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Investigating crop processing using phytolith analysis: the example of rice and millets

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Abstract

The application of crop processing models to macro-botanical assemblages has traditionally been used to interpret past husbandry practices and organisation of labour involved in crop-processing. Phytoliths offer an alternative method of analysis because they are durable in most environments, regardless of whether plant parts are charred, and the identification of plant types and plant parts allows them to be used in much the same way as macro-botanical remains. Indeed macro-remains and phytoliths are complementary datasets for examining the input of plant parts, such as crop-processing waste, into archaeological deposits. We outline crop-processing models in relation to macro-remains and then develop the framework for their application to archaeological phytolith assemblages. Rice and millet processing models are explored in relation to patterns expected in both macro-remains and phytoliths. The utility of these models is demonstrated with archaeological evidence from the site of Mahagara, an early farming site in North-Central India. The results indicate a way to employ phytoliths in archaeology which complements the fragmentary evidence available from plant macroremains.

Keywords: Archaeobotany; Taphonomy; Neolithic; India; Rice; Millet

1. Introduction

Investigating agricultural systems of past human societies is one of the central questions in archaeobotany. Crop processing models are traditionally used with macroscopic plant remains to investigate past agricultural activities [17:261–267,26,69,70] (Jones, unpublished PhD dissertation, 1984). This involves identifying different crop plant components and weed seeds and then comparing the proportions of each to find out the crop processing stage. There are problems that hinder this analytical approach. It relies on macroscopic plant remains coming into contact with fire so that they are preserved by charring. This exposure varies with each type of crop, and the cultural and geographical setting, which may determine that fire is not needed. Even if the crop does come into contact with fire, some of the plant components will be burnt away due to high temperatures resulting in a loss of material, especially chaff [6,67,70]. By contrast, phytoliths offer a robust dataset for distinguishing certain key stages of crop-processing sequences and are more commonly preserved when macro-remains are unavailable or uninformative.

Phytoliths are not organic and therefore do not have the same preservation problems as organic plant remains. Burnt plant materials will leave behind phytoliths in ash, but equally unburnt plant parts that decompose will leave phytoliths in archaeological sediment. Thus the likelihood of recovering evidence for any particular species, or plant part, may be better for phytoliths than for carbonized evidence. Major cereals, such as barley [55], wheat [3,4,55], and rice

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[16,47,73,77,78], as well as specific plant parts [57] can be identified using phytoliths. Currently, phytoliths are being used to identify farming techniques such as harvesting methods and irrigation [56,58], to distinguish the major fuel inputs into fires, whether dung or wood fuel [39], and different sources of plants in terms of vegetation communities that contribute to middens and dung-derived deposits [52]. We would like to expand this range of analytical uses by recommending the application of phytolith assemblage analysis for assessing inputs of crop-processing waste into archaeological deposits. The approach we propose relies on a combination of identifying taxon specific morphotypes and the quantitative characterization of phytolith suites that are non-specific to taxon but imply patterns in plant part distribution. In this paper, established crop processing models involving macroscopic remains are evaluated and an argument is made for the use of phytoliths to aid and substitute as an analytical tool. An example of how phytoliths can be used in this manner is discussed with a dataset from an early farming site in North-Central India, Mahagara [23].

2. Traditional crop processing approaches

A key aim of archaeobotanical investigation is interpreting past agricultural strategies. The recognition that most plant remains in carbonized assemblages of prehistoric Europe, consisting of grains, chaff, and probable arable weeds, lead to the recognition that crop-processing activities might make significance contributions to the structure of archaeobotanical assemblages, which therefore do not reflect simply ratios of species used [13,14,25,34,35]. Refined crop-processing models were developed based on detailed ethnoarchaeological studies of traditional, non-mechanized crop-processing and the analysis of product and by-product assemblages was carried out first by Hillman [25–27], and replicated and extended by Jones [30,31] (unpublished PhD dissertation, 1984), especially for wheats, barley, and some pulses of Mediterranean agriculture. Other models have since been produced, which include barley and rye in Fennoscandia [15,72], or the western Mediterranean [49] quinoa and other crops in Peru [7], millets in India [53,54] (Reddy, unpublished PhD dissertation, 1994), in China [37], in Nepal [38], in Africa [12,75,76], and rice in Thailand [69]. These models are based on detailed ethnographic studies of present-day non-mechanized crop processing and its effect on the composition of assemblages of grains, "chaff" (including glumes, lemmas, paleas, rachises), culm nodes from straw, and weed seeds of various size and weight categories. Their application to archaeology is based on the uniformitarian assumption that plant morphology constrains the range of methods that can be applied to break apart and sort plant components. This approach has become a standard tool for assessing the relationship of archaeobotanical assemblages to these activities, which may allow the assessment of missing categories of evidence, e.g. weed categories removed in early processing stages, and thus is the first step in using archaeobotanical evidence to address specific archaeological questions. Through an understanding of crop-processing aspects of the distribution of production, distribution and consumption of crops, and their by-products can be understood and thus provide insights into the social organisation of past communities.

