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RESEARCH

To waste or not to waste: a multi-proxy analysis of human-waste interaction and rural waste management in Indus Era Gujarat

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Abstract
Waste management is paramount to town planning and ancient civilizations across the world have spent resources and mobilized labor for waste disposal and reuse. The study of waste management practices offers a unique window into the daily lives, social organization, and environmental interactions of ancient societies. In the Indus Valley Civilization, known for its urban planning, understanding waste disposal in rural settlements provides crucial insights into the broader socio-economic landscape. While extensive research has documented sophisticated waste management systems in urban Indus centers, little is known about practices in rural settlements. This gap limits our understanding of regional variations and rural-urban dynamics within the civilization. In this paper, using isotopic and microscopic proxies, we characterize the waste disposed of at the rural Indus settlement of Kotada Bhadli to reconstruct the sources of waste, including heated animal dung, and burned vegetation. We propose that rural agro-pastoral settlements in Gujarat during the Indus Era systematically discarded such waste in specific locations. By characterizing waste produced at Kotada Bhadli, we are also able to reconstruct the natural environment and how the natural and cultural landscape around the settlement was exploited by the residents of the settlement for their domestic and occupational needs. Our identification of the attention paid to waste disposal by the inhabitants of Kotada Bhadli adds significant data to our understanding of waste disposal as an insight into past lives.

Keywords Indus Valley civilization · Waste management · Sediment · Phytoliths · Spherulite · Carbon isotope · Nitrogen isotope

Introduction

The way in which societies have created, defined, managed, and disposed of waste is critical to understanding human settlement patterns across space and time. Indeed, as archaeologists, our work often revolves around discarded objects, rather than their production and usage contexts (Shanks et al. 2004; Sosna and Brunclíková 2017). Waste encompasses discarded artefacts or portions thereof, food remains, unwanted materials, and detrital materials either lost accidentally or discarded intentionally (Schiffer 1996). Waste can be disposed of immediately or recycled and reused at different times and possibly by different people. Moreover, what constitutes waste is socially defined and culturally mitigated (Reno 2014). In this context, archaeological research can shed light on a society's perception of waste, how waste was symbolically constructed (Douglas 2003), how the materiality of waste was valued (Thompson 2017),

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as well as how people may have recycled resources from socio-culturally as well as politically categorized wastes (Alexander and O'Hare 2020). Archaeological investigation of waste can help reconstruct human actions and beliefs (social, cultural and economic) related to waste, including actors who were involved in the production, processing and managment of that waste.

Comprehending waste disposal is equally as vital as understanding what constitutes waste. By studying how and where wastes were discarded, we can evaluate the efforts and resources mobilized in their disposal within or outside of settlements. Waste disposal often occurs in defined places that are determined by cultural as well as political-economic practices (Alexander and O'Hare 2020; Rathje and Murphy 2001). Exploring waste disposal practices in ancient societies allows us to understand past human interactions with space and how meanings were created and attributed to these spaces. Space, an important cultural medium, allows individuals to culturally organize and undertake social, aesthetic, political, and religious or ceremonial practices (Aucoin 2017). The culture-space relationship is dynamic and can vary both regionally and temporally. The ability to archaeologically investigate the association between waste and waste disposal areas can help in reconstructing the lived experience of a place and the spatial practices within a landscape. Investigating this association at an archaeological site like Kotada Bhadli is crucial for evaluating how rural space was assigned, managed and modified during the Indus period and how such practices varied from those in the much more densely populated urban settlements.

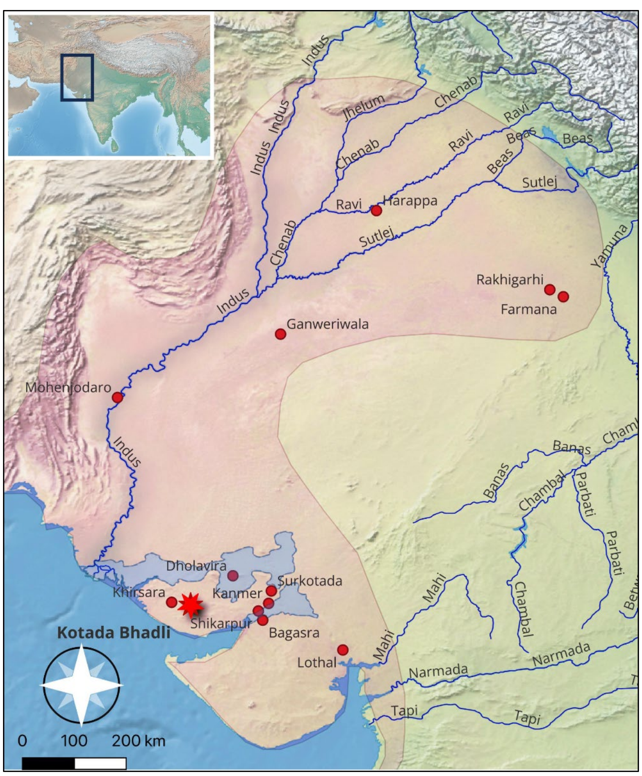

Fig. 1 Distribution of sites mentioned in the text, the shaded area showing the approximate extent of Mature Harappan Period sites

This study addresses the lack of knowledge about waste management in rural Indus settlements by examining the Indus Valley or Harappan Civilization site of Kotada Bhadli in Gujarat between the third and second millennium BCE. Specifically, we ask: What types of waste were produced and how were they disposed of? How do waste composition and disposal practices reflect the settlement's economy and social organization? How do these practices compare to those in urban centers? To answer these questions, we employ a multi-proxy approach combining archaeological context analysis, radiocarbon dating, phytolith and spherulite analysis, and stable isotope analysis of sediments. This multidisciplinary approach allows us to characterize waste composition, identify disposal patterns, and infer aspects of the settlement's economy and environmental interactions. By examining waste management practices at Kotada Bhadli, this study aims to provide new insights into rural lifeways during the Indus period and contribute to our understanding of regional variations within the civilization. The paper proceeds by describing the site and its context, detailing our methodological approach, presenting results from multiple analyses, and discussing their implications for understanding rural Indus settlements.

Waste management during the Indus era in South Asia

The Indus Valley or the Harappan Civilization was one of the oldest and largest of the world's early urban civilizations, with roots in north-western South Asia from before the fifth millennium BCE and complex political systems including large cities developing by the mid-third millennium BCE. Archaeological research over the last century has resulted in excavation of numerous settlements identified as cities, towns and villages linked to this civilization (Fig. 1). While most specialists agree that there is little evidence for centralized hierarchical bureaucratic administrative systems of the sort seen in contemporaneous third millennium BCE urban societies in Mesopotamia and Egypt (e.g., Green 2021; Kenoyer 2000; Possehl 1998; Wright, 2017), a multi-tiered hierarchy of settlement sizes that were engaged in different economic, socio-political, and possibly ritualistic activities is quite evident (Kenoyer 2000; Mughal 1990). These different activities produced different kinds of waste across settlements, and the Indus era settlements exhibit some of the earliest organized waste management systems in history. Based on varied economic conditions and socio-political as well as religious ideologies within these settlements, it is also very likely that waste was identified, managed and removed differently. Despite extensive archaeological research, only a few studies have examined how residents from these diverse settlements identified and interacted with wastes produced through continuous occupation and activities within and outside these settlements (Jansen 1985, 1989, 1993; Kenoyer 1991; Kharakwal et al. 2012; Shinde et al. 2008; Wright and Garrett 2017). Organized waste management is paramount for settlement planning, requiring both labor and resource mobilization, especially for densely populated cities and towns. During the Mature Harappan or Urban Period, significant investments were made in waste management at least for cities and towns; however, our understanding of waste management in smaller rural settlements is lacking. Therefore, it is crucial to investigate waste management, especially when deliberating on disparities in resource availability and utilization by various sizes and types of settlements. Unfortunately, such discussion has largely been neglected for the Indus Civilization.

As stated above, our current understanding of waste management during the Indus Era is primarily restricted to larger Indus centres. By far the most detailed work is Jansen's (1989) discussion of the complex sub-surface, brick-built sanitation and sewage system at Mohenjo-daro, including the use by some households of terracotta pipe drains and closed sewage catchment vessels to collect and transport waste. Similar complex drainage systems can also be observed at other urban and town centres such as Harappa, Dholavira, Rakhigarhi, Lothal, and Kalibangan, where soak pits, which were assumed to have been periodically cleaned by scooping off settled deposits, were also common (Bisht 2015; Kenoyer 1991; Lal et al. 2015; Nath and Kumaran 2017; Rao 1979). Wright and Garrett (2017) also argue that some garbage was likely removed from the streets and waste storage pits by wooden carts, the streets were likely swept regularly, water jars regularly filled, and drains and pits scooped out to remove any solid matter.

In contrast, there is a limited understanding as to how various groups residing in other types of Indus settlements, such as small towns and rural settlements, defined waste based on their material and symbolic qualities, distinguished between domestic and industrial wastes, allocated resources for their collection and disposal, and defined space within or outside the settlement as locations where diverse categories of waste were discarded. Kharakwal et al. (2012) and Shinde et al. (2008) have briefly discussed how some of the solid domestic wastes were discarded in their respective excavation reports on Kanmer (a Harappan small town) and Farmana (a Harappan village), but this is not common. Our understanding of waste management is even more limited for debris from agro-pastoral economic activities at rural settlements. Scholars have briefly discussed that much of the agricultural waste brought into settlements likely ended up in hearths or served as animal fodder; additionally, some of the animal wastes were recycled as fuel (Chase et al. 2014a, 2018, 2020; Lancelotti 2018; Lancelotti et al. 2017; Reddy 1994). Biowastes, especially dung, were likely also used as fertilizers for the fields, although no direct evidence exists as yet to support the use of bio-fertilizers by the people of the Indus Era.

