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# Integrating Lipid and Starch Grain Analyses From Pottery Vessels to Explore Prehistoric Foodways in Northern Gujarat, India

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This study attempts a holistic approach to past foodways in prehistoric northern Gujarat, India, by considering evidence of food production, distribution, preparation and consumption. We present here the results of a pilot residue study, integrating lipid and starch grain analyses, conducted on 28 ceramic vessels from three Chalcolithic/Harappan settlements (c. 3300–2000 cal. BC) in northern Gujarat, which are discussed in the light of previous evidence of plant and animal acquisition and preparation strategies in this region. We aim to explore how the prehistoric inhabitants of northern Gujarat transformed ingredients into meals, focusing on how different foodstuffs were processed. When assessed on their own, the lipid and compound-specific isotopic data suggest that animal fats were primarily processed in ceramic vessels, specifically non-ruminant fats. However, lipid residue analysis favors the detection of fat-rich animal products and is often unable to disentangle signatures resulting from the mixing of plant and animal products. The incorporation of starch grain analyses provides evidence for the processing of a range of plants in the vessels, such as cereals, pulses and underground storage organs. Together, the results provide a holistic perspective on foodways and a way forward in overcoming preservational and interpretational limitations.

**Keywords:** food, culinary practices, archeology, lipids, starch grains, South Asia

## INTRODUCTION

Archeological research has long focused on the cultural, social and economic practices concerning food production and consumption (often referred to as “foodways”; Staller and Carrasco, 2009; Peres, 2017), especially since the systematic recovery of macrobotanical and microfaunal remains through flotation techniques became widespread in the 1970s. Through the analysis of plant and

animal remains, often combined with the analysis of food-related artifacts such as ceramics and grinding stones, archeologists have explored issues such as the social division of labor during food production (e.g., Bolger, 2010), distribution (e.g., Welch and Scarry, 1995) and preparation (e.g., VanDerwarker and Detwiler, 2002), intra- and inter-cultural culinary preferences (e.g., Kirch and O'Day, 2003) and the role of food in social aggregation and cooperation (e.g., Bray, 2003), among other topics.

Despite the diversity of methodological and theoretical approaches used to explore prehistoric foodways and the abundant literature discussing this topic, few studies have considered both plant and animal resources holistically (e.g., Spielmann, 2002; Bogaard et al., 2009; Kansa et al., 2009; Twiss et al., 2009; Ivanova et al., 2018; Gastra et al., 2019; McClatchie et al., 2019; Dunne et al., 2021). However, the acquisition, preparation and consumption of both plants and animals are firmly tied together in integrated agro-pastoral systems and, therefore, both resources need to be considered together in order to explore prehistoric foodways and pursue a better understanding of how food systems operated in the past.

In the last few decades, past food preparation and consumption activities have been explored through the analysis of residues from archeological artifacts and human dental calculus. Chemical (lipids and proteins; e.g., Craig et al., 2015; Hendy et al., 2018) and microbotanical (starch grains and phytoliths; e.g., Lu et al., 2005) analyses have greatly contributed to our understanding of the use of plant and animal ingredients in prehistoric cuisines, often highlighting the presence of foodstuffs not detected through conventional archeobotanical and zooarcheological methods (e.g., Högborg et al., 2009; Salque et al., 2012; Saul et al., 2013). Phytoliths are often found on non-edible plant parts but can also represent the use of taxa often underrepresented in conventional archeobotanical analyses, such as spices (Saul et al., 2013); whereas starch grains are mainly produced in the edible plants parts (seeds, fruits, underground storage organs, etc.) and are usually regarded as a direct evidence of the consumption of starchy plants, including, among others, cereals, pulses and tubers (Torrence and Barton, 2006). In parallel, the analysis of lipids from pottery vessels has thrown light on our understanding of the exploitation of animal fats and the origin of dairying practices (e.g., Craig et al., 2005; Evershed et al., 2008), as well as on the use of leafy vegetables, plant oils (Charters et al., 1993; Charters et al., 1997; Copley et al., 2001, 2005; Dunne et al., 2016) and apicultural products (Roffet-Salque et al., 2015).

Individually, phytoliths, starch grains and lipids provide valuable information on the consumption of plant and animal resources. However, their independent analysis might underestimate the importance of certain resources. For example, fat-rich animal products are more easily identified in lipid residue analysis, while the contribution of lipid content of plant-based products, generally at least tenfold lower, is likely masked by animal fats (Charters et al., 1995; Hammann and Cramp, 2018; Miller et al., 2020). Plant waxes, sterols and seed oils have been identified in pottery vessels, but generally in archeological settings with good organic preservation (e.g., Copley et al., 2001, 2005; Dunne et al., 2016). Additionally, there are only a few

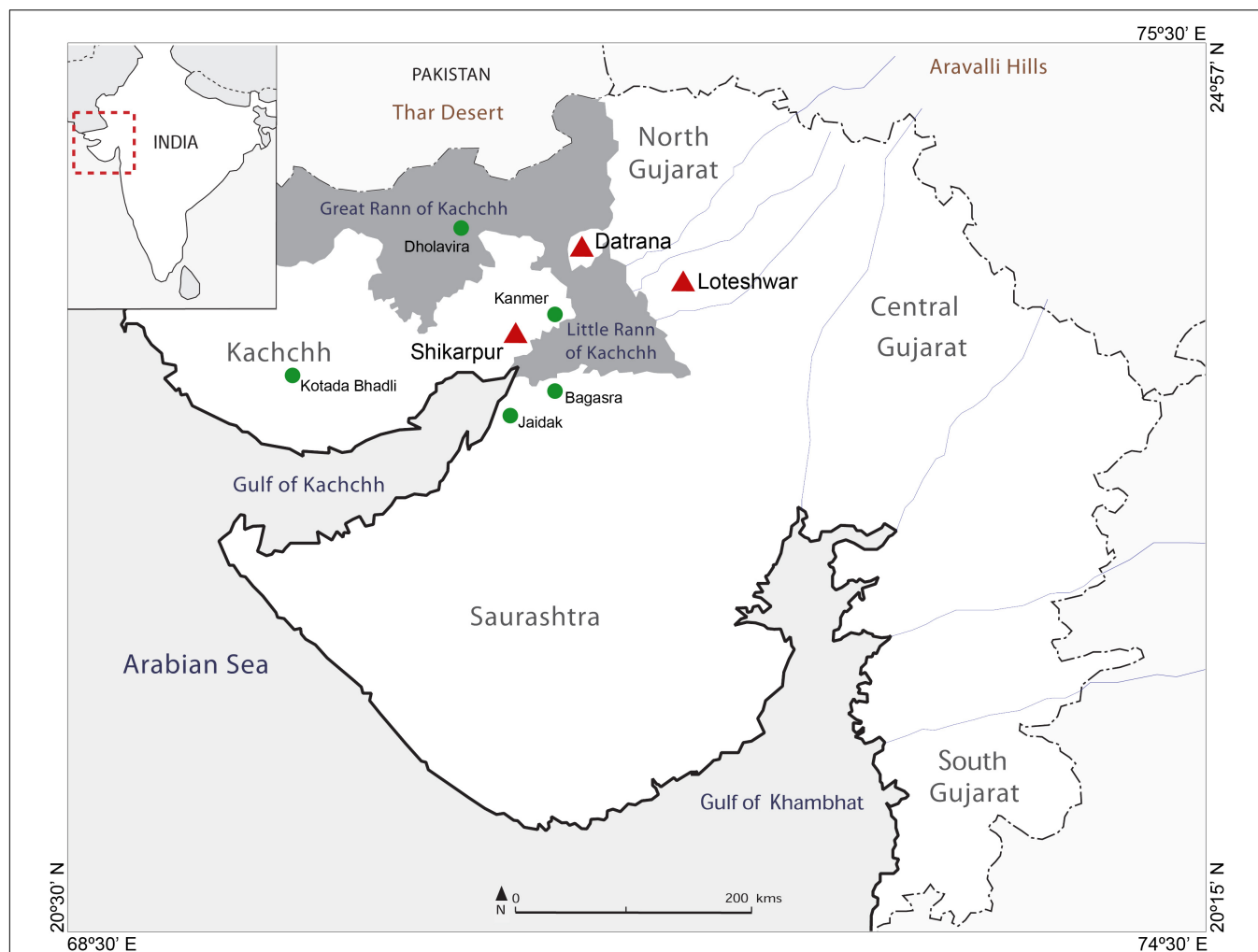
established biomarkers for specific plant products (brassica leaf waxes, maize and some millet species; Charters et al., 1997; Reber and Evershed, 2004; Heron et al., 2016). These preservational and interpretational biases can potentially skew our interpretation of past resource- and vessel-use in respect to plants, rendering the use of plant products in pottery vessels “invisible”.