The strength of these crop processing models lies in their reliance on constrained patterns of plant morphology to infer variation in human behaviour. The development of crop-processing studies was part of a wider movement in archaeology toward refining the use ethnographic analogy for interpreting archaeological evidence [2,22,33,74] and developing a theoretical framework for understanding formation processes [11,61,62,64], or what Binford [5] dubbed "Middle Range Theory". As outlined by Hillman [25], his ethnographic research was aimed at developing "ethnographic models" that transcended simple analogy and provided a basis for inferring human activities that had structured the composition of plant assemblages. These models could be employed even though these assemblages might lack association with a clearly intelligible context with behavioural implications. This development is important as it parallels the development in archaeozoology of using body part representation and fragmentation patterns to infer past butchery or scavenger impacts on bone assemblages. Thus behavioural patterns can be inferred even if assemblages do not come from primary contexts in which past behaviour may be inferred from preserved archaeological features, and such primary depositional contexts, are extremely scarce for plant remains which are normally preserved through the mediation of fire leading to carbonization. This represents analogy strengthened through consideration of relevance and determining structures [74], or what Hodder [29] advocated as relational analogy. The structural properties of the plants, which are beyond cultural construction, constrains the methods and results of processing and structures the resulting plant assemblages.

Subsequent studies have borne out Hillman's argument of relevance for his ethnographic model developed from fieldwork in Turkey [27]. Fundamentally, there are a restricted range of crop-processing aims—removing edible from inedible, freeing edible grain from "chaff," removing contaminating weed seeds—and there are relatively few efficient methods of crop processing for non-mechanized farmers, which involve a combination of pounding/threshing and separation, either by differential density (winnowing) or differential size (sieving). While there are variations between crops and between traditions of cultural practice [53,72], such as harvesting techniques, whether crops are threshed by human force or domestic animals, or what tools are used in winnowing. Additional ethnographic studies on different crop plants have been important for identifying some of these minor cultural variations and for clarifying crop-specific patterns of part separation, but the basic contours of Hillman's original processing model have been affirmed. The importance of crop-processing models is that they provide a formation theory for archaeobotanical assemblages of agriculturalists which allow the source of archaeological plant assemblages to be interpreted on the basis of assemblage *content* rather than context. Context is often uninformative or may be misleading for charred plant remains.

Preservation is a very prominent constraint on archaeobotanical research. Macroscopic plant remains on most archaeological sites only survive by means of charring. This necessitates that during the processing of a crop it will have to come into contact with fire and at a relatively low temperature to have any chance of survival in the archaeological record. This can occur in a number of ways [26]: (a) during a drying or parching of the crop product; (b) burning of diseased crop; (c) use of crop waste as fuel and incorporation of waste into dung used as fuel; (d) accidental burning during cooking or the destruction of a house by fire. This has two implications for the charred plant assemblages. Firstly, light chaff fractions and fragile weed seeds may not survive because they are burnt away [6]. This can affect the proportions of each fraction making it difficult to determine the processing stage [67,70]. Secondly, early processing by-products, such as straw waste, are unlikely to come into contact with fire and thus are not preserved by charring [31]. Based on analyses of macroremains it is very often late processing stages, such as dehusking waste and fine-sieving waste, which constitute charred assemblages, i.e. on-site routine activities [17,20,67]. Consequently, these early stages of crop processing are less likely to be found on archaeological sites. This will affect what interpretations can be drawn from the dataset, especially concerning the question of distinguishing between crop producer and crop consumer sites.