Rural settlements may have had fewer resources to develop and maintain the sophisticated waste disposal practiced at large centers. At the same time, they would also have had less need to have sophisticated systems than in the crowded cities and towns. At the small village site of Farmana in the Ghaggar-Hakra region noted above, garbage pits were identified in which broken pottery along with broken seals and possibly organic refuse were dumped. Solid domestic and occupational waste, such as ash, broken pottery, bones, and craft refuse were additionally found dumped on lanes (Shinde et al. 2008). This sort of dumping was also seen at sites with more formal waste disposal; e.g., at the urban site of Harappa, streets were used as dumping areas for nearby houses during its occupation, while abandoned buildings were also filled with waste prior to the construction of a later phase (Kenoyer 1991). Similar waste disposal was also observed at the urban site of Rakhigarhi (K.S.C. personal observation). Despite the variety of research conducted, a comprehensive study on what constitutes waste, and how and where it was disposed of, reutilized, and recycled across different types of settlements occupying different regions within the Indus Era remains elusive.

Researchers have long emphasized the existence of regional variation during the Indus period and questioned an overemphasis on Indus homogeneity (Marta 2013; Miller 2013; Petrie et al. 2017; Petrie and Lynam 2020; Possehl 1998, 2004; Shinde et al. 2008), but primarily with a focus on the larger urban centers. Rural settlements provide additional insights on diversity. While these regional small settlements were economically, technologically and likely also ideologically connected to their nearby urban centres, they were also heavily influenced by the regional geography, climate and contemporary regional Chalcolithic cultures (Chase 2014; Chase et al. 2014b; Gadekar and Ajithprasad 2015; Kharakwal et al. 2012; Kuldeep K. Bhan & P. Ajithprasad, n.d; Lindstrom 2013; Sonawane et al. 2003). These additional aspects likely impacted their interpretation of waste and cultural definition of potential areas for waste disposal. This paper is focused on detailed identification of waste materials and their disposal patterns at Kotada Bhadli in Gujarat. It is thus not intended to fully cover the diverse rural landscapes of the Indus Civilization and pan-Indus rural waste management, as differences likely existed in the ways waste and space were perceived and constructed by the communities living in various regions.

Study area: the settlement of Kotada Bhadli

Kotada Bhadli, located in the Nakhatrana taluka, district of Kachchh in Gujarat, India, was excavated between 2010 and 2013. This small settlement, encompassing 3.11 ha, was occupied for a relatively short period of time. The excavations unearthed a central residential area with 10 interconnected rooms and a huge stone-built wall surrounding the settlement (Fig. 2) (Shirvalkar and Rawat 2012). The surviving height of this settlement wall is approximately 10 m, and the approximate maximum width of the wall (including the central pillar) is 8.9 m. Excluding the central pillar, the width of the actual wall varies between 3 and 3.5 m. There are no indications that this wall was used as a fortification for military purposes. Rather, it is likely that one of the primary purposes of this wall was to keep the herds inside the settlement, as animal herding was one

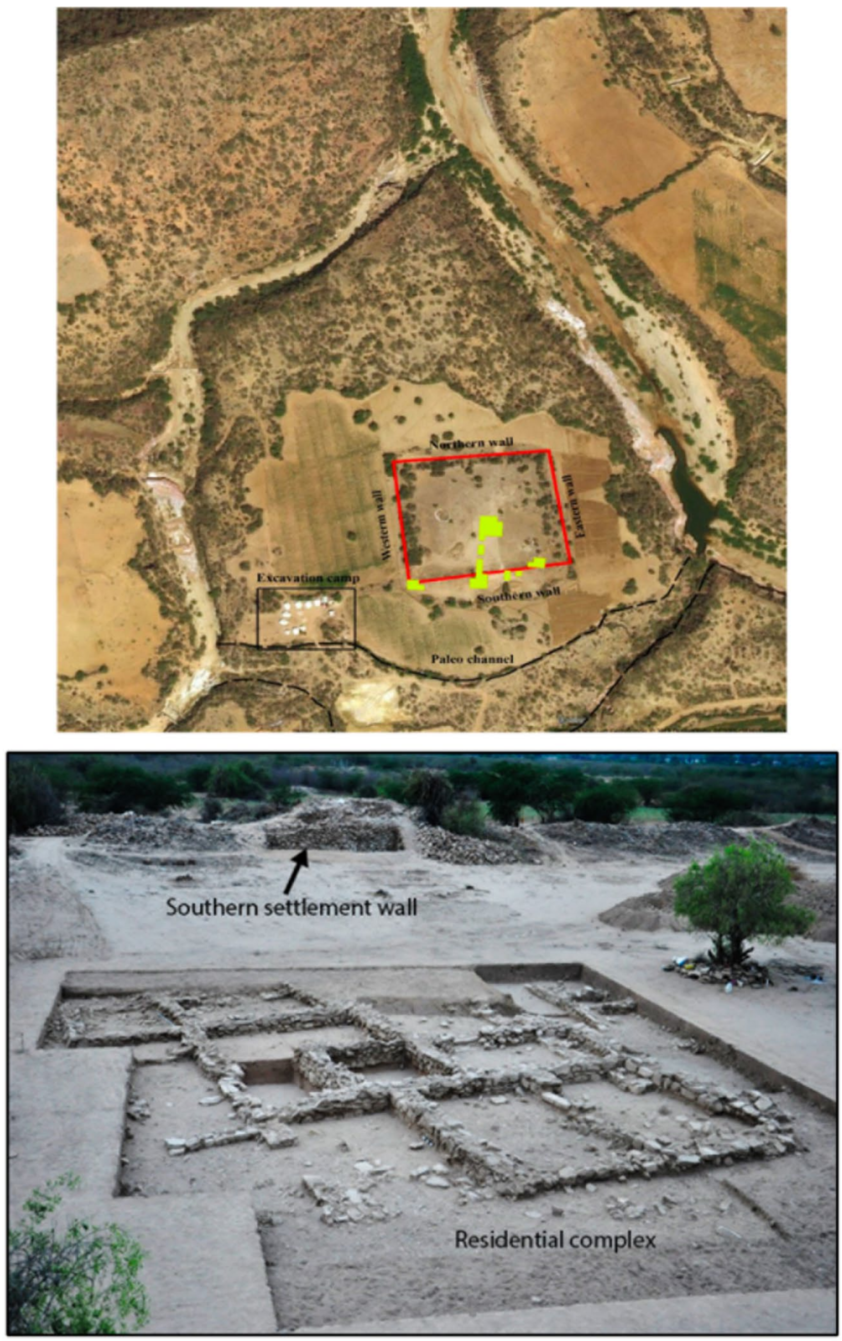

Fig. 2 Google Earth image (top) of the settlement of Kotada Bhadli from 2012, showing its location, the settlement wall and the extent of excavation. The bottom photo taken from north facing south shows the inner face of the southern settlement wall with the central residential structure with interconnected rooms in the foreground

of the primary economies at this settlement. The wall likely also served to provide a sense of security to the residents of this settlement, and to provide a barrier from natural hazards like floods and storms (Chakraborty 2019; Chakraborty et al. 2018). This wall was continuously maintained during the occupation at Kotada Bhadli.

Biogenic isotopic analysis of animal dentition and absorbed lipid residue analysis of archaeological vessels suggest that a form of sedentary to semi-sedentary pastoralism, along with domestic level cultivation, was probably the main economy at Kotada Bhadli. Animals were likely raised locally with seasonal movement to nearby grasslands and possibly supplemented with some agricultural leftovers (Chakraborty et al. 2018). Dairy from cattle/water buffalo, and meat from cattle/buffalo, goat, sheep and monogastric animals (such as pig), were likely a major part of the everyday diet, and possibly a source of surplus that tied into a regional interaction network (Chakraborty et al., 2019, 2020). Craft production beyond the household level of non-perishable goods has not been identified at this site. However, the presence of some Harappan-style objects such as beads and other paraphernalia at this settlement indicates that the occupants were probably active consumers of some of the specialized crafts circulating around the wider region. Rather than production and trade in non-perishable craft products, as is frequently suggested for sites in this region, this settlement may have participated in the regional economy by providing nearby settlements with animal products, and animal and human labour. Therefore, it is also possible that the settlement wall served as a checkpoint of control over who entered and exited the settlement.

The ceramic assemblage, architectural pattern, and other household materials used at this settlement indicate its association with the regional Sorath tradition (Shirvalkar and Rawat 2012). The Sorath tradition is usually thought to be either a regional manifestation of the Indus Civilization in Gujarat, developed by migrants from the Indus alluvial plain (Possehl and Herman 1987; Possehl and Raval 1989), or a regional Indus Valley tradition (Shirvalkar 2013) developed indigenously within the region of Gujarat during the Indus period. While the association between the Sorath and the Harappan tradition is beyond the scope of this article, the economic activities at this settlement suggest its residents were engaged in a local economy focused on a sedentary to semi-sedentary form of pastoralism and household level cultivation, coupled with participation in the larger Indus-dominated economy of the region.

One of the most striking features of this settlement is the multi-layer deposits of fine ash mixed with sediments and other cultural debris such as animal bones, broken pottery, and broken pieces of ornaments. These deposits were found only along both the inner and outer edges of the southern settlement wall (Table 1; Fig. 3). The heterogeneity of its contents and tapering nature of its spread suggest that these ash layers were formed due to dumping activities. While the ash deposits mixed with cultural debris were found both along the inner and the outer face of the settlement wall, the concentration of these deposits was higher in the inner edge of the wall. As only the southern side of the settlement wall was excavated, it is uncertain whether these ash dumps were only located specifically along the southern settlement wall or whether they were distributed throughout the settlement along the inner side of all four walls. Scatters of fine ashes mixed with sediment were also visible in residential areas but were absent inside the multi-room residential structure (Table 1; Fig. 3 bottom). A lack of structures associated with activities involving fire at this settlement makes it difficult to determine the source of this ashy waste. In certain situations, post-depositional conditions may degrade the firing structures, making them difficult to find during excavations. In addition, it is difficult to identify the more temporary types of firing structures made in semi-permanent camps and small settlements (Lancelotti et al. 2017). Finally, due to the limited excavations undertaken (Fig. 2), we cannot ascertain whether structures associated with activities involving fire are present in the unexcavated area of the settlement, which might have produced considerable amounts of this ash later dumped along the settlement walls. Unfortunately, the complete destruction of the site by agriculture after the final excavation season prevents further investigation of other areas or additional sampling.