At present, microbotanical remains and lipid residues are seldom analyzed as part of the same study, and when this happens they often come from different vessels, thus impeding an effective integration of the results (see for example, microbotanical and lipid residue analyses conducted at the Neolithic site of Stavroupoli, in northern Greece; García-Granero et al., 2018; Whelton et al., 2018). The integrated analysis of lipid residue and microbotanical proxies has the potential to widen the spectrum of identifiable food resources and examine differential pathways of the processing and consumption of food (Kooiman et al., 2021). Moreover, an integrated analysis can help overcome the interpretative limitations of individual proxies.

We present here the results of a pilot study aiming at assessing the potential of an integrated lipid residue and microbotanical analysis to explore prehistoric foodways in Chalcolithic/Harappan northern Gujarat, western India (**Figure 1**). The materials analyzed in this study comprise 28 ceramic vessels potentially used for food preparation and consumption from three settlements in northern Gujarat: Chalcolithic deposits from Datrana (c. 3300–3000 cal. BC) and Loteshwar (c. 2700–2300 cal. BC), and late Urban Harappan deposits from Shikarpur (c. 2200–2000 cal. BC)—see **Table 1** for a summary of the archeological contexts and **Supplementary Material** for a more detailed description of the full stratigraphy of the sites. The results are discussed in the light of previous evidence of plant and animal acquisition and preparation strategies in this region to explore how the Chalcolithic/Harappan inhabitants of northern Gujarat transformed ingredients into meals, thinking through the potential culinary pathways of different foodstuffs.

## AREA OF STUDY

For the purposes of this study, we define northern Gujarat broadly, encompassing the northern part of mainland Gujarat (often referred to as North Gujarat), the island of Kachchh and the northern part of the peninsula of Saurashtra, a region characterized by a semiarid climate (400–600 mm of average annual precipitation), with most of the rainfall occurring during the Indian summer monsoon (June–September). Several ceramic traditions co-exist in northern Gujarat during the Chalcolithic/Harappan period, including the Anarta (c. 3700–2250 cal. BC), the Pre-Prabhas (c. 3300–2900 cal. BC) and the Classical and Sorath Harappan (c. 2500–1900 cal. BC). Anarta pottery has been recovered in different proportions from over 60 prehistoric sites, but it is most common in seasonal camps occupied by semi-nomadic agro-pastoralists, such as Loteshwar (Ajithprasad and Sonawane, 2011; Rajesh et al., 2013a), whereas Pre-Prabhas pottery has only been recovered at Datrana, a lithic blade workshop (Ajithprasad, 2011; Gadekar et al., 2013;



**FIGURE 1 |** Map of Gujarat showing the case studies (red triangles) and other archeological sites mentioned in the text (green circles). Background map prepared by Francesc C. Conesa.

**TABLE 1 |** Summary of the available archeological information for the deposits where the samples analyzed in this study were recovered.

Site	Chronology of the analyzed samples	Site description	Ceramics	Lithics	Other material culture	References
Datrana	c. 3300–3000 BC	Dune occupied by agro-pastoral groups focused on the production of lithic blades	Mostly pre-prabhas, very little Early Harappan Sindh and Anarta	Tools and debitage, mostly made of chalcedony, some Rohri chert blades, grinding tools	Carnelian beads	Ajithprasad, 2002, 2011; Gadekar et al., 2013; Rajesh et al., 2013b; García-Granero et al., 2017a
Loteshwar	c. 2700–2300 BC	Dune seasonally occupied by semi-nomadic agro-pastoral groups	Mostly Anarta, very little Harappan	Tools and debitage, mostly made of chalcedony and chert, grinding tools	Terracotta, shell and copper objects, steatite and semi-precious stone beads	Rajesh et al., 2013a; Gadekar et al., 2014a; García-Granero et al., 2016
Shikarpur	c. 2200–2000 BC	Fortified rural settlement	Mostly Classical and Sorath Harappan, some Anarta	Chert blades and cores (including Rohri chert), grinding tools	Terracotta, shell and copper objects, steatite and semi-precious stone beads	Bhan and Ajithprasad, 2009; Gadekar et al., 2014b; Chase et al., 2020

Rajesh et al., 2013b), and a few other sites (Rajesh et al., 2018). Classical Harappan pottery of the Indus Civilization is found mostly in walled settlements, with the characteristic Indus city

plan and associated material culture, ranging from villages such as Shikarpur (Bhan and Ajithprasad, 2009) to major urban centers such as Dholavira (Bisht, 2015). Finally, Sorath Harappan pottery

is the dominant regional ceramic tradition associated with the Harappan sites (mostly) of Saurashtra (see e.g., Farooqui et al., 2013, p. 2632 and references therein).

Recent archeobotanical and zooarcheological research in northern Gujarat has provided extensive evidence for the production and distribution of plant and animal resources during the Chalcolithic and Harappan period. The analysis of macroscopic plant remains (charred and mineralized fruits and seeds) from Anarta and Harappan sites shows that prehistoric populations relied on the cultivation of monsoon-adapted crops native to South Asia, particularly small millets such as little millet (*Panicum sumatrense*), browntop millet (*Brachiaria ramosa*), bristly foxtail (*Setaria verticillata*), green foxtail (*S. viridis*), Kodo millet (*Paspalum scrobiculatum*) and barnyard millet (*Echinochloa* spp.), as well as tropical pulses such as horsegram (*Macrotyloma uniflorum*), mung bean (*Vigna radiata*) and black gram (*V. mungo*) (Fuller, 2011; Pokharia et al., 2011, 2017; García-Granero et al., 2015, 2016). Sesame (*Sesamum indicum*) was also recovered from Loteshwar (García-Granero et al., 2016) and a few Harappan sites in the region (Pokharia et al., 2011, 2017). Small amounts of barley (*Hordeum vulgare*) and, to a lesser degree, free-threshing wheat (*Triticum aestivum/turgidum*) are also recovered from all studied sites; these were probably not cultivated locally but traded in from other Indus regions more suitable for the cultivation of winter crops (García-Granero, 2015). Wild plants are also normally recovered from Chalcolithic/Harappan sites in northern Gujarat but there exists no clear evidence of their use for human consumption, with the possible exception of Egyptian crowfoot grass (*Dactyloctenium aegyptium*) at Loteshwar (García-Granero et al., 2016).

There is abundant evidence for animal husbandry in Chalcolithic and, especially, Harappan northern Gujarat, where hunting appears to have played a minor role, particularly during the Harappan period. Cattle (*Bos* sp.) herding seems to have been the main animal-related activity during the Anarta period (Patel, 2009), later complemented with sheep (*Ovis aries*) and goats (*Capra hircus*) in Harappan settlements—and, possibly, water buffaloes (*Bubalus bubalis*) and pigs (*Sus* sp.), the domestic status of which has not been clarified to date (Thomas et al., 1996, 1997; Chase, 2010, 2014; Joglekar and Goyal, 2011; Goyal, 2013; Joglekar et al., 2013). The domestic animal slaughter patterns at Harappan Bagasra and Shikarpur suggest that cattle and buffalo were generally kept for secondary products and/or animal traction prior to consumption, whereas sheep and goats were raised primarily for meat (Chase, 2010, 2014). Fishing, particularly of marine habitats, also seems to have been an important activity in Harappan Gujarat (Abhayan, 2016). Judging by the abundance of otoliths and other fish bones at archeological sites in northern Gujarat, fish must also have been an important resource for prehistoric populations, although its role in their subsistence is currently unknown due to the scant attention fish remains have received in South Asian zooarcheology (Abhayan et al., 2016).