In recent years, crop-processing stages have been considered as a means to distinguish sites of agricultural producers versus those of consumers. As an interpretative framework, this can be traced back to comments by Hillman [26], which have been widely discussed in the context of wheat/barley based agricultural contexts [32,65,67,70]. The search for this distinction has also been transferred to the methodological use of crop-processing studies of millets [54] (Reddy, unpublished PhD dissertation, 1994) and rice [69]. The basic approach attempts to oppose sites on the basis of the presence or absence of early versus late stages of crop-processing based on the assumption early stages will be carried out by primary producers. On strictly archaeological grounds this model is difficult to apply as it relies on the assumption that all stages practised by a community will be preserved *on site,* although biases in preservation through charring and the likelihood that some activities, especially, threshing and winnowing after harvest may be carried out in fields away from site. In other words the key distinction relies on imputing absence of evidence (for early stages) to be evidence for absence [17:266,20:348]. Ethnographic and economic realities also argue against a simple producer:consumer division of this sort [67], and specific ethnographic examples from India demonstrate this. In the Cauvery river valley of Tamil Nadu (South India) for example, occupational specialists, such as metalworkers, are generally paid in kind in sheaths of rice, immediately after the harvest and prior to processing, for services rendered to the farmers in previous seasons [66:102]. Thus the distribution to consumers occurs in an unprocessed stage that would resemble the predicted "producer" pattern. This is due to the economic value of the straw and crop-processing residues, which amongst other uses are an important source of animal fodder (see also [71]). Nevertheless, on a regional scale the presence of early stages is likely to imply cultivation within the region, especially for small scale societies such as those of the Neolithic.

The use of crop-processing residues in fodder raises the issue of whether dung is burnt as fuel and the potential contribution of this pathway to archaeobotanical assemblages. The use of dung for fuel has been suspected on a number of western Asian sites [10,24,41,42,44,45], and has been the focus of controversies in archaeobotanical interpretation [10,28,43,59]. Charles [10] has argued that a better approach is to examine the plant composition of the seed samples, and look for patterns to suggest non-arable, non-harvested sources. The study of phytolith suites provides another means of identifying the use of dung fuel archaeologically, which is independent of seed evidence. Madella [39] has examined hearths from Pakistan, which has great implications for the problem of identifying dung use as fuel. A separation could be identified between different fuel uses of which one was goat dung. This assemblage contained a high frequency of stem and leaf phytoliths and a lower frequency of grass inflorescence and dicotyledons. Other microscopic methods, such as the analysis of faecal spherulites, can also be used to determine the presence of dung in archaeological deposits [8,9].

Despite these complications, it is still of interest to understand the presence and distribution of crop-processing stages and residues as these are the outcome of socially organized labour connected to the production and consumption of food. Those plant macro-remains which dominate the range of deposits and contexts across an archaeological site are most likely to represent the outcome of repetitive, routine activities [17:266,18:35,20:346–348,67]. The processing stages represented are therefore likely to reflect the labour employed routinely in processing material that has come out of storage, and thus by implication allows inference of how much processing was carried out prior to storage, and thus how much labour could be mobilized at the period of harvest. The application of phytoliths provides the opportunity to both test the representation of crop-processing in charred evidence, as phytoliths may also come from those stages not exposed to fire, and to identify routes into the archaeological deposits of agricultural residues other than routine refuse that is charred. Ultimately such evidence will contribute to a more nuanced understanding of agricultural production and the utilization of its produce.

3. Why phytoliths can work

Since the 1970s, phytolith analysis has been a fast developing discipline within archaeology and palaeoecology [51,57]. Phytoliths are microscopic mineralised bodies formed in living plants. They are primarily composed of amorphous silica but are also formed of calcium oxalate. Monosilicic acid is brought into the plant through the uptake of water and this precipitates to form opaline silica within and between cells. They occur in a wide variety of plants both monocotyledons and dicotyledons. Monocots, which include grasses, produce more abundant and distinctive phytoliths. Grasses are commonly exploited by people and therefore phytoliths can be used to understand the economic exploitation of plants.

The vast potential of phytoliths lies in their durability. Phytoliths are inorganic and are not broken down by bacteria. They are stable in a wide pH range (3–9) and preserve well in wet, dry, and alternating wet and dry conditions [46,50,57]. Unlike organic plant remains, they do not rely on exceptional conditions for survival and are therefore found in most environments. Contrary to macro-botanical remains, phytoliths do not rely on charring to be preserved at archaeological sites although they will be a significant component of ash from fires. At the majority of archaeological sites they are abundant and therefore available to be analysed. They also come from plant parts (e.g. stems, leaves, husks), which are rarely represented by macro-botanical remains. Hence, establishing their use for the analysis of crop processing stages would be of advantage. Phytoliths on archaeological sites will be affected by crop processing in the same way as macroscopic remains and therefore do not represent accurately the proportions of the crops grown but products and by-products of processing stages. In order to develop such a method of determining these stages there are a number of factors that have to be considered when using phytoliths: the production of phytoliths, sampling procedures, processing, quantification, and identification.