Large quantities of ash dumps are evident in many other Indus period settlements from Gujarat, particularly during the Late Mature Phase of the Indus Civilization (2300 – 1900 BCE), which is marked by an increased use of Sorath-type artefacts (Bisht 2015; Kharakwal et al. 2012; Shirvalkar and Rawat 2012; Uesugi. et al., 2015). Large quantities of fine ash were found from Period 1 C of Surkotada (Joshi 1990), from the Middletown of Dholavira, at Pabumath, and from Period KMR IIB of Kanmer (Kharakwal et al. 2012), as well as at Kotada Bhadli (Shirvalkar and Rawat 2012). Kharakwal et al. (2012) posited that such "large dumping of ash" is most likely an indication of vigorous long-term craft activities and a growing influence by Sorath people that may also have involved periodic conflict. Unfortunately, Kharakwal et al. (2012) provide no evidence to substantiate either assertion. Subsequent work by Lancelotti (2018), however, confirms that the majority of these fine ashes at Kanmer and at Shikarpur resulted from the burning of animal dung, as well as agricultural byproducts and locally available firewood from different environments, the kinds of fuel one would use for both domestic and industrial purposes. This is a close match with our interpretation of the ash layers from Kotada Bhadli. In order to investigate the characteristics

Table 1 Detailed discussion of the layers excavated at the settlement of Kotada Bhadli (Shirvalkar and Rawat 2012)

Location	Location	Association	Description
Settlement Wall Area	Layer S1	Post-occupational Layer	Composed of fallen debris from the settlement wall along with aeolian sand.
	Layer S2	Occupational Layer	Brownish in color and composed of fine sand; cuts through layers 3 and 4.
	Layer S3	Occupational Layer	Light grey in color and composed of fine ash and burnt materials; contains considerable amount of cultural debris.
	Layer S4	Occupational Layer	Hard and composed of fine sand mixed with some ashy materials.
	Layer S5	Occupational Layer	Similar to layer 3, in that it is light grey in color and composed of fine ash and burnt materials. However, layer 5 has some small, discontinuous lenses throughout, some with more ash and some with less. None of these lens extended across the excavation area, and represent multiple short-term depositional events rather than occupational phases. As the overall matrix continued throughout, all of these small lenses and patches were combined into one layer, albeit representing many activities.
	Layer S6	Occupational Layer	Foundation layer of the settlement wall, composed of compacted river sand; only visible under the wall and does not extend into the adjacent areas.
	Layer S7	Occupational layer	Light grey in color and contains high amount of fine sand and cultural debris; located below layer 6 but extends into the adjacent areas. This layer probably represents the earliest occupation at this settlement.
	Layer S8	Occupational Layer	Compact and light grey in color, devoid of any cultural material. Like layer 6, this layer is also visible only under the fortification wall; between layer 6 and 7.
	Layer S9	Pre-occupational Layer	Compact brown layer likely representing the natural soil in the settlement area.
Residential Area	Layer 1	Topsoil	Sealing layer of the residential area, composed of fine loose sand and devoid of any cultural material.
	Layer 2	Post-occupational Layer	Brown and silty in nature and contains very little cultural debris; rests on layer 3 and mostly contains the fallen materials from the stone wall.
	Layer 3	Occupational Layer	Occupational layer on top of the natural soil, mostly contains compacted floors. All the archaeological materials from the were found in this layer. The thickness of this occupational layer varies between 31 and 43 cm.
	Layer 4	Pre-occupational layer	Natural soil, composed of fine and coarse sand.

and origins of these ashy layers at Kotada Bhadli, we have undertaken multi-proxy analyses of the ash and sediments, including microscopic and isotopic analyses, as described below.

Methods

AMS dating

Five tiny fragments of charcoal and three animal tooth samples were collected from throughout the settlement of Kotada Bhadli for radiocarbon dating (Fig. 4B). Due to their small size, wood identification of the charcoal samples was not possible. During excavation, the samples were immediately wrapped in aluminum foil after collection, while wearing gloves, and then transferred into plastic vials. Out of these 8 samples, only 4 charcoal samples produced enough carbon for dating (Table 2). Three of those four samples were collected from the area near the southern settlement wall, and one was collected from the residential area (Fig. 4).

Samples were pretreated following the protocol as discussed in (Crann et al. 2017). Samples were processed at the AMS facility at the University of Ottawa. Radiocarbon analyses were performed on a 3MV tandem accelerator mass spectrometer built by High Voltage Engineering (HVE). 12,13,14 C + 3 ions were measured at 2.5 MV terminal voltage with Ar stripping. The fraction modern carbon, F14C, is calculated according to Reimer et al. (2004) as the ratio of the sample 14 C/12 C ratio to the standard 14 C/12 C ratio (in our case Ox-II) measured in the same data block. Both 14 C/12 C ratios were background-corrected and the result was corrected for spectrometer and preparation fractionation using the AMS measured 13 C/12 C ratio and

Fig. 3 Layers along the inner edge as well as underneath the settlement wall showing high concentration of fine ash and the dumping of occupational debris (top), and layers from inside of the multi-room residential structure which are devoid of ash (bottom)

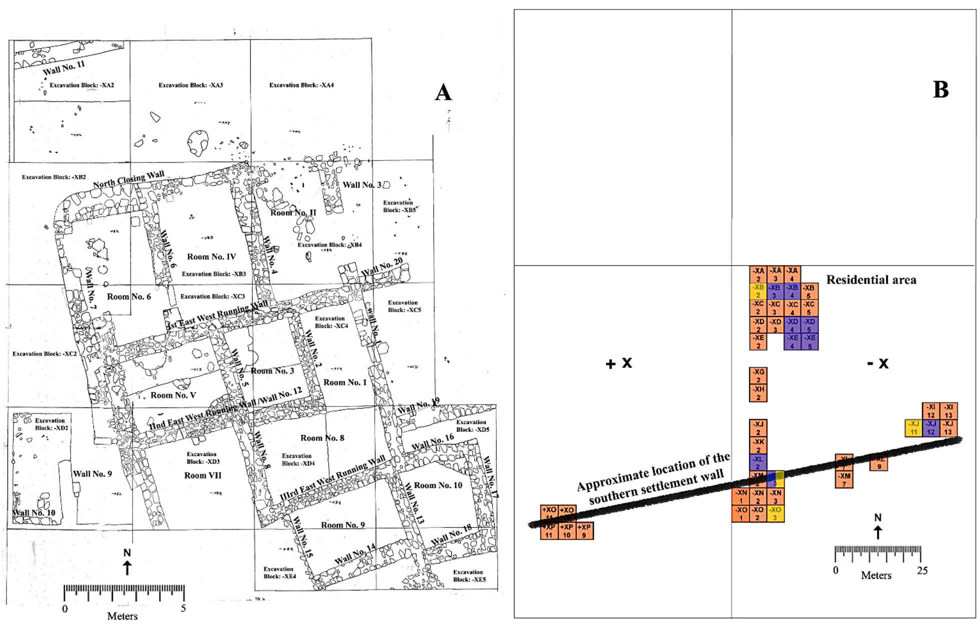

Fig. 4 **(A)** Schematic diagram of the residential area with interconnected rooms, and the location of sediment and charcoal samples collected from the residential area. Grids in 5 m. **(B)** Trench map of the settlement of Kotada Bhadli; maroon 5m^2 boxes indicate excavation blocks, yellow boxes indicate the sampling location for charcoal samples for AMS dating and blue boxes indicate the location of sediment samples for phytoliths and spherulites

Table 2 Radiocarbon results. Calibration was performed using OxCal v4.4.2 (Ramsey 2009) and the IntCal20 calibration curve (Reimer et al. 2020). Material codes are described in (Crann et al. 2017)

Lab ID	Sample ID	Trench No	Depth below datum (meters)	Layer	Area of the settlement	^{14}C yr. BP	F^{14}C	Calibrated age (BCE) (2σ uncertainity & 95.4% confidence level)
UOC-4155	KTB/CH-2	-XM3	-3.61	Layer S3	Wall	3731±43	0.6285±0.0034	2290 – 1980
UOC-4156	KTB/CH-3	-XJ11	-4.05	Layer S5	Wall	3677±43	0.6327±0.0034	2200 – 1930
UOC-4157	KTB/CH-4	-XB2	-4.2	Layer 3	Residence	3758±43	0.6264±0.0034	2300 – 2030
UOC-4158	KTB/CH-5	-XO3	-4.2	Layer S9	Wall	3858±43	0.6186±0.0033	2470 – 2200

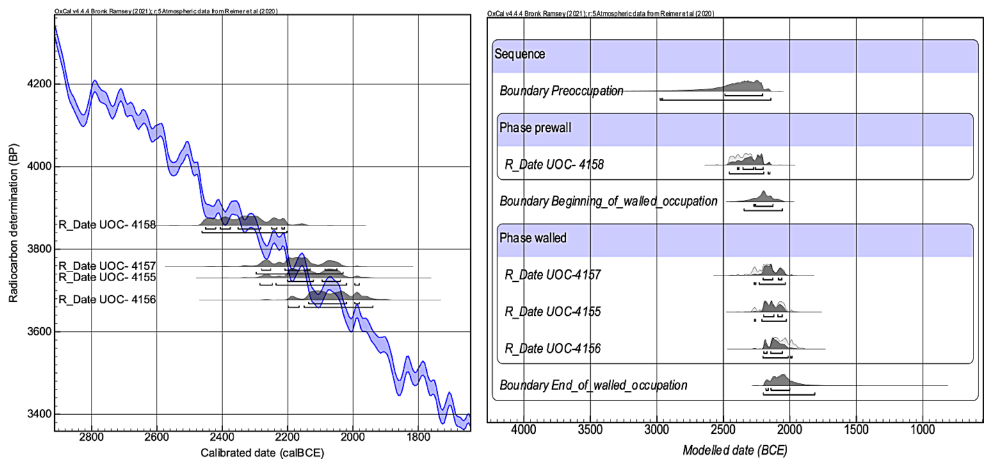

Fig. 5 Modeled calibrated ages of charcoal samples from Kotada Bhadli produced using OxCal v4.4.4 (Ramsey 2009) and the IntCal20 calibration curve (Reimer et al. 2020)