Husbandry practices were further explored at Harappan Bagasra, Shikarpur, Jaidak and Kotada Bhadli through stable isotope analyses ( $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $\delta^{13}\text{C}$ , and  $\delta^{18}\text{O}$ ) of animal tooth

enamel. At Bagasra, strontium ratios suggest that most sheep and goats were raised locally, whereas around half of the analyzed cattle were raised further afield, in several locations throughout central Saurashtra (Chase et al., 2014, 2018). Carbon and oxygen values further suggest that cattle were predominantly fed agricultural fodder (millet cultivation by-products), as shown by the presence of  $\text{C}_4$  plants in their diet, whereas sheep and goats consumed a mixed diet made of both agricultural fodder and wild plants (mixed  $\text{C}_3$ – $\text{C}_4$  diet) (Chase et al., 2014). Results from nearby Shikarpur and Jaidak (Chase et al., 2020) seem to confirm the patterns observed at Bagasra.  $\Delta^{13}\text{C}$ -values from Kotada Bhadli, however, showed that both cattle/buffaloes and sheep/goats consumed a mixed  $\text{C}_3$ – $\text{C}_4$  diet (Chakraborty et al., 2018), thus suggesting that livestock management practices were not uniform throughout Harappan northern Gujarat.

Despite the relatively rich literature discussing food production and distribution in Chalcolithic northern Gujarat, less attention has been devoted to food preparation activities, and the remains of food consumption have been largely unexplored. Evidence for the pre-consumption preparation of plant resources comes from the analysis of microbotanical remains (starch grains and phytoliths) from grinding stones from Loteshwar, Datrana and Shikarpur, which show that these were mostly used to grind small millets and pulses, with a minor presence of other resources such as wheat/barley and underground storage organs (García-Granero et al., 2015, 2016, 2017a,b). Evidence for the preparation of animal resources comes from the analysis of cut-marks in cattle/buffalo and sheep/goat from Bagasra, which showed different butchery practices between those residing within and without the walled settlement (Chase, 2012). Using a different approach, Goyal (2017) suggested that preparation via roasting was more common in wild animals, particularly deer, than in domestic animals at Kanmer. Presence of burnt marks and the scarcity of cut marks in the fish assemblages from Bagasra, Kanmer and Shikarpur suggest that at least some fish resources were also prepared via roasting (Abhayan, 2016: 298).

## MATERIALS AND METHODS

### Sample Details

A total of 28 pottery vessels were analyzed in this study: 11 from Datrana (excavated in 2010), six from Loteshwar (excavated in 2009) and 11 from Shikarpur (excavated in 2012). All samples from Datrana come from bases of medium or large pots/dishes characterized as Pre-Prabhas. Samples from Loteshwar come from body sherds of medium pots, five characterized as Anarta and one characterized as probably Sorath Harappan (but definitely not Anarta). Finally, samples from Shikarpur come from bases of a variety of Classical Harappan vessels, including four pots/vases, four goblets, two pots/jars and one flat platter (a detailed description of the vessels can be found in **Supplementary Table 1**).

After retrieval from the archeological matrix potsherds were wrapped in aluminum foil and stored at the Department of



Archeology and Ancient History, M.S. University of Baroda, Vadodara, India, where they were sampled for lipid residue and microbotanical analyses in November 2013. Sampling took place in a controlled environment—a closed room with no airstream. A small portion of each sherd (c. 1 cm<sup>2</sup>) was detached from the main sherd, wrapped in aluminum foil and sent to the BioArch Laboratory, University of York, United Kingdom, for lipid residue analyses.

Microbotanical residue recovery consisted of a two-step process in which the outer layer of sediment was first dry brushed from the inner surface of the vessel (dry sample), and then the inner layer of sediment was brushed with deionized water (wet sample). By removing the outer layer of sediment the likelihood of contamination from the burial environment decreases considerably (Hart, 2011), so our analysis focused on the wet samples. Microbotanical samples were transferred to the BioGeoPal Laboratory, IMF-CSIC, Barcelona, Spain, where wet samples were immediately dried at 40°C and stored. Gloves were not used during the sampling of potsherds or the extraction and analysis of starch grains to prevent starch contamination (Crowther et al., 2014).

## Lipid Residue Analysis: Extraction and Analytical Protocol

Lipid extracts were obtained and prepared from the pottery sherds ( $n = 28$ ) at the BioArch Laboratory using previously reported protocols of extraction and methylation (Craig et al., 2013). Each sherd was first cleaned with a high-speed drill to eliminate any surface contamination. Ceramic was then drilled from the interior surface (1 g). The ceramic powder was weighed and sealed in glass vials prior to all analyses. Methanol (4 ml) was added to the powdered pottery and the mixture was sonicated for 15 min. Then, sulfuric acid (800  $\mu$ l) was added and heated at 70°C for 4 h. Lipids were extracted from centrifuged pottery powder with *n*-hexane (3  $\times$  2 ml) and dried under a gentle stream of N<sub>2</sub>. Internal standard (10  $\mu$ l of hexatriacontane C<sub>36:0</sub>) was added in all the samples prior analysis to quantify the relative abundance of lipids. All samples were analyzed by Gas Chromatography-Flame Ionisation Detection (GC-FID) ( $n = 28$ ), Gas Chromatography-Mass Spectrometry (GC-MS) ( $n = 28$ ) and Gas Chromatography-Combustion-Isotope Ratio Mass Spectrometry (GC-C-IRMS) ( $n = 27$ ).

GC-FID was carried out using an Agilent 7890S gas chromatograph (Agilent Technologies, Cheadle, Cheshire, United Kingdom). The sample (1  $\mu$ l) was injected into the GC at 300°C with a splitless injector, using helium as carrier gas (2 ml min<sup>-1</sup>). The GC column was a polyimide coated fused-silica DB-1 (15 m  $\times$  320  $\mu$ m  $\times$  0.1  $\mu$ m; J&W Scientific, Folsom, CA, United States). The GC oven was set at 100°C for 2 min, then increased by 20°C min<sup>-1</sup> until 325°C, where it was held for 3 min.

GC-MS was carried out using an Agilent 7890 B Series Gas Chromatograph attached to an Agilent 5977 B Mass Spectrometer with a quadrupole mass analyzer (Agilent technologies, Cheadle, Cheshire, United Kingdom). All samples were initially screened

using a split/splitless injector in splitless mode, which was maintained at 300°C. The GC carrier gas was helium, configured at a constant flow rate of 1 ml min<sup>-1</sup>. The column (HP-5MS) was coated with 5% phenyl-methylpolysiloxane (30 m  $\times$  0.25 mm  $\times$  0.25  $\mu$ m; Agilent technologies, Cheadle, Cheshire, United Kingdom). The oven temperature was set at 50°C for 2 min, then raised by 10°C min<sup>-1</sup> until 325°C was reached, where it was held for 15 min until the end of the run. The ionization energy of the mass spectrometer was 70 eV and spectra were obtained in scanning mode between  $m/z$  50 and 800.

In order to assess the presence of miliacin, each Total Ion Chromatogram (TIC) was scanned for  $m/z$  189,  $m/z$  204,  $m/z$  231,  $m/z$  425,  $m/z$  440, corresponding to miliacin fragmentation. Additionally,  $\omega$ -(*o*-alkylphenyl) alkanolic acids (APAAs) were screened by searching the TIC for the molecular ions ( $M +$ ) for APAAs of C<sub>16</sub>–C<sub>22</sub> at  $m/z$  262, 290, 318, and 346 and the fragment ion of the base peak  $m/z$  105.

The stable carbon isotope values of palmitic and stearic FAMES were measured by GC-c-IRMS, using an Agilent 7890B series GC (Agilent Technologies, Santa Clara, CA, United States), linked by an Isoprime GC5 interface (Isoprime Cheadle, United Kingdom) to an Isoprime 100 (Isoprime, Cheadle, United Kingdom) and to an Agilent 5975C inert mass spectrometer detector (MSD). Samples were re-dissolved in hexane and 1  $\mu$ l was injected into DB-5MS ultra-inert fused-silica column (60 m  $\times$  0.250 mm  $\times$  0.25  $\mu$ m, J&W Scientific, Folsom, CA, United States). The temperature program was 50°C for 0.5 min, 25°C min<sup>-1</sup> to 175°C, 8°C min<sup>-1</sup> to 325°C, isothermal hold for 20 min. The carrier gas used was ultra-high purity grade helium (3 ml min<sup>-1</sup>). The gas flow eluting from the column was split into one stream that was directed to the MSD for compound identification, and another stream that was directed through the CuO furnace tube at 850°C to convert all the carbon species to CO<sub>2</sub>. Ion intensities (44, 45, and 46  $m/z$ ) of eluted products were recorded and the corresponding <sup>13</sup>C/<sup>12</sup>C ratios were computed. Data was analyzed using IonVantage and IonOS software (Isoprime, Cheadle, United Kingdom) and the samples were compared with a standard reference gas (CO<sub>2</sub>) of known isotopic composition. The results are expressed in per mill (‰) relative to an international standard (VPDB). Within each batch, a mixture of *n*-alkanoic acid ester standards of known isotopic composition (Indiana standard F8-3) was used to check instrument accuracy ( $\pm 0.3$ ‰) and precision on repeated measurements ( $\pm 0.5$ ‰). Each sample was measured in duplicate. The resulting data were corrected to account for methylation of the carboxyl group through comparisons with a C<sub>16:0</sub> and C<sub>18:0</sub> fatty acid standard of known isotopic composition that were processed with each batch under identical conditions. As only a couple modern reference dairy fats from South Asia are available (Craig et al., 2005), data obtained from other published modern ruminant, dairy, non-ruminant fats, marine fats and plant oils (Copley et al., 2003; Craig et al., 2005; Spangenberg et al., 2006; Gregg et al., 2009; Outram et al., 2009; Steele et al., 2010; Dunne et al., 2012) were compared with the obtained results.