The production of phytoliths within living plants is not uniform. The deposition of silica can be the product of plant physiology as well as the result of the environmental factors and the growth conditions of the plant [57]. Therefore, in different environments and in separate growing years, a different number of phytoliths will be produced. Whether this will have a significant effect on the proportion of phytoliths in archaeological samples is hard to determine but if it is assumed that the archaeological assemblages were produced all in the same general climatic zone then the phytolith production will be similar throughout the crop.

If phytoliths are to be used in a similar manner to macroscopic remains it is important to create a sampling strategy, which will aid the interpretative process. The number of samples taken from different types of features and replicate sampling needs to be considered along with the amount of time it takes to process and analyse phytoliths, which is considerably longer than with macroscopic remains. A balance has to be struck that will give the optimum amount of information in the time available for analysis.

The processing of soil samples to make slides of phytoliths is a lengthy process. The principle is to try to separate the opaline silica from the sand, silt, clay, and organic matter. The final separation is conducted using a heavy liquid [40] at a matching specific weight to opaline silica so that they can be collected. The actual methods used vary between researchers. A quantitative method has been developed by Albert and Weiner [1]. This includes weighing the sediment at the beginning and the product at the end of the process. The advantage of this method is that after counting the phytoliths calculations can be used to determine the absolute number of each type of phytolith per gram of soil. This allows phytolith types to be compared within a sample much like numbers of different macroscopic remains are compared, but with the advantage of fewer biases due to carbonization. Proportions of different plant parts within a sample could be used to infer a specific crop processing stage.

The development of phytolith identifications is the key to interpreting crop-processing stages but there are two aspects of identification: plant species and plant part. A great deal of research concentrates on the identification of phytoliths on a taxonomic level. Within archaeology, this is focused on agricultural plants and the number of crops that can be identified using phytoliths is continuously growing. Currently, wheat, barley, maize, rice, some millets and legumes can be recognised in archaeological assemblages to different degrees of refinement. Equally important to identifying specific taxa, and more important in the framework of this paper is the recognition of plant parts. Grass culms and leaves can be distinguished by their range of morphotypes from inflorescences (glumes, lemma, paleas). This allows us to address identifying the signatures of straw, as opposed to spikelets and husks. This has the potential to contribute to seasonality studies, given that husks are produced and silicified during the seasonal window tied to plant flowering and fruiting times.

Rice is a good example of a crop plant that can be used in this particular way.

The identification is sufficiently advanced to allow different plant parts to be distinguished, using single-celled and multi-celled panels of phytoliths, to the taxonomic genus *Oryza*, and some scholars even identify to species [16,47,73,77] although reservations are still warranted. Within the present study identification is supported by the presence of carbonized rice grains, the most ubiquitous taxon in flotation samples from the same contexts analyzed for phytoliths. At this stage, identification is a problem for millets. Very little work has been conducted on the phytoliths of millets but they potentially have distinctive husks and bilobes/crosses, which occur in the leaves [36] (Harvey, unpublished MSc dissertation, 2002). Macro-remains from the site studied here include evidence for small millets, especially *Brachiaria ramosa* and *Setaria verticillata*. Phytoliths, however, provide important complementary information through the recognition of rice plant parts other than grains. Floral parts are recognised by double- and single-peaked husk cells and also silica skeletons from husks can be identified. Specifically shaped bulliforms and ‘scooped’ bilobes come from the leaves of rice (see Fig. 1). When analysing archaeological samples these phytolith types can be counted and the abundances compared within each sample and the co-variation of different forms assessed [57]. Below we argue that this can be related to the presence of waste from specific crop processing stages. While the present study benefits from having both phytolith and macro-remains evidence, the patterns demonstrated here indicate the utility of phytolith analysis for crop-processing studies and could thus be extended to sites with less macro-remains evidence or complete lack of them.