Table 3 Details of the sediment samples along with their phytolith and spherulite content. Phytoliths were counted between 200 and 300 per slide; spherulites were counted only 20 per slide

Location	Sample ID	Trench/Room	Location	Association	Ash content	Monocot phytolith count per slide	Spherulite count per slide
Settlement Wall Area	Wall_L1	-XL2	Layer S1	Post-occupational	None	231	0
	Wall_L2	-Xl2	Slayer S2	Occupational	Low	8	> 20
	Wall_L3	-XL2	Layer S3	Occupational	High	265	> 20
	Wall_L5A	-XJ12	Layer S5	Occupational	High	298	> 20
	Wall_L5B	-XL2	Layer S5	Occupational	High	288	< 10
	Wall_L7A	-XM3	Layer S7	Occupational	High	215	< 10
	Wall_L7B	-XL2	Layer S7	Occupational	High	253	> 20
	Wall_L9	-Xl2	Layer S9	Pre-occupational	High	22	> 20
Residential Area	Res_Fl-1	Room 4	Layer 3	Occupational	None	8	0
	Res_Fl-2	Room 9	Layer 3	Occupational	None	8	0
	Res_Fl-3	Room 10	Layer 3	Occupational	None	3	0
	Res_L4	-XB4	Layer 4	Pre-occupational	None	2	< 5

was normalized to δ13C (PDB). Radiocarbon ages were calculated as -8033ln(F14C) and reported in 14 C yr BP (BP = AD 1950) as described by Stuiver and Polach (1977). The errors on 14 C ages (1σ) are based on counting statistics and 14 C/12 C and 13 C/12 C variation between data blocks. We do not report δ13C as it is measured on the AMS and contains machine fractionation. Calibration was performed using OxCal 4.4.2 and the calibrated dates are presented with the 2σ range corresponding to a 95.4% confidence level, and were rounded to the nearest 10 years (Table 2; Fig. 5).

Phytolith and spherulite analysis

Micro-botanical remains and the presence of spherulites were analyzed from twelve sediment samples (Table 3), four of which were collected from the residential area and eight of which were collected from six different layers along the inner face of the southern settlement wall (Table 3; Figs. 4 and 6). Three of the four samples from the residential area were collected from tentatively-identified floors of three different rooms (within layer 3) while one was collected from the culturally sterile layer below the built structures (layer 4). Preliminary analysis of the phytoliths was carried out at the University of Toronto in Canada by Chakraborty, and the final analysis of the phytolith remains was carried out at Sichuan University in China by Bestel. The identification of spherulites was carried out at the University of Toronto and at the Max Planck Institute of Geoanthropology by Chakraborty.

Sediment samples for phytolith analysis were prepared using standard protocols (e.g.,Rosen et al. 2017), with the heavy liquid sodium polytungstate mixed to a specific gravity of 2.3. No other sample preparation was undertaken to minimize the risk of loss of sample or contamination. The lighter components of the sediments were collected after centrifugation and were mounted in water on slides and partly sealed with nail polish for examination. Slides were scanned at Toronto by Chakraborty under a Cambridge Instruments Galen III microscope using the times 40

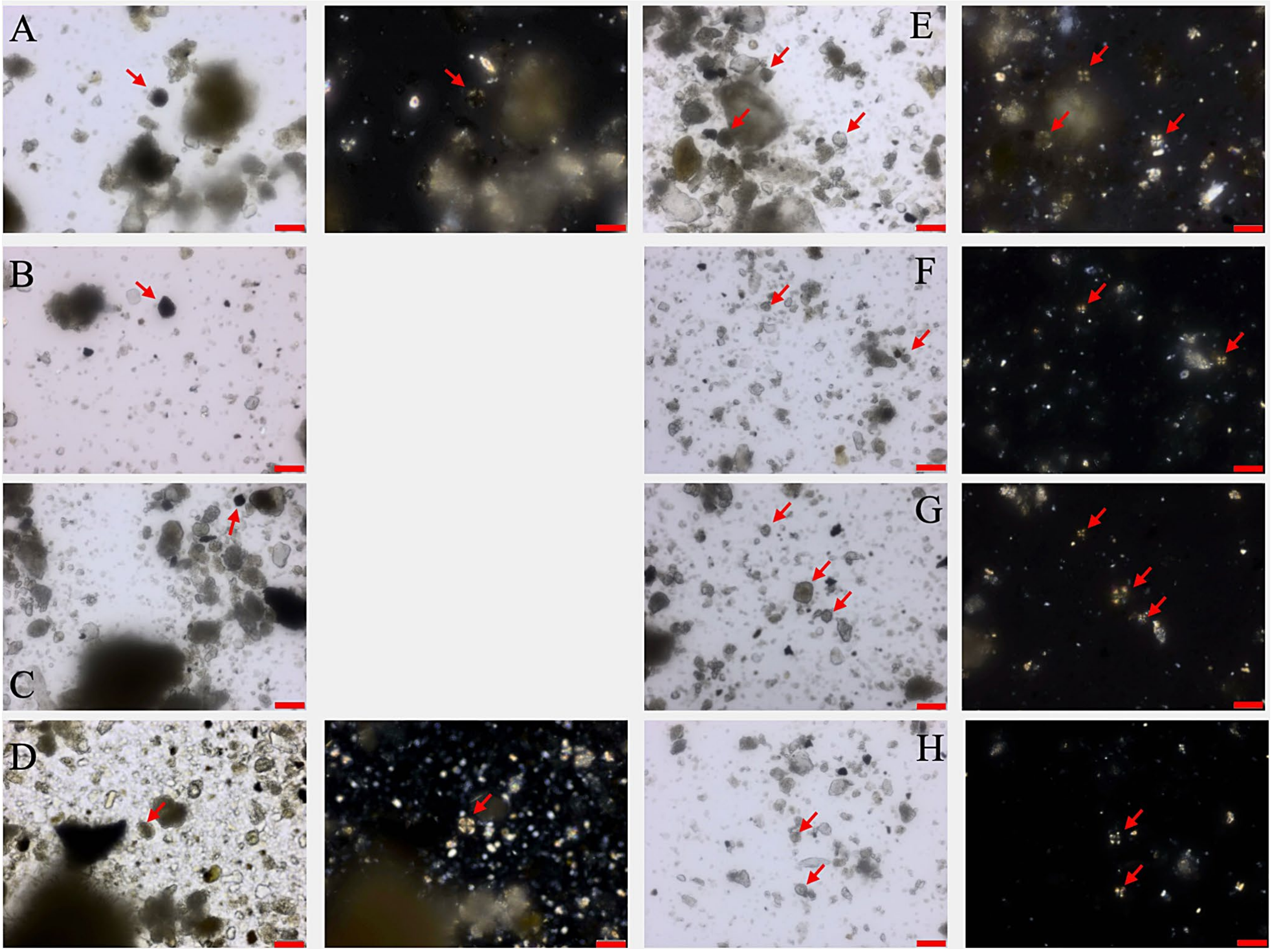

Fig. 6 Examples showing different kinds of spherulites present in the samples of Kotada Bhadli: darkened spherulites **(A**, **B**,**C)**, darkened/borderline darkened **(D**, **E)**, not darkened **(F**, **G**,**H).** Scales are all 20 µm

objective at a magnification of x400. Final phytolith identifications by Bestel were made based on prior experience with grass, wood and dicotyledon phytoliths, and using a plant reference collection of over 2000 specimens housed at Sichuan University. Phytoliths and other microfossils were identified, including fibres, hairs, and charcoal fragments.

A small amount of sediment from each of the twelve sediment samples was sieved using a 200 µm mesh in preparation for fecal spherulite observation. The sediment that passed through the mesh was poured onto a glass slide (one slide per sample) and water mounted. Up to 20 spherulite per slide were counted at 200X magnification at Toronto and at the MaxPlanck Institute of Geoanthropology by Chakraborty. Darkened and normal spherulites were identified based on the criteria provided by Canti (1998), Canti and Brochier (2017), and Canti & Nicosia, (2018). Each identified spherulite was observed under both plain polarized light (PPL) and cross polarized light (XPL).

Carbon and nitrogen isotope analysis

Sediment samples were first homogenized and screened through a 0.25 mm mesh and then approximately 3 g of homogenized sediment was treated with 15 ml 1 N HCl for 20 h to remove inorganic carbonate. After 20 h, the sediment samples were washed using ultrapure water. The samples were then dried in an oven at 70 °C overnight. Treated sediment between 5 and 11 mg, for carbon isotope analysis, and between 20 and 25 mg, for nitrogen isotope analysis, was weighed into tin capsules. Stable isotope analysis was conducted using a Thermo Fisher Scientific Flash Elemental Analyzer coupled to a Thermo Fisher Scientific Delta V Isotope Ratio Mass Spectrometer via a ConFloV system at the Max Planck Institute of Geoanthropology. The temperature of the oxidation tube was set up at 1080 °C and the reduction tube was set up at 650 °C, and the samples were passed through a water trap. The samples were run in duplicate. A two-point calibration was performed using measurements of international standard reference materials, USGS40 ($\delta^{13}C = -26.4‰ \pm 0.04‰$, $\delta^{15}N = -4.5‰ \pm 0.1‰$), USGS61 ($\delta^{13}C = -35.05‰ \pm 0.04‰$, $\delta^{15}N = -2.87‰ \pm 0.04‰$), IAEA N2 ($\delta^{15}N_{true} = 20.3‰ \pm 0.2‰$) and IAEA C6 ($\delta^{13}C = -10.49‰ \pm 0.01‰$). The standard UREA ($\delta^{13}C = -36.54‰$, $\delta^{15}N = -2.35‰$) was used for instrument quality check and an in-house fish standard ($\delta^{13}C = -15.8 \pm 0.02‰$, $\delta^{15}N = 13.75 \pm 0.01‰$) was used for instrument precision. Replicate precision of the standards was used to determine the machine measurement error, with a standard deviation of $\pm 0.3‰$ for $\delta^{15}N$ and $\pm 0.2‰$ for $\delta^{13}C$.