## Microbotanical Remains

Processing and analysis of the wet samples from potsherds took place at the BioGeoPal Laboratory, IMF-CSIC, Barcelona, Spain. Samples were chemically processed for the extraction of starch grains and phytoliths following the protocols described in García-Granero et al. (2017b), which involve the use of 5% sodium hexametaphosphate  $[(\text{NaPO}_3)_6]$  to deflocculate clays, sodium polytungstate  $[\text{Na}_6(\text{H}_2\text{W}_{12}\text{O}_{40})]$  at a specific gravity of  $1.8 \text{ g/cm}^3$  to isolate starch grains, 5% hydrochloric acid (HCl) to dissolve calcium carbonate, 33% oxygen peroxide ( $\text{H}_2\text{O}_2$ ) to oxidize organic matter and sodium polytungstate at a specific gravity of  $2.35 \text{ g/cm}^3$  to isolate phytoliths. Samples were observed under plain and cross-polarized transmitted light in a Leica DM2500 optical microscope with a Leica DFC490 camera for microphotography. 10% of the starch residue from each sample was mounted in 50% glycerine and fully scanned at  $\times 200$  magnifications, whereas c. 1 mg of the phytolith residue from each sample was mounted in Entellan® and scanned at  $\times 630$  magnifications until 250 identifiable single-cell phytoliths were observed. Samples where less than 100 identified phytoliths had been encountered after scanning 10% of the slide were considered sterile and the analysis did not proceed any further. Microbotanical remains encountered in archeological samples were compared with the modern plant reference collection housed at the BioGeoPal Laboratory (Supplementary Figure 1).

## RESULTS

### Lipid Preservation and Molecular Evidence (Gas Chromatography-Flame Ionisation Detection and Gas Chromatography-Mass Spectrometry)

Lipid yields ranged from 4.6 to  $339.1 \mu\text{g/g}$  ( $\bar{x} = 74.5 \mu\text{g/g}$ ) (Table 2). All but one sample (DTR116) had lipid yields above  $5 \mu\text{g/g}$  ( $n = 27$ , 96%). The lipid yields are relatively higher than those reported from other lipid residue studies in South Asia, such as at Kotada Badli, a Sorath Harappan settlement in Gujarat (Chakraborty et al., 2020, using a slightly different extraction protocol; Correa-Ascencio and Evershed, 2014), and Harappan sites in northwest India (Suryanarayan et al., 2021, using the same extraction protocol as in this study). Comparisons of lipid yields suggest there are no differences in lipid yields across sites {Kruskal-Wallis test of effect of site [ $\chi^2(2) = 2.6$ ,  $p = 0.27$ ]}. All lipid profiles were dominated by mid-chain ( $\text{C}_{14:0}$ ,  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$ ) fatty acids and small peaks of long-chain fatty acids ( $\text{C}_{20:0}$ – $\text{C}_{24:0}$ ). All the profiles also contained odd-chain fatty acids such as  $\text{C}_{15:0}$  and  $\text{C}_{17:0}$ , as well as branched-chain fatty acids such as  $\text{C}_{15}$  and  $\text{C}_{17}$ . Such profiles are characteristic of degraded animal fats (Dudd and Evershed, 1998; Dudd et al., 1999; Halmemies-Beauchet-Filleau et al., 2013, 2014; Supplementary Figure 2). The palmitic/stearic (P/S) ratio of the extracts ranged between 0.7 and 1.2, which is also indicative of animal products.

No peaks of  $n$ -alkanes, which can be indicative of plant waxes (Kolattukudy, 1970), were detected in the extracts. Similarly, miliacin, the chemical “biomarker” for *Panicum* spp. and some other small millets (Lu et al., 2009; Bossard et al., 2013), could not be identified in the extracts. Other chemical biomarkers, such as compounds formed during exposure to high temperatures or those indicating heated fish products—mid-chain ketones and long-chain ( $> \text{C}_{18}$ )  $\omega$ -( $o$ -alkylphenyl) alkanolic acids and isoprenoid fatty acids, respectively—could also not be identified in the lipid extracts using the methods described.

### Compound-Specific Isotopic Evidence (Gas Chromatography-Combustion-Isotope Ratio Mass Spectrometry)

The fatty acid  $\delta^{13}\text{C}$ -values from the analyzed extracts ranged between  $-30.5$  and  $-24.5\text{‰}$  ( $\text{C}_{16:0}$ ) and between  $-29.9$  and  $-23.5\text{‰}$  ( $\text{C}_{18:0}$ ), reflecting a relatively narrow spread of values. The  $\Delta^{13}\text{C}$ -values ranged from 3.2 to  $-2.7\text{‰}$ , which are consistent with modern reference fats from non-ruminant and ruminant adipose fats (Figure 2, Table 2, and Supplementary Figure 3). Most of the extracts ( $n = 21$ , 78%) had  $\Delta^{13}\text{C}$ -values which fall within the range of reference non-ruminant fats, while the remaining ( $n = 6$ , 22%) fall within the range for ruminant adipose fats, suggesting they were predominantly used to process the carcass fats of cattle/buffalo, sheep/goat or wild ruminant animals such as deer or nilgai (*Boselaphus tragocamelus*). None of the extracts had values consistent with reference dairy-based products. Some extracts also have fatty acid  $\delta^{13}\text{C}$ -values that are consistent with those reported for plant oils, especially  $\text{C}_3$  oilseed plants such as sesame (Steele et al., 2010). However, plants have a much higher palmitic/stearic ratio than animal fats, and they produce significant deviations in  $\Delta^{13}\text{C}$ -values depending on the absolute  $\delta^{13}\text{C}$ -values of the end-members (Steele et al., 2010; Hendy et al., 2018). Clear evidence for plant products was not detected in the lipid extracts in this study.

The  $\delta^{13}\text{C}_{16:0}$  values of the extracts indicate the input of both  $\text{C}_3$  and  $\text{C}_4$  plants, likely routed through animal diet (Halmemies-Beauchet-Filleau et al., 2013, 2014). A moderate negative correlation coefficient between the  $\delta^{13}\text{C}_{16:0}$  and  $\Delta^{13}\text{C}$  values was observed ( $-0.35$ ,  $p = 0.012$ ), suggesting that samples with more negative  $\Delta^{13}\text{C}$ -values produced fatty acids enriched in  $^{13}\text{C}$ , likely from tissues of ruminant animals that were consuming  $\text{C}_4$  plants. However, there was no effect of site or vessel form on  $\delta^{13}\text{C}_{16:0}$  values [ $\chi^2(2) = 1.3$ ,  $p = 0.53$  and  $\chi^2(6) = 4.6$ ,  $p = 0.59$ , respectively] or on  $\delta^{13}\text{C}_{18:0}$  values [ $\chi^2(2) = 0.4$ ,  $p = 0.82$  and  $\chi^2(6) = 2.3$ ,  $p = 0.89$ , respectively]. This indicates that no significant differences in the usage of vessels across sites and vessel forms can be detected (see Supplementary Figure 4).