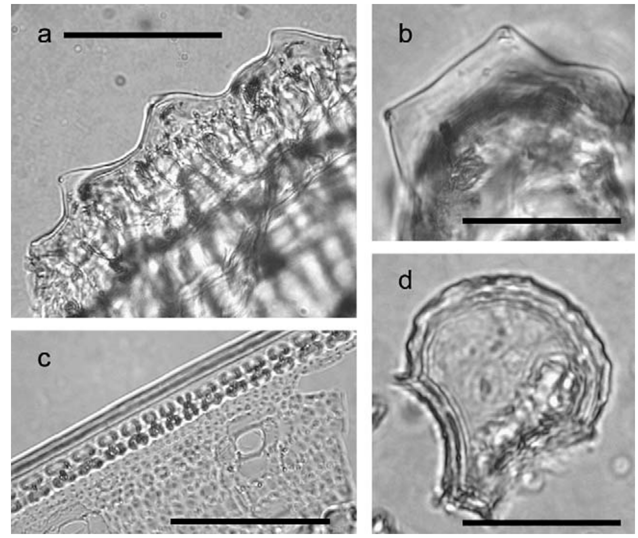

Fig. 1. Photographs of rice phytolith types. (a) Rice husk multi-cell panel; (b) double-peaked husk cell; (c) scooped bilobes from the rice leaf; (d) fan-shaped bulliform from the leaf. Scale bar = 20 μm.

4. Examining crop processing models

In this paper, crop processing models are being examined for rice and millets, which are both important Asian crops. Baseline ethnographic studies of non-mechanized processing were conducted by Thompson [69] in Thailand on rice, and Reddy [53,54] (unpublished PhD dissertation, 1994) on various millets in India. Fundamentally there are similarities, as native Asian millets (in the genera *Brachiaria*, *Digitaria*, *Echinochloa*, *Panicum*, *Paspalum*, *Setaria*) and rice share basic aspects of processing as hulled cereals that require a specific dehusking stage. Other millets, introduced from African origins, such as *Eleusine coracana*, *Pennisetum glaucum*, and *Sorghum bicolor* (some races) are free-threshing. For rice the basic processing pathways and potential choices are outlined in Fig. 2, while Fig. 3 provides a schematic representation of those stages most significant in producing patterning that might enter the archaeological record. Similarly, for small millets, Fig. 4 provides an outline of processing pathways, while Fig. 5 highlights the main stages that pattern product and by-product assemblages.

An important difference of these schemes from the better known sequences for wheat and barley is the absence of important sieving steps. In crop-processing there are two basic methods for separating components after they have been broken by threshing/pounding. One is to use winnowing which separates assemblages based on weight, and the other is to use sieves which separate based on size; sieves play a prominent role in wheat and barley processing [26,27,67] (Jones, unpublished PhD dissertation, 1984). Neither Thompson [69], Reddy [53], nor Lundstrom-Baudais et al. [38] found much use of sieving in rice or millets. Thus in rice and millet processing it is primarily winnowing that separates waste from products on the basis of weight. Raking or broom sweeping is used on the heavy product of winnowing in order to separate incompletely threshed panicles and return them to the threshing floor.

The first stage in crop-processing is harvesting, and here choices in harvesting height have potentially a great