Results

AMS dates

The sample (UOC – 4158) producing the oldest date (2470 – 2200 cal BCE) was collected from layer 9 near the southern settlement wall (Table 2; Figs. 3 top and 5). This layer was formed prior to or contemporary with the building of the settlement wall and lacks any associated cultural material. Since there is no indication of any human occupation prior to the building of the settlement wall, this layer may indicate the beginning of human occupation at the site. The remaining three samples (UOC – 4155, UOC – 4156 and UOC – 4157) that were collected from the occupational layers produced calibrated dates of 2290 – 1980 cal BCE, 2200 – 1930 cal BCE, and 2300 – 2030 cal BCE. These dates fit within the range of the unpublished radiocarbon dates from the same site mentioned in Pokharia et al. (2017), as seen personally by Chakraborty. When modelled using OxCal v4.4.4, it appears that the occupation at the walled settlement began around 2270 BCE and continued till 2000 BCE (68.3% confidence interval), or between 2350 BCE and 1810 BCE (95.4% confidence interval) (Fig. 5); that is, during the Late Mature Phase or the Transitional Phase between Urban and the Post-Urban Period of the Indus Civilization in Gujarat (2300 – 1900 BCE). By the onset of the Late Period of the Indus Civilization (post 1900 BCE), this site was most likely abandoned and was never reoccupied.

Phytoliths and spherulites

Of the twelve sediment samples, half produced between 200 and 300 diagnostic phytoliths per sample, whereas the remainder produced fewer than 50 diagnostic phytoliths (Tables 3 and 4). The majority of the samples with low phytolith counts were collected from the tentative floors of the rooms and from the sterile layers, indicating an environment where phytoliths were not deposited, or deposited in low numbers, and/or were not preserved due to periodic cleaning of floors by the residents of the settlement. Due to fallen debris from the walls being embedded in the floors, the floors could only be tentatively identified, potentially impacting the sample collection. All the ash samples except *Wall_L9* produced high phytolith counts. A low priority sample *Wall_L1*, although producing high phytolith counts, was collected from the top layer along the settlement wall which formed after the site was abandoned. Non-ash sediment samples from the settlement wall (*Wall_L2*) produced low phytolith counts.

The high counts of cf. Asteraceae type phytoliths in some samples reflect the ubiquity of this type of phytolith in the archaeological record, as well as a high degree of fragmentation of these morphotypes, which form extensive, perforated plate structures. For this reason, this morphotype was not included in basic phytolith counts as the fragmentation can skew minimum numbers of individual taxa *(mni)* data for the samples. Occasionally, it is also difficult to separate small fragments of Asteraceae perforated platelets out from thin fragments of charcoal, which is another reason this group was treated separately.

Non-siliceous phytoliths, similar to those found in wood and in tubers, were identified in small numbers (Table 4). These phytoliths are not highly diagnostic, making it difficult to interpret whether they are from any particular wood or from tubers. High levels of burning were evident in the tiny wood charcoal at the site and burnt phytoliths are also present in some of the samples, indicating that along with dung and likely burned fodder/agricultural waste, some woods were also part of this ash.

At Kotada Bhadli, the percentage of monocot phytoliths tends to be higher than dicot phytoliths, especially in ash samples with high phytolith counts (Table 4). The dicot phytoliths, although very low in number, were distributed throughout the settlement in both ashy and non-ashy layers along the settlement wall and in the residential area (Table 4). These dicot phytoliths may relate to the use and discard of furniture, housing materials, food stuffs, and/or woods used for fuel. In contrast, the high counts of monocot phytoliths indicate that the outdoor environment was dominated by grasses, and/or indicate the presence of mats, grass baskets, and grass-based foods or fodders.

A minimum of sixteen distinct plant taxa from varied ecologies were represented by the diverse phytolith morphotypes recovered from the site (Table 4). The occurrence of several types of grasses from diverse ecozones in one settlement likely indicates that different habitats were exploited, and the micro-botanical assemblages formed were created via a composite of these diverse habitats. This could be explained by a mosaic or patchwork ecozone community

Table 4 Distribution of phytoliths in the sediments from Kotada Bhadli (* category not included in the final count)

Moncot/Dicot	Oeder	Family	Subfamily	Phytolith types	Wall_L1	Wall_L2	Wall_L3	Wall_L5A	Wall_L5B	Wall_L7A	Wall_L7B	Wall_L9	RES_FL-1	RES_ FL-2	RES_ FL-3	RES_ L4
Monocot	Poales	cf. Cyper-aceae		cf. sedge-bubbly				1		1	1					
Monocot	Poales	Cyper-aceae		sedge - small cones						1						
Monocot	Poales	Cyper-aceae		sedge hex			3		2		1					
Monocot	Poales	Poa-ceae/ Cyper-aceae		long cell	147	2	86	111	70	101	61	22	5	4	3	1
Monocot	Poales	Poa-ceae/ Cyper-aceae		bulliform	36	3	64	64	69	69	70		3	2		
Monocot	Poales	Poa-ceae/ Cyper-aceae		fan			1			5						
Monocot	Poales	Poa-ceae/ Cyper-aceae		blocky reed-like					3	5	1					
Monocot	Poales	Poa-ceae/ Cyper-aceae		dendritic lc			1	3	12	3	3					
Monocot	Poales	Poa-ceae/ Cyper-aceae		dendritic multi					3							
Monocot	Poales	Poa-ceae/ Cyper-aceae		lc multi burnt	36	3		7			9					1
Monocot	Poales	Poa-ceae/ Cyper-aceae		lc multi - indet	12		42	21	44	7	36					
Monocot	Poales	Poa-ceae	Aristidoi-deae	bilobe - aristi-doid			1	4	1		2					

Table 4 (continued)

Moncot/Dicot	Oeder	Family	Subfamily	Phytolith types	Wall_L1	Wall_L2	Wall_L3	Wall_L5A	Wall_L5B	Wall_L7A	Wall_L7B	Wall_L9	RES_FL-1	RES_FL-2	RES_FL-3	RES_L4
Monocot	Poales	Poaceae	Bambusoideae	bamboo cross			2	1		1	2					
Monocot	Poales	Poaceae	Bambusoideae	rondel cf. bamboo					2	1	1					
Monocot	Poales	Poaceae	Bambusoideae	squashed saddle				2								
Monocot	Poales	Poaceae	Chloridoideae	saddle small indet			12	34	3	2	11			1		
Monocot	Poales	Poaceae	Ehrhartoideae	bilobe - ehrhartoid						1	1					
Monocot	Poales	Poaceae	Ehrhartoideae	husk rice							1					
Monocot	Poales	Poaceae	Panicoideae	bilobe - panicoid			24	18	12	3	8					
Monocot	Poales	Poaceae	Panicoideae	cross-panicoid					1							
Monocot	Poales	Poaceae	Panicoideae	husk setaria			1	1	4							
Monocot	Poales	Poaceae	Panicoideae/Pooideae	rondel indet			1	1	2	1	5			1		
Monocot	Poales	Poaceae	Bambusoideae/Chloridoideae	saddle long indet				6	1	2	7					
Monocot	Poales	Poaceae	Bambusoideae/Chloridoideae/Panicoideae	bilobe indet			21	15	14	10	15					
Monocot	Poales	Poaceae	Bambusoideae/Panicoideae	Cross			2	3	1	1	1					
Monocot	Poales	Poaceae	Chloridoideae/Panicoideae	lc multi bilobate			2	4	3		7					
Monocot	Poales	Poaceae		cf. husk indet			1		31		3					
Monocot	Poales	Poaceae		grass short cell indet			1	2	10	1	7					

Table 4 (continued)

Moncot/Dicot	Oeder	Family	Subfamily	Phytolith types	Wall_L1	Wall_L2	Wall_L3	Wall_L5A	Wall_L5B	Wall_L7A	Wall_L7B	Wall_L9	RES_FL-1	RES_FL-2	RES_FL-3	RES_L4
Total Monocot Phytoliths					**231**	**8**	**265**	**298**	**288**	**215**	**253**	**22**	**8**	**8**	**3**	**2**
Dicot	Asterales	Asteraceae		asteraceae perf			12	4		11	25	1	1			
Dicot				dicot	18	2	1		12	3	2	6	2	1		2
Dicot				platy		2	4	3		12	5	5	2	2		2
Dicot				facetted			3					3		1		
Dicot				mc-dicot	57	11	25	7	7	54	9			3	1	14
Dicot				jigsaw						1	1					
Dicot				globular		5			2	4	5					
Total Dicot Phytoliths					**75**	**20**	**45**	**14**	**21**	**81**	**47**	**15**	**5**	**7**	**1**	**18**
Dicot*	cf. Asterales	cf. Asteraceae		phyto cf. Asteraceae	90		82	58	20	11	500+					
Charcoal				char thick			95		61	122	18		7	2	7	
Charcoal				char indet	123	4	9	200		24	180			3		
cf. Wood*				cf. wood multi			18	4	4		6					
cf. Wood*				cf. wood single			7	2	11		6					