### Microbotanical Evidence

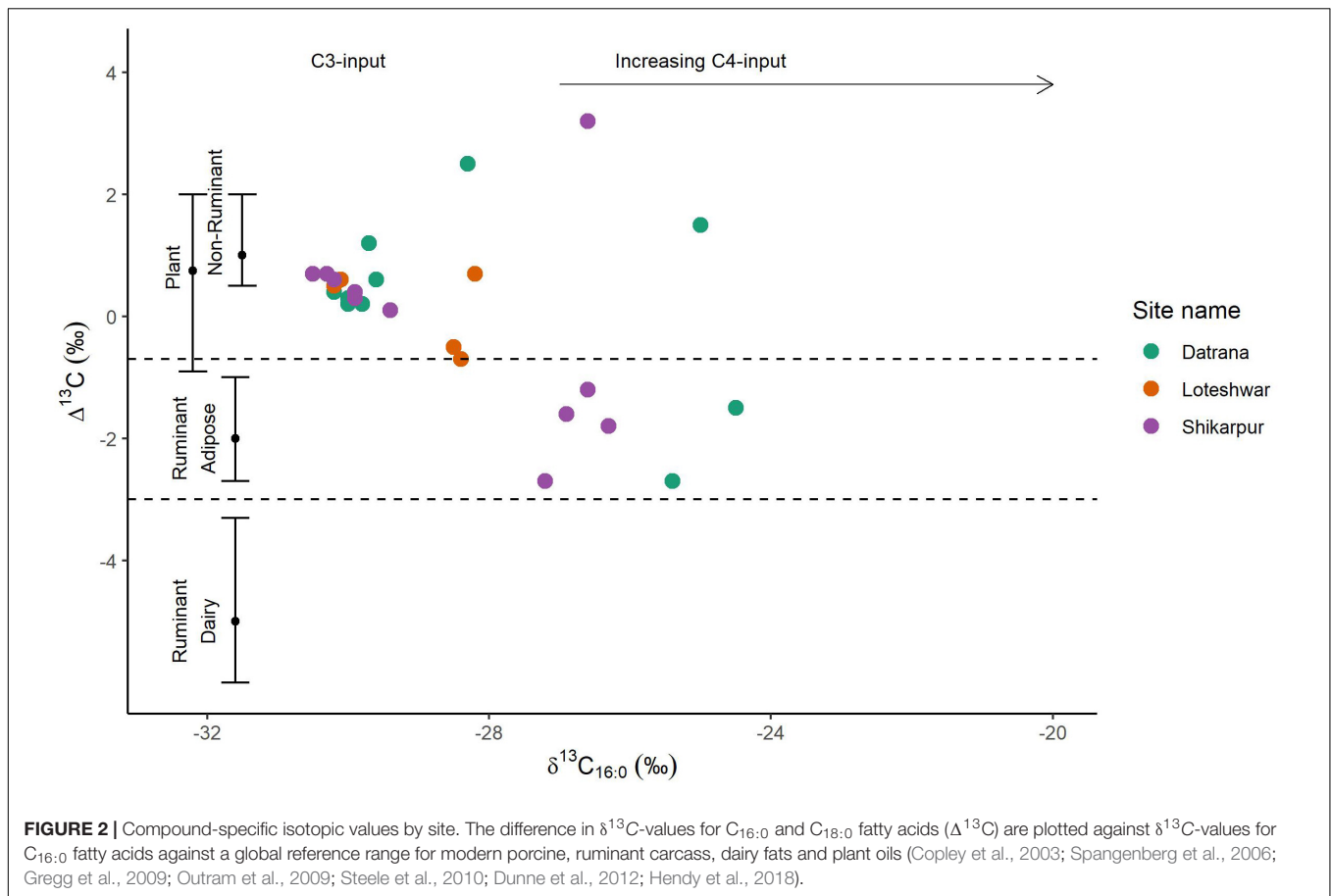
Starch grains were generally scarce in most samples (0–8 grains per sample) but very abundant in sample DTR116 ( $n = 256$ ) (Table 2). The presence and relative abundance of starch types varies greatly among sites (Figure 3 and Table 3). Thus, whereas at Datrana most starch grains (99% of the assemblage) belong to the Hordeae tribe (Poaceae, grasses), these are a minor component of the assemblage at Shikarpur (7%) and completely absent at Loteshwar. Plants from the Hordeae tribe are not

**TABLE 2 |** Results of the chemical and starch grain analyses from pottery vessels from Datrana, Loteshwar and Shikarpur.

	Molecular evidence		GC-c-IRMS			Starch grains						
	Lipid conc. ( $\mu$ g/g)	P/S ratio	$\delta^{13}\text{C } \text{C}_{16:0}$	$\delta^{13}\text{C } \text{C}_{18:0}$	$\Delta^{13}\text{C } (\text{C}_{18:0}-\text{C}_{16:0})$	Small millets	Job's tears	Wheat/barley	Pulses	Ginger	USO (other)	UNID starch
<b>Datrana</b>												
DTR101	130.4	0.8	-28.3	-25.8	2.5	0	0	0	0	0	0	0
DTR104	107.5	0.9	-29.6	-29.0	0.6	0	0	0	0	0	0	0
DTR105	43.0	1.1	-25.4	-28.1	-2.7	0	0	2	0	0	0	1
DTR106	67.0	0.7	-25.0	-23.5	1.5	0	0	0	0	0	0	0
DTR107	41.7	0.9	-29.7	-28.5	1.2	0	0	0	0	0	0	0
DTR109	17.4	0.8	-30.2	-29.8	0.4	0	0	0	0	0	0	0
DTR113	30.0	1.1	-30.0	-29.6	0.3	0	0	1	0	0	0	0
DTR115	9.2	0.9	-29.8	-29.6	0.2	0	0	0	0	0	0	0
DTR116	4.6	-	-	-	-	0	0	256	0	0	0	0
DTR117	94.8	0.9	-30.0	-29.8	0.2	0	0	0	0	0	0	0
DTR120	27.9	1.2	-24.5	-26.0	-1.5	1	0	0	0	1	0	1
Total Datrana	--	-	-	-	-	1	0	259	0	1	0	2
Ubiquity Datrana	--	-	-	-	-	9%	0%	27%	0%	9%	0%	18%
<b>Loteshwar</b>												
011109/4	34.6	0.9	-28.2	-27.5	0.7	0	1	0	0	0	0	0
021109/2	52.4	1.1	-28.5	-29.0	-0.5	0	0	0	4	0	0	2
021109/8	12.8	1.0	-30.3	-29.6	0.7	0	0	0	0	0	0	0
031109/11	130.6	0.9	-30.1	-29.5	0.6	0	1	0	0	0	0	0
071109/19	60.3	0.9	-30.2	-29.7	0.5	0	0	0	0	0	0	0
071109/20	42.8	1.0	-28.4	-29.1	-0.7	0	0	0	4	0	0	0
Total Loteshwar	--	-	-	-	-	0	2	0	8	0	0	2
Ubiquity Loteshwar	--	-	-	-	-	0%	33%	0%	33%	0%	0%	17%
<b>Shikarpur</b>												
240112/23	99.2	0.9	-29.9	-29.5	0.4	0	0	1	0	0	0	0
240112/29	97.7	0.9	-26.9	-28.5	-1.6	0	0	0	2	0	0	0
250112/8	12.8	1.0	-30.5	-29.8	0.7	0	0	0	0	0	1	0
270112/8	86.1	0.9	-30.2	-29.6	0.6	0	0	0	0	0	0	0
010212/16	339.1	1.0	-26.3	-28.0	-1.8	0	0	0	0	0	0	0
010212/19	79.8	0.9	-26.6	-27.8	-1.2	0	0	0	1	0	0	0
020212/9	52.2	0.9	-29.9	-29.5	0.3	0	0	0	0	0	0	0
050212/12	44.9	0.9	-29.4	-29.3	0.1	0	0	0	1	0	0	0
050212/8	25.4	1.0	-27.2	-29.9	-2.7	0	0	0	7	1	0	0
070212/12	139.1	0.9	-30.3	-29.6	0.7	0	0	0	0	0	0	1
090212/7	135.1	0.7	-26.6	-23.5	3.2	0	0	0	0	0	0	0
Total Shikarpur	--	-	-	-	-	0	0	1	11	1	1	1
Ubiquity Shikarpur	--	-	-	-	-	0%	0%	9%	36%	9%	9%	9%

The description of the features used to taxonomically identify starch grains can be found in **Table 3**.





native to Gujarat, suggesting these starch grains most likely represent wheat (*Triticum* sp.) and/or barley (*Hordeum vulgare*) traded in from other areas of the Indus Civilization, such as the Indus plain in present-day Sindh (Pakistan). Conversely, starch grains from the Faboideae subfamily (Fabaceae, pulses) predominate at both Shikarpur (73%) and Loteshwar (67%) but are completely absent from Datrana. The starch assemblage further includes one small millet (Paniceae tribe, Poaceae) grain from Datrana, two Job's tears (*Coix lacryma-jobi*, Andropogoneae tribe, Poaceae) grains from Loteshwar, two ginger (*Zingiber* sp., Zingiberaceae) grains (one from Datrana and one from Shikarpur), one grain from an unidentified underground storage organ from Shikarpur and a few grains that could not be identified due to severe damage ( $n = 1$ ), the lack of comparable modern reference material ( $n = 1$ ) or the lack of diagnostic features in the starch grains ( $n = 3$ ). Phytoliths were virtually absent from all but three vessels (Supplementary Table 3) and are therefore not considered in the discussion of the results.