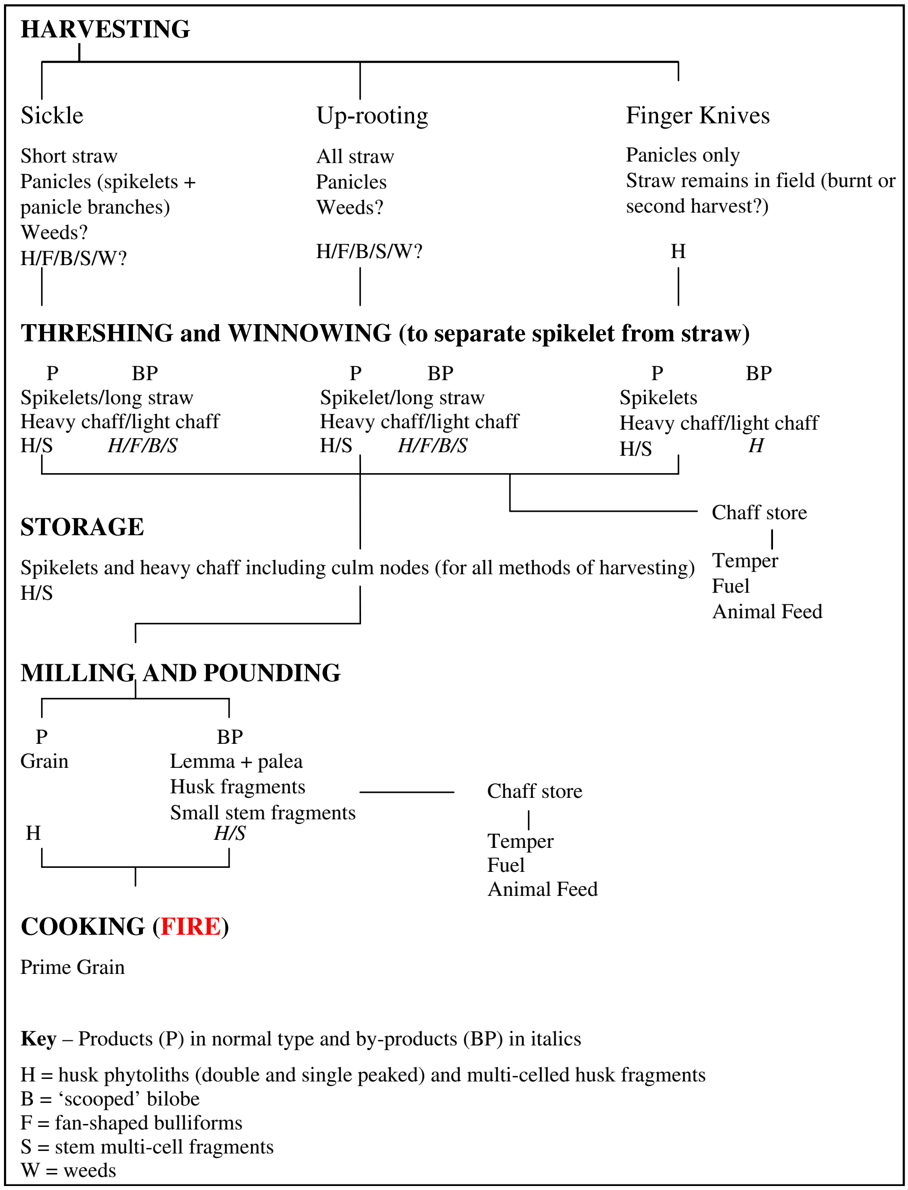

Fig. 2. Simplified outline of rice crop processing (based on Thompson [69]).

impact on plant parts and weeds incorporated with the harvest. For both millets and rice, a range of harvesting options are available, and harvesting of just the panicles will select against the incorporation of many weeds and straw (culms). Reddy (unpublished PhD dissertation, 1994) [53] suggests that large panicle millets, especially introduced sorghums and *Pennisetum* are more likely to be harvested by cutting at the top of the stalk therefore only taking the panicle and not the stalks or any weeds. This is in contrast to the smaller varieties, which are generally harvested by gathering a handful of stalks and cutting at the base. Similarly for rice, harvesting may focus on just the panicles and therefore incorporates few weeds. Thompson [69] has suggested that weeds are not as significant a contaminant in rice crops, as is the case in wheat and barley. Rice in some cases is much less likely to be contaminated with weeds as a result of thorough plot clearance, drowning out weeds in wet rice practices, and reaping by finger knives. Obviously, different methods of cultivation of rice do have greater degrees of weed infestation. In archaeobotanical studies of wheat and barley, weeds play a key role in determining crop processing stages especially harvesting methods [26,30,31]. Consequently, rice and large, naked panicle millets should have fewer weeds incorporated into the crop processing waste. Nevertheless, the presence of wild taxa known to be rice weeds in archaeobotanical samples, such as sedges and certain grasses, suggests that weeds were incorporated into harvests and should be considered as a potential source of archaeobotanical information about processing and arable ecology.