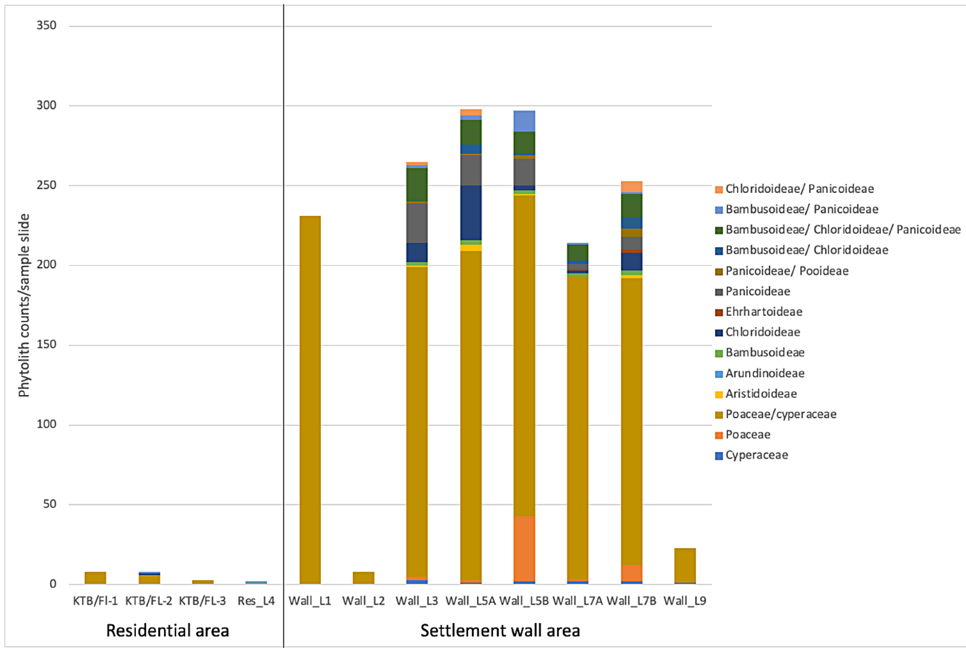

Fig. 7 Distribution of identified monocot phytoliths at the settlement of Kotada Bhadli, not including dicot, cf. wood and cf. Asteraceae type phytoliths

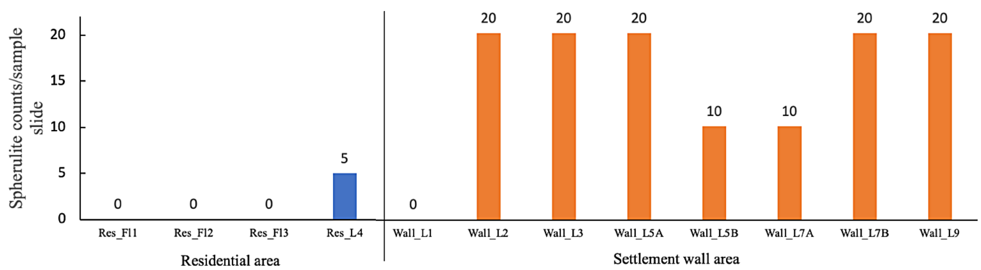

Fig. 8 Spherulite counts in the sediments from the residential area and in the dump area along the inner face of the settlement wall at Kotada Bhadli (counts were stopped at 20)

near the site, and human or animal mobility across these ecozones resulting in deposition of such diverse phytoliths.

The majority of the phytoliths encountered at the site are from the stems and leaves of various grasses and are rarely from husks; the latter are often indicative of cultivated plants collected for grains (Table 4). The exceptions include one phytolith from the husk of a millet-like plant in each of samples *Wall_L3* and *Wall_L5A* and four phytoliths from the husks of millet-like plants in sample *Wall_L5B*. A single husk phytolith of possible rice was present in Wall_L7B. These make up the only existing evidence of potential crops at the site. A number of possible husk-type phytoliths occurred in *Wall_L5B*, *Wall_L7B* and *Wall_L3* from the ash deposits along the southern settlement wall; however, these were most likely not from crops and may represent the husks of wild grasses.

In contrast, a significant quantity of faecal spherulites (over 20 individual counts), which form in the gut of ruminant herbivorous animals during digestion, are present in almost all the ashy sediment samples from near the southern settlement wall, where large quantities of fine ash were dumped (Table 3; Fig. 7). These spherulites are completely absent in the sediments from the residential area (*Res_FL-1*, *Res_FL-2 and Res_FL-3*), and in the layer of fallen debris along the southern settlement wall (*Wall_L1 and Wall_L2*). Both darkened and normal spherulites were present in the ash samples from the settlement wall area (Fig. 6 and 8). Darkened spherulites were identified as per the criteria proposed by Canti & Nicosia, (2018). The percentage of darkened spherulites in ashy layers varied between 10% and 20%, indicating that herbivorous dung was heated to temperatures between at around 500 °C and 700 °C under conditions of constrained combustion gases.

Stable carbon and nitrogen isotope analysis

At Kotada Bhadli, the $\delta^{13}C_{(sed)}$ from the residential area including the pre-occupation layer ranges between −18.9‰ and −21.5‰ (mean −19±1.2‰, $n=4$), whereas the $\delta^{13}C_{(sed)}$ for the ashy samples from the settlement wall area, excluding the pre- and post-occupation samples, ranges between −15.4‰ and −19.0‰ (mean −17.3±2.2‰, $n=6$) (Fig. 9). The $\delta^{15}N_{(sed)}$ values from the residential area, including the pre-occupational layer, range between 6.7‰ and 9.3‰ (mean 7±1.2‰, $n=4$). By contrast, the $\delta^{15}N$ values of ashy wall samples range between 10.4‰ and 17.3‰

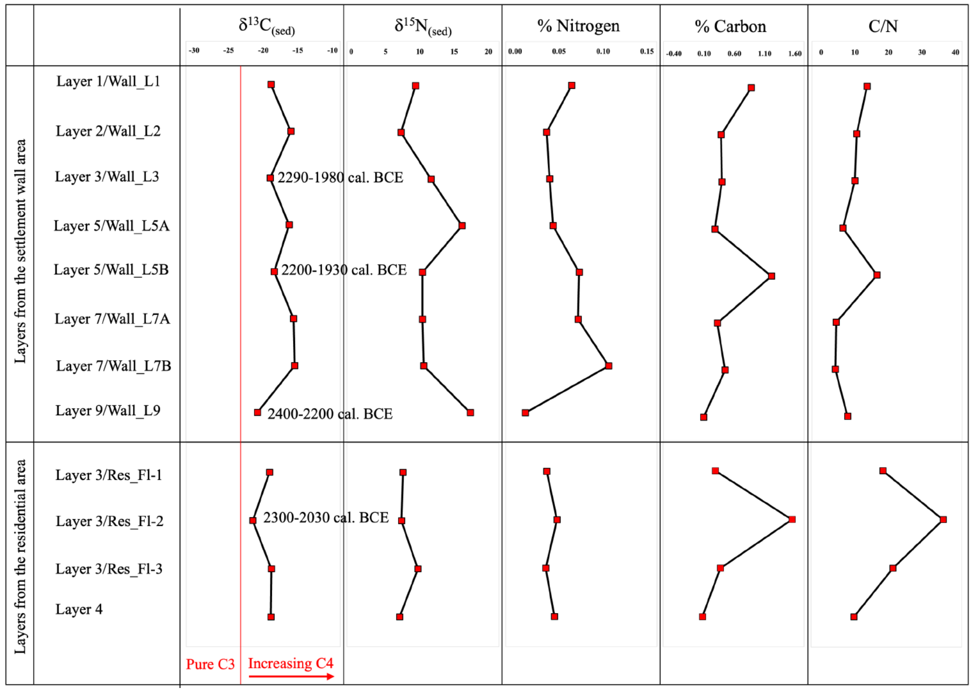

Fig. 9 Isotopic and elemental data of sediments from Kotada Bhadli divided into residential area and settlement wall area. Layer 4 from the residential area and layer 9 from the settlement wall area are the pre-occupational layers, whereas layer 1 from the settlement wall area is the post-occupational layer. The C3 and C4 ranges displayed in the diagram are the global average obtained from (Kirkels et al. 2022)

(mean 11.1±3.2‰, $n=6$). The percentage of total nitrogen and organic carbon as well as the carbon nitrogen ratio also varies between the sediment mixed with ash and sediment without ash. The nitrogen percentage of residential samples varies between 0.03 and 0.04 (mean 0.03±0.006%, $n=4$), whereas for ashy wall samples, it varies between 0.01 and 0.11 (mean 0.06±0.033%, $n=6$). Similarly, the carbon percentage for the residential samples ranges between 0.41 and 1.52 (mean 0.61±0.50%, $n=4$), and for the ashy wall samples, it varies between 0.09 and 1.21 (mean 0.36±0.39%, $n=6$). The weight ratio of total organic carbon and nitrogen in residential sediment ranges between 10.6:1 and 36:1, whereas, for ashy wall samples, it varies between 4.1:1 and 16.6:1.

Discussion

Situating Kotada Bhadli within Indus Era Gujarat

The AMS dates from Kotada Bhadli (2350 – 1810 BCE) align with the Late Mature Harappan Phase of Gujarat, corroborated by both the ceramic assemblage and structural remains. These findings are consistent with other Harappan settlements in the Kachchh region of Gujarat such as Periods IIB and III at Kanmer (Goyal et al. 2013; Kharakwal et al. 2012), Period II at Shikarpur (Ajithprasad and Bhan 2009), Stage VI (1950 – 1800 BCE) at Dholavira (Bisht 2015), the transitional Phase at Khirsara (2350 – 2150 BCE) (Pokharia et al. 2017), Phase III (2200 – 1900 BCE) at Bagasra (Sonawane et al. 2003) and the Sorath phase at Desalpur (thought to be ca. 2100 – 1900 BCE) (Uesugi. et al., 2015). During this Phase, changes in settlement layout have been observed throughout Kachchh. Specifically, at Dholavira the occupation area shrank into the citadel area, and stone structures replaced mud bricks as building materials; although traditional artifacts from the previous stages of occupation continued at the site, typical Harappan-type steatite seals underwent a stylistic change from square to rectangular (Bisht 2015). Similar structural changes were also noticed at Kanmer during Period IIB (Kharakwal et al. 2012). The Late Mature Phase in Kachchh is characterized by the dominance of regional pottery styles, known as Sorath-style pottery, alongside Classical Harappan-style pottery. This phase is also identified by the dominance of foundations of structures made of rubble and stones rather than mud or baked brick, although still following the Classical/Urban Harappan style of cardinal orientation. Thus the chronological dates from Kotada Bhadli also support the existing arguments of an increased utilization of Sorath-type artefacts and building materials in Kachchh around 2300 BCE based on their presence at major Classical Harappan settlements from Kachchh (Ajithprasad and Bhan 2009; Bisht 2015; Kharakwal et al. 2012; Lindstrom 2013).