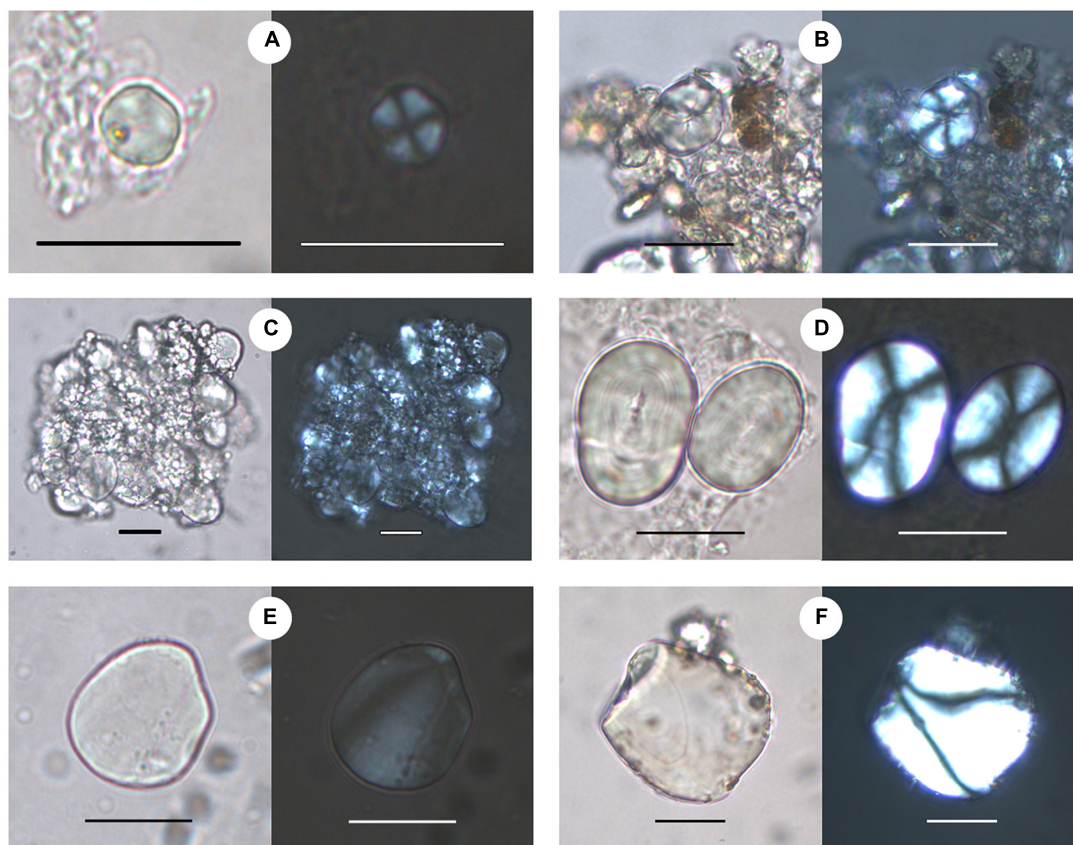
## DISCUSSION

Direct archeological evidence for food preparation and consumption is often limited to exceptional archeological finds (e.g., Lu et al., 2005). In most cases, the reconstruction of past foodways is hampered by the poor survival of organic remains,

taphonomic pathways and depositional and post-depositional processes. In this study, the low preservation of starch grains and survival of only free fatty acids within the lipid extracts limits the extent to which past foodways can be reconstructed. The interpretation of the results from northern Gujarat is further hindered by few previous biomolecular studies and lack of modern reference fats from the region; in fact, this is one of the few lipid residue studies on South Asian archeological material (see also Chakraborty et al., 2020; Suryanarayan et al., 2021) and the only study in South Asian archeology integrating chemical and microbotanical analysis from the same vessels. Nevertheless, a holistic approach to past foodways has the potential to overcome biases by integrating evidence, and opens up new questions to examine the production, distribution, preparation and consumption of both animal and plant resources.

## Plant and Animal Ingredients in Vessels?

The obtained lipid residue results suggest the presence of degraded animal fats in the vessels. When compared with available modern reference fats from other parts of the world, the fatty acid isotopic values suggest the dominance of the processing of non-ruminant fats in the vessels, possibly porcine carcass fats or fats of other monogastric animals, such as birds. However, the presence of non-ruminant fats in vessels does not correlate with the faunal record from



**FIGURE 3 |** Starch grains observed in samples from pottery vessels from Datrana, Loteshwar and Shikarpur: **(A)** Paniceae (small millet) grain form sample DTR120; **(B)** Andropogoneae (Job's tears) grain from sample 031109/11; **(C)** cluster of Hordeae (wheat/barley) grains from sample DTR116; **(D)** Faboideae (pulses) grains from sample 071109/20; **(E)** *Zingiber* sp. (ginger) grain from sample 050212/8; and **(F)** undetermined underground storage organ from sample 250112/8. Scale bar: 20  $\mu$ m (for comparative reference material, see **Supplementary Figure 1**).

**TABLE 3 |** Shape and size of the starch grain morphotypes found in pottery vessels from Datrana, Loteshwar and Shikarpur.

Taxonomy	N <sub>o</sub>	Shape	Size ( $\mu$ m)		
			Mean (SD)	Range	N <sub>m</sub>
Paniceae (small millets)	1	Polyhedral	7,851	–	1
Andropogoneae (Job's tears)	2	Polyhedral	18,734 (1,699)	17,533–19,936	2
Hordeae Type A (wheat/barley)	24	Rounded/ovate, discoidal	23,552 (3,193)	17,942–26,666	7
Hordeae Type B (wheat/barley)	239*	Rounded, spherical	6,302 (1,743)	3,779–7,785	4
Faboideae (pulses)	19	Ovate, ovoid	22,797 (8,049)	10,907–36,994	17
<i>Zingiber</i> sp. (ginger)	2	Ovate, discoidal	23,653 (6,339)	19,171–28,136	2
Unidentified underground storage organ	1	Globose	Broken, not measured	–	–
Unknown	1	Ovate, ovoid	14,305	–	1
Damaged unidentified	1	–	Broken, not measured	–	–

\*This morphotype occurs in numerous plants and therefore was only assigned to wheat/barley when found in association with Hordeae Type A starch grains (e.g., **Figure 3C**). N<sub>o</sub> = number of observed starch grains. N<sub>m</sub> = number of measured starch grains.

Chalcolithic/Harappan northern Gujarat, as there is limited evidence for the exploitation of pigs (domestic or wild) or other omnivorous taxa. Pig remains are relatively scarce (0–15% NISP) in Chalcolithic/Harappan settlements in Gujarat compared to the remains of ruminants, particularly sheep/goat (15–40% NISP) and cattle/buffalo (50–70% NISP), which dominate the faunal

assemblages (Thomas et al., 1996, 1997; Patel, 2009; Chase, 2010, 2014; Joglekar and Goyal, 2011; Goyal, 2013; Joglekar et al., 2013). Similar results were reported from Harappan sites in northwest India, where porcine remains are similarly scarce in the zooarcheological assemblage (Suryanarayan et al., 2021). While it is possible that non-ruminant animal resources were

selectively processed in pots, it is also worth exploring alternative explanations for their predominance in the pottery vessels from northern Gujarat.

