallmark of domestication in seeds (Fuller and Stevens, 2018; Gros-Balthazard et al., 2016). Therefore, it is imperative to only consider intact seeds for accurate studies. Furthermore, it is advisable to quantify both intact and damaged seeds within charred archaeobotanical collections. Doing so could allow for the identification and correction of taphonomic bias, which, if overlooked, might inadvertently skew classification analyses towards wild populations, particularly due to the susceptibility of narrow seed tips to damage.

We advise against relying solely on seed size for differentiating between *Phoenix* species or identifying wild versus domesticated date palms. Our findings reveal that size-based discrimination is limited prior to charring, with charring effects further compromising the use of size as a identification criterion. Moreover, the extent of shrinkage due to charring exhibits considerable unpredictability, varying with the specific conditions of the process, conditions that are typically unknown for archaeological finds, making the application of a correction factor for post-charring size adjustments ineffective. It is worth noting that, unlike in date palms, size has been a reliable indicator for differentiating between wild and domesticated grapes (Bouby et al., 2018), which is likely due to less overlap in the distribution of wild and domesticated size measurements in the latest. Yet, their research also indicates a propensity for size reduction to erroneously skew classifications towards wild types. Despite these limitations, size measurements can still offer valuable insights in certain post-charring scenarios for date palms: seeds with a length exceeding 2.4 cm can confidently be classified as belonging to date palms, and those over 2.8 cm are likely indicative of cultivated varieties.

Our analysis reveals that despite the reduction in seed size due to charring, the proportional relationships between seed dimensions are maintained. This preserved consistency allows for the effective use of size dimension ratios in morphometric comparisons with uncharred reference samples. Importantly, this method is particularly valuable for distinguishing between wild and domesticated date palms, highlighting seed elongation as a significant marker of domestication (Gros-Balthazard et al., 2016). Our discrimination analyses confirm the utility of size ratios in making this distinction, though with a noted bias towards classifying seeds as wild. However, it is important to mention that these ratios do not help discriminate at the species level. For precise identification through morphometric analysis, we have pinpointed crucial ratio benchmarks: a length-to-width >2.5, length-to-thickness ratio >2.9, width-to-thickness ratio >1.3, reliably signal the presence of date palms. Specifically for cultivated varieties, the identification criteria are more stringent, with a length-to-width ratio >3.6, a width-to-thickness ratio >1.4, and a length-to-thickness ratio >3.9 serving as definitive indicators.

The stability of seed shapes that our charring experiment has revealed the method's efficacy and aligns with previous studies on cereals and fruits (Bonhomme et al., 2017; Bouby et al., 2018; Terral et al., 2004). Importantly, the resilience of shape to charring expands the scope of morphometric analysis beyond the binary classification of wild versus cultivated (e.g., in grape, Bouby et al., 2018), opening avenues for more nuanced inquiries into the evolution of *Phoenix* agrobiodiversity.

4.3. New insights into the history of Phoenix fruits consumption

Our study examines 13 charred archaeological seeds from two archaeological sites in the Baluchistan province of present-day Pakistan, serving as a practical demonstration of our experimental insights. The classification results, aligning with their observed roundedness, indicate these seeds likely to belong to wild *Phoenix* rather than to cultivated date palm. This distinction between wild and domesticated *Phoenix* species, maintained despite charring effects, underscores the method's utility. However, differentiating specifically between wild date palm and *P. sylvestris* remains challenging, as our analysis does not favor one over the other. Identifying *Phoenix* species and, for cultivated date palm, specific cultivars emerges as a significant future direction for this research.

The discovery that wild *Phoenix* species were exploited rather than cultivated in Makran in the early 3rd millennium BCE is intriguing. It supports that the subsistence economy was primarily cereal-based, with fruit playing a secondary role (Tengberg, 1998). This is in contrast with neighboring regions where date palm cultivation and in general oasis agriculture became a model from the Early Bronze Age (3rd mill. BCE) (Tengberg, 2012). Indeed, on sites in southeastern Iran, southern Mesopotamia, and East Arabia carbonized seeds from domesticated date palm are plentiful. In the Makran region where cereals and pulses may have benefitted from the annual flooding of rivers such as the Kech and the Dasht, cultivation in irrigated palm gardens seems to correspond to a later phenomenon, perhaps appearing in the 1st mill. BCE even though data is extremely scarce for these later periods.

The presence of wild *Phoenix* at the site raises questions about the existence of wild date palm in the region. Anthracological studies have confirmed the presence, but without determining the precise species concerned (*Nannorhops* or *Phoenix*), leaving open the question of their origin (Tengberg, 1998). While today no wild date palm populations are documented in the region, and *Phoenix sylvestris*'s range is located further east in Pakistan, this does not preclude their past existence in Makran. The native range of wild date palm is unknown but based on archaeobotanical evidence pre-dating domestication (reviewed by Gros-Balthazard and Flowers, 2021) and on current described wild date palms found in and at the foot of Omani Hajar mountains, they likely grow in West Asia. In fact, authors propose a natural range for wild *Phoenix dactylifera* covering the Baluchistan region (Fuller and Stevens, 2019). An alternative hypothesis suggests these wild seeds might have been imported, given known contacts with Baluchistan, the Indus valley, and the Iranian plateau (Tengberg, 1998).

5. Conclusion & perspectives

In conclusion, our empirical investigation into the effects of the charring process on *Phoenix* seeds revealed a significant and consistent size reduction, which closely adheres to an isometric trend. Notably, seed shape is largely unaffected by charring. We found that the study of dimensions on their own is largely unreliable but that studying shapes, as determined by the EFT method, can be reliably compared between charred archaeological seeds and their uncharred modern reference collection.

Our study bridges experimental and archaeometric research, highlighting the practical application of controlled experimentation. Drawing on our experimental findings, we applied the study of charred archaeological seeds to deepen our knowledge of the historical consumption of *Phoenix* fruits. The availability of a substantial collection of archaeological charred seeds opens up a promising avenue for expanding our understanding of the evolution of date palm's agrobiodiversity and its historical trajectory, while also shedding light on the human-environment interactions.

CRediT authorship contribution statement

S. Ivorra: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **M. Tengberg:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Data curation. **V. Bonhomme:** Writing – review & editing, Methodology, Formal analysis. **T. Kaczmarek:** Writing – review & editing, Investigation, Data curation. **T. Pastor:** Data curation. **J.-F. Terral:** Writing – review & editing, Funding acquisition, Conceptualization. **M. Gros-Balthazard:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None.

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Appendices A and B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2024.106052.

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