In contrast to structural and stylistic changes, discussions of economic shifts during the Late Mature Phase are extremely limited. Craft production from the previous phase continued during the Late Mature Phase, and it was only during the end of this phase that extensive craft production ceased to exist at the Harappan settlements in

Kachchh. For example, by the end of Phase III (2200 – 1900 BCE), Bagasra was no longer a center for craft production; along with a decline in craft production, most of the buildings and the perimeter wall also collapsed during this phase (Lindstrom 2013). Similar declines in craft production and architectural maintenance were also observed at the site of Shikarpur (Ajithprasad and Bhan 2009; Chase et al. 2020). At the settlement of Kotada Bhadli, occupied solely during the Late Mature Phase, there is no indication of non-perishable craft manufacturing; however, artefact finds indicate that Harappan-type craft items were entering this settlement and were utilized by its residents. The residents of Kotada Bhadli were primarily engaged in animal husbandry and likely some form of domestic level cultivation (Chakraborty 2019; Chakraborty et al. 2018, 2020), similar to the economic activities carried out at other Sorath settlements from the central Saurashtra region in Gujarat (Possehl 1986, 1992; Possehl and Herman 1990; Sonawane 2000, 2004). There is also the possibility that inhabitants of Kotada Bhadli were engaged in trade in cattle and other animal products for food or labour to other sites, as discussed in Chakraborty (2019).

Identifying waste: microscopic content of the ash layers

The primary form of waste identified at the settlement of Kotada Bhadli was a huge dump of fine ash mixed with sediments and devoid of large pieces of charcoal, although broken household debris such as pottery and tools, and food residues such as bones were also found. Based on archaeological stratigraphy, this ash was undoubtedly generated during the settlement's occupation, as supported by its analyzed contents, including AMS dates. However, due to the absence of structures associated with firing activities, identifying the nature of activities that may have produced such a large quantity of ash requires additional discussion. Interestingly, this ash was not dispersed across the settlement, but was dumped at a very specific location, adjacent to the inner and the outer faces of the settlement wall. This deliberate placement indicates communal decision-making in selecting the dumping area.

The results of phytolith analysis show that the ash samples had very high monocot phytolith counts from a variety of plant taxa from different ecologies (Table 4; Fig. 6). This result is typical for Gujarat settlements where grasses are dominant (García-Granero et al. 2014, 2016; Lancelotti 2018). In addition, the lack of phytolith morphotypes typical of crop husks at the settlement of Kotada Bhadli suggests that waste from cultivated plant processing was not a significant part of the burnt waste that was dumped along the southern settlement wall. This could be because plant processing did not occur at this site and that grains were imported, as observed at the Post-Urban pastoral site of Rojdi (Reddy 1994, 1997). Alternatively, wastes from processing cultivated plants may not have survived in the archaeological record, or later stages of grain processing such as threshing, winnowing and pounding were carried out beyond the settlement wall (Fuller and Weber 2005; Reddy 1997). On the other hand, the high count of culm and leaf phytoliths in the southern settlement wall deposits suggests the presence of plant parts often collected for animal fodder or consumed by grazing animals. As discussed by Lancelotti (2018), animal fodders are typically dominated by culms and leaves, with husks and chaffs rarely used. The lack of large pieces of charcoal is not surprising given that the landscape of Kachchh is primarily dominated by grasses and shrubs, see Lancelotti (2018) for a discussion of remains from similar landscapes.

Animal dung was widely used as a primary fuel source at many Harappan sites, especially at smaller settlements. However, identifying decomposed and/or burned dung, as well as decomposed agricultural waste, in archaeological contexts can be challenging due to taphonomic processes and preservation issues (Lancelotti 2018). Along with several other methods (Canti 1998; Delhon et al. 2008; Evershed and Bethell 1996; Jones et al. 1988; Lancelotti and Madella 2012; Peter 2001; Schelvis 1992; Valamoti and Charles 2005), faecal spherulites have been used extensively to detect herbivorous dung in archaeological sediments (Canti 1998; Canti & Nicosia, 2018; Gur-Arieh et al. 2014), and the presence of darkened spherulites which are formed at temperatures between 500 °C and 700 °C indicates burning of dung around or beneath a fire. This could occur in any fire where herbivorous dung is present or used as fuel, in both domestic and communal situations (Canti & Nicosia, 2018). The high count of both darkened and normal faecal spherulites in the ashy dumps strongly supports animal dung as a major constituent of waste at this rural agro-pastoral settlement (Figs. 8 and 7). In sum, animal dung burned as fuel, as well as the burning of otherwise unused animal fodder, likely formed the primary waste at the settlement of Kotada Bhadli, and possibly at many other agro-pastoral settlements during the Late Mature Harappan Phase onwards when agro-pastoralism became a major part of the Harappan economy, at least in Gujarat (Bhan 2011).

Assessing waste: stable organic carbon isotope ratios of sediments from Kotada Bhadli

To further assess the waste sources at Kotada Bhadli, we determined bulk organic carbon and nitrogen stable isotope ratios of sediments collected from both the wall dump and residential areas (Fig. 9). Carbon stable isotope ratios of sediment organic carbon can provide insights into past vegetation history, primarily the relative coverage of C_3 and C_4 type vegetation. The global Suess-corrected average $\delta^{13}C$ value of C_3 vegetation is around − 27.1‰ (ranging from − 36‰ to -22‰) and that of C_4 vegetation is around − 12.1‰ (ranging from − 16‰ to -10‰). However, these values vary depending on plant functional type, altitude and mean annual precipitation (Dawson et al. 2002; Hare et al. 2018; Kohn 2010; Wang et al. 2008). A local study from the Godavari plain in the south-central region of the Indian peninsula found that the $\delta^{13}C$ values of C_3 type vegetation in that region vary between − 33.2‰ and − 24.3‰ with a Suess-corrected mean value of -27.7‰ and for C_4 type vegetation vary between − 15.1‰ and − 12.7‰ to with a Suess-corrected mean value of -13.2‰ (Kirkels et al. 2022).

Our findings indicate that Kotada Bhadli had a mixed C_3 and C_4 environment during the occupation period, as indicated by the $\delta^{13}C$ values of soil organic carbon from both the residential and the ashy wall dump areas. Not including the pre and post-occupational layer, the $\delta^{13}C$ values of soil organic carbon in the residuential area range between − 21.5‰ to -18.9‰ (mean − 19.8±1.4‰) and in the ashy wall dump areas it ranges between − 19‰ to -15.4‰ (mean − 16.9±1.6‰) (Fig. 9). These values are similar to those observed at nearby archaeological settlements from Gujarat during the same time period, such as Babar Kot (-21.2‰ to -17.5‰), and Oriyo Timbo from Saurashtra (-22.6‰ to -18.4‰) (Reddy 1994), and Khirsara in Kachchh (Pokharia et al. 2017), as well as the Holocene sediments from Runn of Kachchh contemporary to the Indus Era (-20.6‰ to 18.2‰) (Ram et al. 2022) (see Fig. 10).

At Kotada Bhadli, the ashy sediments from the wall dump area indicate a stronger C_4 influence compared to the residential area. A simple Linear Mixing Model (ISOERROR1_04, https://www.epa.gov) using the global mean and Suess-corrected values of C_3 vegetation (-27.1‰) and C4 vegetation (-12.1‰) indicates that the percentage of C_4 plants in the residential area (including the pre-occupational layer) varies between 37% and 55%, whereas for the ashy wall dump layers, it varies between 42% and 78%. Excluding the pre-occupational ash layer 9 (which formed prior to the building of the settlement wall), the percentage of C_4 in the wall dump area increases to 54–78%. Using more local values from the Godavari plains, results in a 6% increase in estimated C_4 plants for both the areas. However, interpreting these results is complicated by taphonomic effects. Burning typically increases $\delta^{13}C$ values for C3 biomass ash but decreases them for C4 biomass ash, due to differences in oxidizable, volatile, and refractory carbon compounds and kinetic fractionation (Sarangi et al. 2022; Turekian et al. 1998). While this makes it difficult to assess the exact proportion of C4 plants in the ashy dumps, the overall higher $\delta^{13}C$ values observed in this area likely result from a combination of factors: (1) Burning of dung from herbivorous animals that consumed increased C_4 vegetation, (2) burning of a high proportion of C4 biomass, and (3) taphonomic effects of burning on C3 and C4 plant materials. This interpretation fits with the biogenic isotope data from domesticated animals at Kotada Bhadli, which reveals that cattle and buffalo foraged on C_4 dominated vegetation (Chakraborty et al. 2018).