Mixing models to investigate how mixtures of plant and animal products processed in ancient vessels can affect compound-specific isotope results have demonstrated that it can be challenging to interpret fatty acids isotopic results when plant and animal products are mixed in vessels, particularly from environments where both  $C_3$  and  $C_4$  plants are available (Hendy et al., 2018; Bondetti et al., 2020; Suryanarayan, 2020; Suryanarayan et al., 2021). Hendy et al. (2018) showed that  $\Delta^{13}C$ -values similar to non-ruminant fats can be created when vessels are used to process mixtures of ruminant adipose products and  $C_3$  plants. Considering the available zooarcheological evidence and the predominance of  $C_3$  plants in the starch assemblage from pottery vessels from Datrana, Loteshwar and Shikarpur, it is possible that the  $\Delta^{13}C$ -values of the extracts resulted from mixtures of plant and animal products rather than non-ruminant animal fats. Although the low lipid contribution of plants may not be enough to influence the  $\delta^{13}C$ -value of the animal-derived lipids (Miller et al., 2020), a likely possibility could be the use of  $C_3$  plant oils, such as sesame, which has been found at Loteshwar (García-Granero et al., 2016), which have higher lipid content. These hypotheses, however, need to be tested through additional mixing models and experimental research.

A small number of vessels from Datrana and Shikarpur have extracts with isotopic values that fall within the range of ruminant carcass fats and have  $\delta^{13}C_{16:0}$  values between  $-27$  and  $-24\text{‰}$ . These values suggest that fats processed in these vessels were from animals with a mixed  $C_3$ – $C_4$  plant diet (e.g., Roffet-Salque et al., 2016). The zooarcheological record in prehistoric northern Gujarat includes both domestic (cattle, sheep and goats) and wild ruminants (e.g., nilgai). The stable carbon isotope signature of animals grazing on wild vegetation would reflect the consumption of mostly  $C_3$  plants, which form the majority of the local flora (Chase et al., 2014: 4). On the other hand, the stable carbon isotope signature of animals grazing on agricultural fodder would reflect the consumption of both  $C_4$  (e.g., small millets) and  $C_3$  plants (e.g., tropical pulses), as shown by stable carbon isotope analyses of tooth enamel of domestic ruminants at Bagasra (Chase et al., 2014, 2018), Shikarpur (Chase et al., 2020), Jaidak (Chase et al., 2020) and Kotada Bhadli (Chakraborty et al., 2018). Therefore, the presence of  $C_4$  plants in the diet of the ruminants processed at Datrana and Shikarpur seems to indicate that they were partly fed agricultural by-products, and thus the molecular evidence likely represents the processing of domestic animals in vessels. Moreover, the study of burnt animal bones from Kanmer suggested that, unlike domestic taxa, wild mammals such as deer were regularly prepared via roasting (Goyal, 2017), further suggesting that the ruminant fats from Datrana and Shikarpur derive from domestic animals.

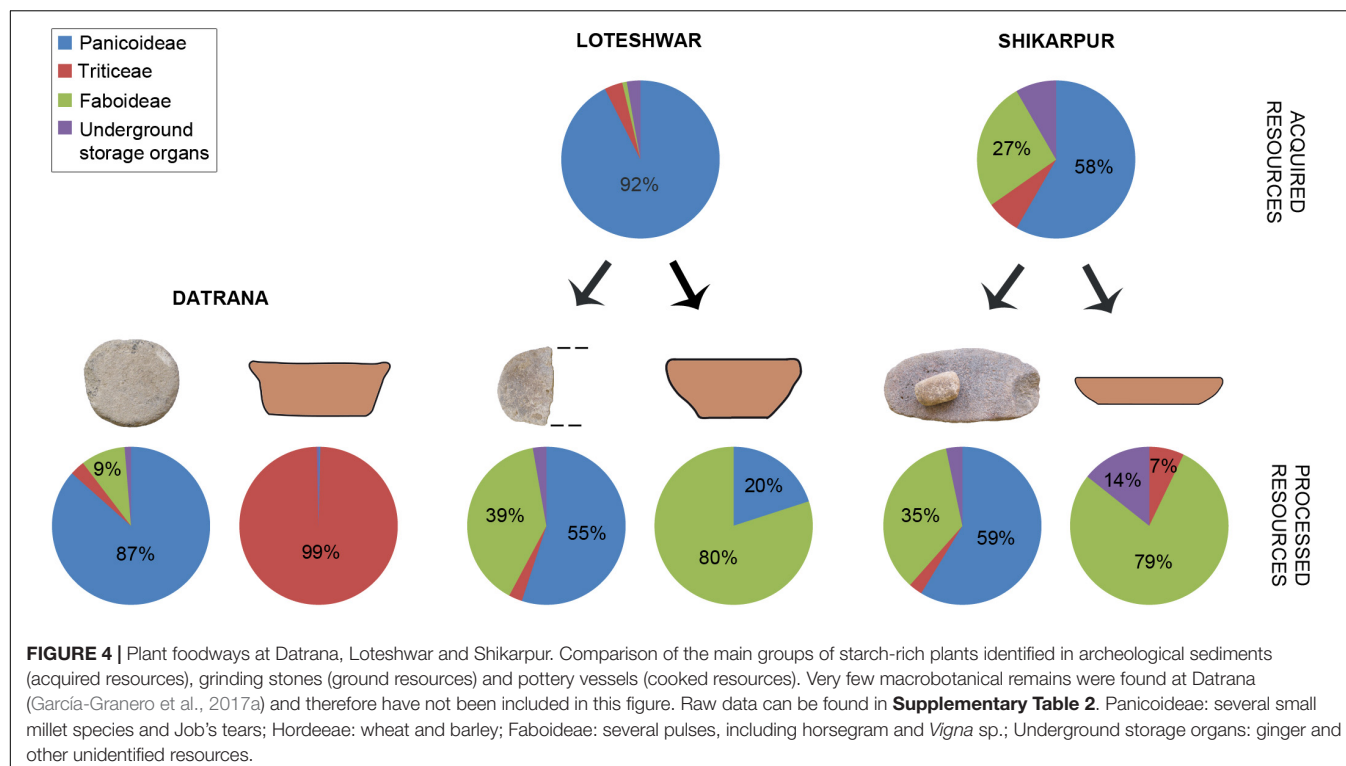
## Prehistoric Foodways in Northern Gujarat

Archeobotanical and zooarcheological research has shown that the inhabitants of Chalcolithic/Harappan northern Gujarat

consumed a wide array of plant and animal resources. Lipid residue and starch grain analyses, however, only identified a few of these resources in the pottery vessels from Datrana, Loteshwar and Shikarpur. Although we acknowledge that the small set of samples analyzed may not be generalizable, the results open up questions about the culinary pathways of certain foodstuffs.

Among the food ingredients potentially consumed by prehistoric populations in northern Gujarat, two were not detected in the extracts: fish and dairy products. Molecular markers for fish products were not detected in the analyzed extracts, and the compound-specific isotopic results do not suggest aquatic input. In contrast, aquatic products were tentatively identified from a single vessel at Kotada Bhadli (Chakraborty et al., 2020). Although “absence of evidence is not evidence of absence”—and the techniques required to detect fish products in lipid extracts may need to be more sensitive in nature—fish might have had a specific culinary pathway at the sites examined in this study. Fish (both marine and riverine) seem to have been an important component of the Harappan diet, but how this resource was part of the Harappan cuisine has rarely been explored. Ichthyoarcheological studies on the materials from several Indus Civilization sites highlighted the paucity of cut marks on the recovered bones ( $< 2\%$  of the assemblages in all studied sites; Abhayan, 2016; Belcher, 1998). At Bagasra, Kanmer and Shikarpur, most cut marks were noticed on the vertebral elements, which probably indicates standardization in chopping (Abhayan, 2016; Abhayan et al., 2018) and suggests that fish might have been cooked mostly whole and not dismembered. Visible signs of heat alteration on some of the fish bones (Abhayan, 2016, p. 298) is also commensurate with roasting or frying rather than cooking in vessels, potentially explaining why fish products were not detected in the vessels analyzed in this study.