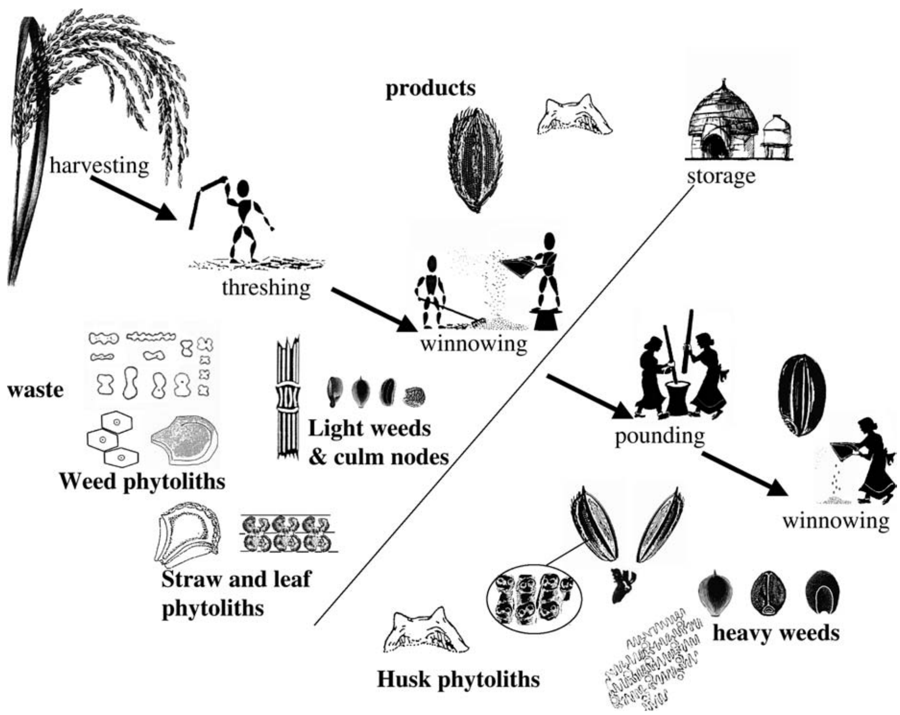

Fig. 3. Schematic representation of the major processing stages for rice showing the products and waste produced by each process. Phytoliths are in white and macro-remains in black. For example, first winnowing produces grains with spikelets and therefore husk phytoliths, and the waste contains rice leaves and stem (fan-shaped bulliforms and scooped rice bilobes) and various weeds associated with rice cultivation such as grasses (bilobes shown, also saddles, long cells), sedges, and phragmites (keystone bulliform). After dehusking the waste of winnowing includes husks as well as large weeds, which also may be removed by hand picking.

After harvest, crops may be stored and exchanged as panicles or sheaths, but ethnographic evidence indicates they are more likely to undergo at least some processing. Threshing and winnowing will separate straw and leaves, as well as light weed seeds. Thus the disposal of this waste on fire should result in charred culm nodes as well as small/light weed seeds. Phytoliths distinctive of stalks and leaves, such as rice bulliforms and scooped bilobes, as well as generic rice culm/leaf long cells should be representative of this early processing waste. Although this is "waste" in relation to the human consumption of the grain, these by-products may have significance as animal fodder, fuel, or may even be used in thatch. At this stage the spikelets, still in their protective husk (lemma and palea) are likely to be stored [53,69]. In order to more fully process these spikelets to clean grain, which is often encountered in modern markets in India or Southeast Asia, a much greater labour investment in terms of people and time is necessary. Given that there is normally a major labour bottleneck during the period of harvest [68], it is unlikely that such processing will be done unless there are very large communal labour pools or centralized demand. These early processing stages are often carried out in fields or threshing floors on the periphery of villages (Reddy, unpublished PhD dissertation, 1994), and thus they are much less likely to come into contact with hearths and on-site fires that lead to preservation as charred organic remains.

After being brought on to the site and stored, crops are likely to be processed in a piecemeal fashion as need arises, and thus on a routine and repetitive basis [48,69:121]. This is likely to be carried out in or around domestic spaces by the women of a household, or through the joining of labour of women from neighbouring houses. Prior to recent mechanisation with the availability of mechanical rice dehusking machines, this was the pattern amongst the Malay of Rembu [48:48]. Use of traditional mortars for dehusking will tend to see some grains/spikelets lost that fall out of the mortar during pounding; if these are not gathered up and returned to the mortar in their entirety they will contribute to the waste product assemblage. After being pounded to break or remove the husks, the mortar contents are winnowed to remove waste that should be dominated by lemmas and paleas, as well as some weed seeds, although some grains, especially those which are abnormally small will be lost. In addition grains that retain their husk will tend to be slightly heavier than dehusked grain and may separate to some degree with winnowing. These may then be returned to the mortar for dehusking but some may also be added to the waste. The final stage involves hand-picking to remove persistent weed seeds and other contaminants that are