Organic characterization of waste: stable nitrogen isotope ratios of sediments from Kotada Bhadli

Nitrogen stable isotope values of sediments can also provide insights into the sources of organic matter; however, interpreting these values requires consideration of multiple factors that can affect isotopic composition (Riddle et al. 2022; Szpak 2014). Several studies have demonstrated an increase of $\delta^{15}N$ in herbivore feces compared to diet. For example, Sponheimer et al. (2003) found 2–3‰ increase in $\delta^{15}N$ of feces compared to herbivore diet, and similarly, Codron et al. (2012) reported about 2‰ increaset in fecal $\delta^{15}N$ values relative to diet across multiple herbivore species. However, when examining archaeological contexts, the increase can be much more pronounced. Shahack-Gross et al. (2008), conducted one of the few studies attempting to identify the presence of dung in archaeological settlements by analyzing

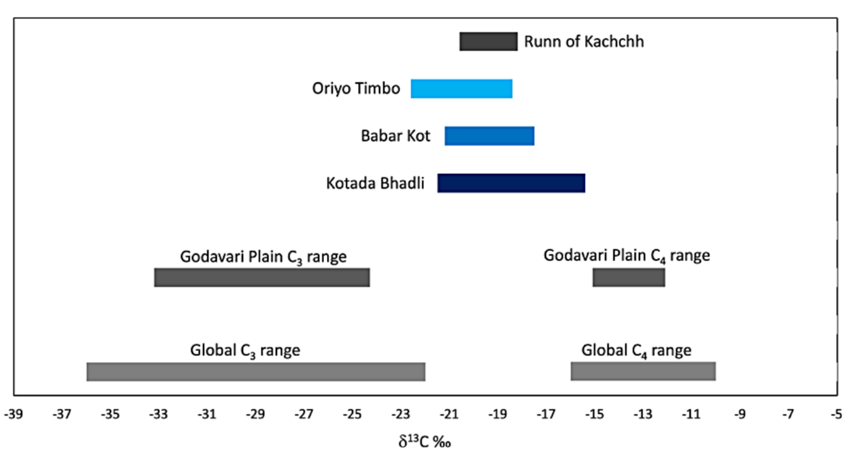

Fig. 10 Comparison of $\delta^{13}C_{(sed)}$ values of Kotada Bhadli and contemporary settlements from Gujarat with global and local (Godavari) vegetation values. ($\delta^{13}C$ values were obtained from (Dawson et al. 2002; Hare et al. 2018; Kirkels et al. 2022; Kohn 2010; Ram et al. 2022; Reddy 1994; Wang et al. 2008)

sediment $\delta^{15}N$ from a caprine enclosure that produced $\delta^{15}N$ values between 12.8‰ and 19.7‰, while a cattle enclosure resulted in values between 12‰ and 16.3‰. These results suggest that over time, processes such as decomposition and microbial activity can further increase the $\delta^{15}N$ values in dung-rich sediments beyond what is observed in fresh feces (Steele and Daniel 1978; Szpak 2014). Similarly, ash produced from burned biomass could also produce higher $\delta^{15}N$ values compared to the parent vegetation due to preferential volatilization of lighter isotopes during burning (Saito et al. 2007). Several studies have demonstrated this effect across different ecosystems. In grasslands, Grogan et al. (2000) found increases of 2.5–3.5‰ in $\delta^{15}N$ of ash after burning vegetation. Similar results were observed in forest environments, with Saito et al. (2007) reported increases of 1–3‰ in $\delta^{15}N$ of ash from burned forest litter. In savanna ecosystems, Aranibar et al. (2003) noted increases of 2–4‰ in soil $\delta^{15}N$ following fires. The magnitude of $\delta^{15}N$ increase can depend on burning temperature and duration, with higher temperatures and longer burning times tending to produce greater increases (Saito et al. 2007; Turekian et al. 1998). Based on a control laboratory burn, Turekian et al. 1998 noted an increase of 2.5‰ in $\delta^{15}N$ of ash from fresh vegetation. It is important to note that these studies analyzed pure ash, while our samples represent a composite of burned and unburned materials.

At Kotada Bhadli, the $\delta^{15}N$ values from the residential area (Fig. 9), as well as the pre- and post-occupational layers, range between 6.7‰ and 9.4‰ (mean 7.8±1.2‰), consistent with typical terrestrial soil values (Frank et al. 2004; Shahack-Gross et al. 2008). In contrast, the $\delta^{15}N$ values of ash samples from the wall dump area are notably higher, ranging between 10.4‰ and 17.3‰ (mean 12.7±3.2‰), similar to what was observed by (Shahack-Gross et al. 2008) for animal enclosures. This increase of around 5‰ in $\delta^{15}N$ in the ashy wall sediments could be attributed to the presence of animal dung (Frank et al. 2004; Lee et al. 2011; Shahack-Gross et al. 2008) and/or burning of dung and vegetation at a high temperature for extended periods (Turekian et al. 1998). While $\delta^{15}N$ values alone cannot definitively distinguish between animal dung and burned vegetation, the significantly higher $\delta^{15}N$ values in the ashy dumps (10.4‰ to 17.3‰) compared to the residential area (6.7‰ to 9.4‰) at Kotada Bhadli likely reflect a combination of burning effects, the inherently higher $\delta^{15}N$ of animal dung, and potential further increases due to microbial processing over time.

Percentage and ration of organic elemental carbon and nitrogen in the sediment from Kotada Bhadli

The interpretation of total soil organic carbon and nitrogen in the sediments from Kotada Bhadli is complex. While high intensity fire is responsible for the partial or complete loss of SOC due to combustion, low intensity fire is often either responsible for no change or an increase of soil SOC due to the incorporation of partially burned and unburned biomass into the soil (Agbeshie et al. 2022; Roshan and Biswas 2023). Overall, at the settlement of Kotada Bhadli, SOC in ashy dumps are lower (mean 0.39% ± 0.38%) compared to the non-ashy sediments (mean 0.58% ± 0.53%). This may be due to high temperature burning, but considerable inter-sample variation in both the residential area and in the dump area suggests heterogeneous composition and varied heating events. Fire activity generally reduces nitrogen content via volatilization and mineralization; however, total nitrogen can also increase primarily due to the addition of nitrogen-rich ashes. Post-fire microbial activities are also responsible for an increase of nitrate in the soil (Agbeshie et al. 2022; Roshan and Biswas 2023). At Kotada Bhadli, we observe higher total nitrogen in the ashy dumps (0.07% ± 0.03%) compared to the residential area (0.03% ± 0.01%). This increase may be attributed to nitrogen-rich ashes and organic matter from sources such as dung and biomass in the ashy dumps. Additional factors, such as elevated soil pH from basic cations in burned dung, may result in higher retention of nitrogen relative to carbon. This nitrogen retention is further amplified by a high content of refractory soil organic matter derived from the burned dung (Li et al. 2021; Wang et al. 2022). The interplay of these factors helps explain the different C/N ratios observed between the ashy dump and residential areas.

Conclusion

The ashy sediments from the inner face of the settlement wall of the Late Mature Harappan Phase (2300 – 1900 cal. BCE) site of Kotada Bhadli exhibit clear signs of significant disposal of burned animal dung along with burned vegetation and other cultural debris. These signs include a high content of grass phytoliths, input of C_4 vegetation, higher carbon and nitrogen isotopes values, lower C/N ratio and the presence of normal and darkened dung spherulites in the sediments dumped along the inner (and presumably outer) face of the wall. Other than burned dung and burned vegetation, domestic waste materials such as broken pottery, tools and jewelry, housing materials, likely broken furniture and wooden objects, as well as dietary wastes such as animal bones and plant refuse, were also deposited in this area.

In the Kachchh region where the site of Kotada Bhadli is located, wood for fuel was scarce. Therefore, dung was likely used as the primary domestic fuel source. Ash generated from various domestic and/or economic fire-related activities was dumped in specific locations (along the settlement wall), as defined by the community. However, soot marks visible on the inner wall face clearly indicate that some waste was also burnt in-situ, possibly to reduce odours, a practice commonly observed in modern day villages engaged in animal herding. Such efforts suggest the inhabitants' interest in maintaining cleanliness by removing waste to the settlement's edge.

Unlike the Ash Mounds of the Southern Indian Neolithic (Paddayya 2019), it is difficult to determine whether ash production and dumping within the boundary of Kotada Bhadli served any ritualistic or ceremonial significance. While regular domestic and agro-pastoral likely produced these occupational layers, we cannot discount the possibility of ritual and/or ceremonial activities related to this ash debris taking place within this settlement, at either the communal or household level. Some communal or personal ceremonial activities involving fire and dung may also have contributed ash production. However, it remains unclear whether ritualistic origin of this ash warranted special disposal practices that kept the ash within the settlement, rather than dumping it primarily outside the wall. While it might have been convenient for the residents to dump the waste along the wall, which is at the edge of the settlement; substantial dumping of domestic waste along the faces of the wall may have bolstered its structure, potentially reducing its regular maintenance costs.

The analysis of occupational waste at the settlement of Kotada Bhadli provides new insights into rural Indus Era settlement that was occupied during the Late Mature Phase between 2300 BCE and 1900 BCE in Gujarat. The evidence for large amounts of (burned) dung and possibly fodder supports the interpretation that sedentary to semi-sedentary pastoralism was a primary economic activity (Chakraborty et al. 2018). The substantial quantities of these materials within the settlement suggest that at least some animals were penned inside the settlement at night and grazed outside during the day contributing to the accumulation of dung and the varied distribution of monocot phytoliths. Soil organic carbon analysis indicates a mixed C_3-C_4 environment in this part of Gujarat, with a slight dominance of C4. This aligns with previous enamel isotopic data of bovines from Kotada Bhadli, which also showed a mixed C_3-C_4 diet, with a slightly higher proportion of C_4 compared to C_3 (Chakraborty et al. 2018).

Our findings highlight the adaptation of rural Indus communities to local environmental conditions and their integration into regional economic networks. Unlike the large Harappan settlements with elaborate drainage and waste management systems, Kotada Bhadli used a simpler, ad-hoc but systematic community-organized waste management approach. Waste was systematically accumulated and disposed of in designated areas along the settlement wall, likely managed by individual households. This practice indicates either the lack of necessary resources for maintaining a centralized waste management system, as adopted by larger settlements, or lack of the necessity in smaller rural contexts. Nevertheless, the deliberate waste disposal efforts demonstrate a concern for settlement cleanliness and hygiene. Examining these waste disposal practices at Kotada Bhadli can help us to better understand the continuous interaction between humans, their settlements and the surrounding physical and cultural environment. An acknowledgement of the presence of waste and a discussion on its management in rural settlements provides a rare window into the lives of the inhabitants who had to manage waste materials on a daily basis.

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Declarations

Competing interests The authors declare no competing interests.

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