None of the fatty acid  $\delta^{13}C$ -values from the lipid extracts were consistent with modern references of dairy products, including an ethnographic dairy vessel from Gujarat (Craig et al., 2005). Our results are similar to those obtained from northwest India, where only a small percentage of vessels had evidence of dairy products (Suryanarayan et al., 2021), but contrast with lipid residue analysis of vessels from Kotada Bhadli, where 6 out of 21 vessels (mostly bowls) had evidence of dairy use (Chakraborty et al., 2020). Although the origins of dairying in prehistoric South Asia are still unknown, it is assumed that secondary products such as dairy were an important part of the economy, especially during the Harappan period (Gouin, 1990; Bourgeois and Gouin, 1995; Miller, 2004; Wright, 2010; Chase et al., 2014). Once again, “absence of evidence is not evidence of absence”; however, a number of possibilities must be explored. It is possible that the Chalcolithic semi-nomadic agro-pastoralists at Loteshwar and inhabitants of Datrana were not engaging in dairying; however, this is harder to explain for Shikarpur, where zooarcheological analysis suggests that cattle and buffalo were probably kept for secondary products and/or animal traction (Chase, 2010, 2014). It may also be possible that at Datrana, Loteshwar and Shikarpur milk and dairy products were processed in containers, such as bowls, that were not part of this study, or in



**TABLE 4 |** Plant foodways at Datrana, Loteshwar and Shikarpur.

Acquired resources	Ground resources	Cooked resources
<b>Datrana</b> <i>Cultivated:</i> – <i>Gathered:</i> underground storage organs (USOs) <i>Traded:</i> <b>small millets</b> , Job's tears, <b>barley</b> (and wheat?), pulses and ginger		
<b>Loteshwar</b> <i>Cultivated:</i> <b>browntop millet</b> , <b>Setaria spp.</b> , other small millets, Job's tears, horsegram and sesame <i>Gathered:</i> Egyptian crowfoot grass and USOs <i>Traded:</i> wheat (and barley?)	<b>Small millets</b> , <b>Job's tears</b> , wheat/barley, pulses and USOs (incl. ginger)	Small millets, <b>wheat/barley</b> and USOs (incl. ginger)
<b>Shikarpur</b> <i>Cultivated:</i> <b>browntop millet</b> , <b>Setaria spp.</b> , Job's tears and <b>Vigna sp.</b> <i>Gathered:</i> USOs <i>Traded:</i> barley (and wheat?), rice and ginger	<b>Small millets</b> , <b>Job's tears</b> , wheat/barley, <b>pulses</b> and USOs	Wheat/barley, <b>pulses</b> and USOs (incl. ginger)

Comparison of macroscopic remains of cultivated, gathered and traded edible plants most commonly recovered from archeological sediments (acquired resources), starch grains recovered from grinding stones (ground resources) and starch grains recovered from pottery vessels (cooked resources). Most common plant resources in each category are highlighted in bold.

vessels that have not survived in the archeological record (e.g., wooden vessels). In present-day traditional northern Gujarat milk is collected in small or medium pots with a slightly wide, open mouth and consumed in bowls or cups (P. Ajithprasad personal observation), and milk collection vessels are seldom used for any other purpose. Thus, it is possible that their representation in archeological contexts might also be limited. Finally, it is also possible that the mixing of resources in vessels has made it harder to detect the direct processing of dairy products in vessels.

By comparing the starch evidence from the ceramic vessels with the evidence for the use of starch-rich plant parts

from previously published macro and microbotanical analyses at Datrana, Loteshwar and Shikarpur we can attempt to disentangle the different culinary pathways potentially followed by each plant resource (Figure 4 and Table 4). The starch evidence from potsherds was generally scarce and therefore any interpretation using this proxy must be considered with caution. Only 10% of the starch residue was analyzed from each sample to allow comparability with previous starch analyses on grinding stones, which may have contributed to the low number of starch grains recovered in this study—which suggests that grinding stones might provide a more suitable environment for the preservation of starch grains, although



such a discussion is beyond the scope of the present study. In any case, the marked taxonomic differences observed between the assemblages from grinding stones and pottery vessels in all studied sites suggests culinary choices and the different pathways in which plant ingredients were processed and prepared. At Datrana, macrobotanical remains and phytoliths were extremely scarce. However, the starch evidence from grinding stones suggested the inhabitants of this lithic blade workshop consumed mainly small millets and Job's tears, complemented by small amounts of pulses, wheat/barley and ginger (García-Granero et al., 2017a). In striking contrast, small millet and Job's tears starch grains were virtually absent from pottery vessels, which mostly included wheat/barley and a single ginger starch grain. At Loteshwar and Shikarpur, both the macrobotanical assemblage and the microbotanical evidence from grinding stones suggested that locally cultivated small millets and, to a lesser degree, Job's tears and pulses formed the basis of the diet of the inhabitants of these settlements, complemented by wheat and barley traded in from other regions within the greater Indus Valley more prone to the cultivation of winter cereals (García-Granero et al., 2015, 2016). The starch evidence from pottery vessels, on the other hand, was mostly composed of pulses, with a minor presence of Job's tears at Loteshwar and underground storage organs (including ginger) and wheat/barley at Shikarpur.

The evidence from the analyzed pottery vessels thus suggests that plant resources were not only acquired in different ways (cultivated, gathered or traded in) but also followed different culinary pathways. Small millets were probably ground to prepare flour-based products. Job's tears seems to have been consumed in a similar way, possibly mixed with small millet flour. Miliacin was not detected in the lipid extracts (although perhaps more sensitive techniques are required), which might suggest millets were not cooked in vessels. Starch grains of pulses, on the other hand, are detected in both grinding stones and from pottery vessels, which might indicate they were incorporated in a wider range of meals using different processing techniques. Grinding stones may have been used both for grinding pulses into flour or used for preparing other dishes—and for splitting the seeds to form the basis of stews or soups. Starches of wheat and barley are not common in the studied sites but appear in abundance in vessel DTR116 from Datrana. Other types of starch grains were not found in this vessel, and it had a very low lipid concentration (below 5  $\mu\text{g/g}$ ). The detection of cereals via lipid residue analysis remains challenging, since biomarkers such as plant sterols and alkylresorcinols are highly susceptible to degradation, and their uptake into the ceramic matrix is very limited (Hammann and Cramp, 2018). All the available evidence, thus, seems to suggest that vessel DTR116 was used exclusively to prepare wheat/barley-based foods. Finally, ginger may have been ground on grinding stones and also incorporated during cooking. Based on a qualitative assessment of our reference collection, taxa within the ginger family produce notably less starch grains than cereals and pulses. Therefore, the presence of ginger at Datrana and Shikarpur, though minor, attests to its culinary use at these

sites. Ginger starch grains were also documented in human dental calculus from Harappan Farmana, in Haryana (northern India) (Weber and Kashyap, 2010; Kashyap and Weber, 2013), highlighting that their use as food condiments may have been widespread across the greater Indus Valley during the Chalcolithic/Harappan period.

## CONCLUSION

The combination of methods used in this study provides a unique means to explore the culinary use of both plant and animal ingredients that may not be detectable via conventional techniques in archeobotany and zooarcheology. They also provide a way to overcome interpretational limitations posed by individual methods, especially for the detection of plant remains within vessels. This preliminary study suggests the dominance of animal fats in vessels, although the interpretation of the compound-specific results is challenging, and pottery vessels may have been used to process  $\text{C}_3$  plants/oils and fats from ruminants, which is supported by microbotanical analyses. The presence of  $\Delta^{13}\text{C}$ -values similar to non-ruminant fats or other omnivorous taxa might have resulted from the combination of these ingredients, either as part of a single dish combining plant and animal foodstuffs or as a result of multiple cooking events. No differences in culinary practices can be detected across the studied sites, which had markedly different ceramic traditions and relied on different subsistence strategies. In particular, the predominance of non-ruminant fats and/or admixtures of plants and ruminant fats in pottery vessels and the use of small millets for producing flour have been observed in all studied sites. Overall, the interpretations offered are, of course, tentative given the sample size and issues of differential preservation of the molecular and microbotanical evidence but nonetheless illustrative of how finer grained interpretations may be gleaned from multi-proxy approaches of this nature. Future research in this and neighboring areas will assess whether the observed culinary continuity (spanning over a thousand years) is representative of deeper cultural practices common to prehistoric populations in northern Gujarat and other Indus regions.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

PA and MM acquired funding, provided samples, and designed the study. JG-G, AS, MCu, OC, and MCá analyzed the data. JG-G, AS, MCu, OC, and MM interpreted the data. JG-G and AS drafted the main manuscript and prepared the figures. All authors reviewed the manuscript.



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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2022.840199/full#supplementary-material>

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