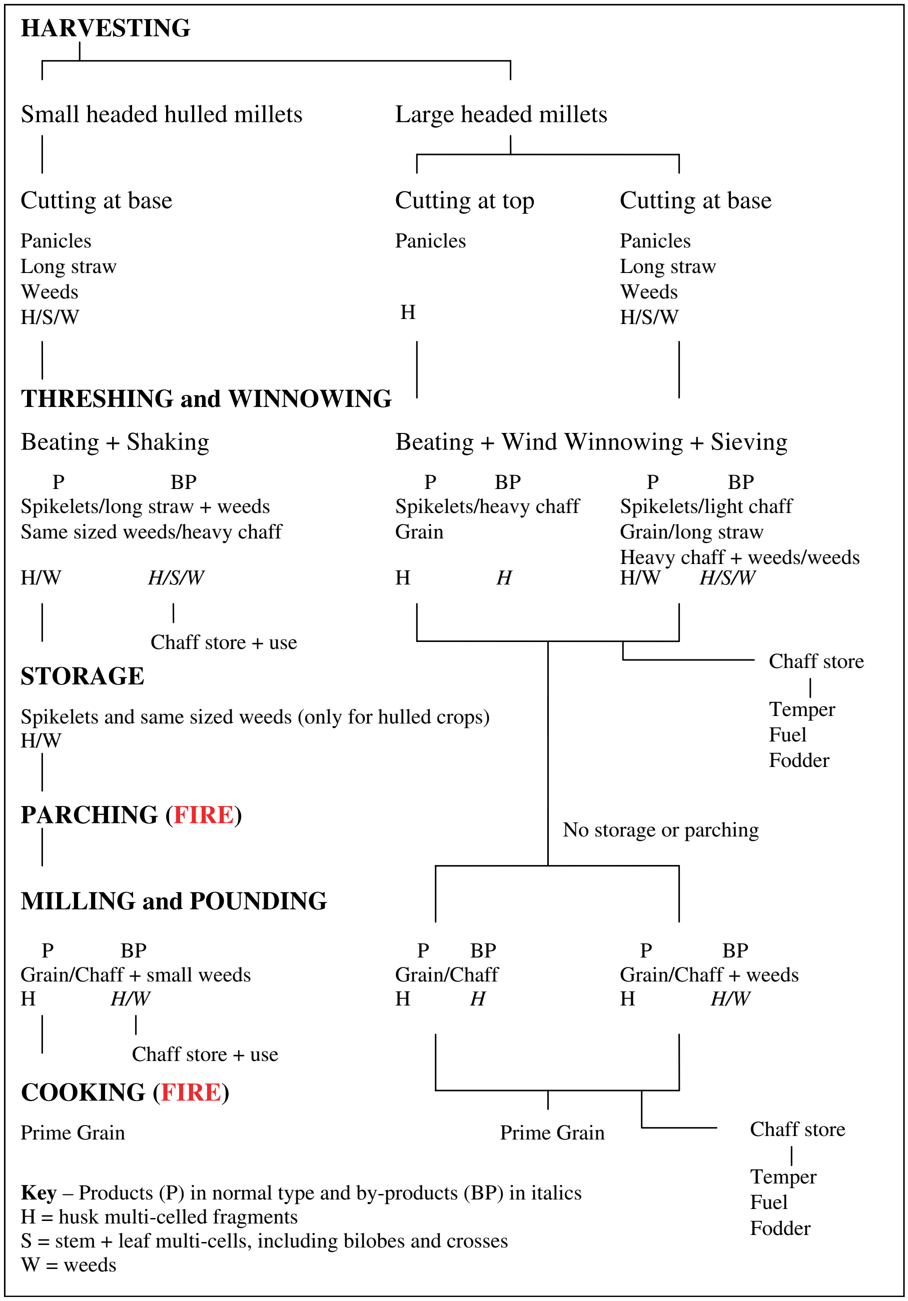

Fig. 4. Simplified outline of millet crop processing (based on Reddy, unpublished PhD dissertation, 1994).

too close in size and weight to the average crop grains. The combined waste from these stages should be dominated by lemma, palea, and weed seeds with some smaller grains, although its detection through macro-remains is complicated by the fact that lemmas and paleas are likely to be destroyed rather than preserved by charring. Thus resulting charred assemblages will be dominated by grains and weed seeds. On this basis charred millet-weed assemblages from Neolithic South India have been interpreted as the waste and loss from dehusking and final cleaning [18:354–356, 19,21].

Small millets are very small in size compared to wheat or barley and therefore their chaff is more delicate. As reported by Boardman and Jones [6] wheat and barley chaff is highly differentially destroyed on contact with fire relative to grains [67,70]. This is likely to be even more exaggerated in the case of millet chaff. Thus if millets come into contact with fire with husks on, they are unlikely to be preserved with husks intact. This seems clear from archaeobotanical assemblages with millets examined by the authors (including those from South India, e.g. [19,21]) as small fragments of lemma and palea adhere to the millet grain in a minority of

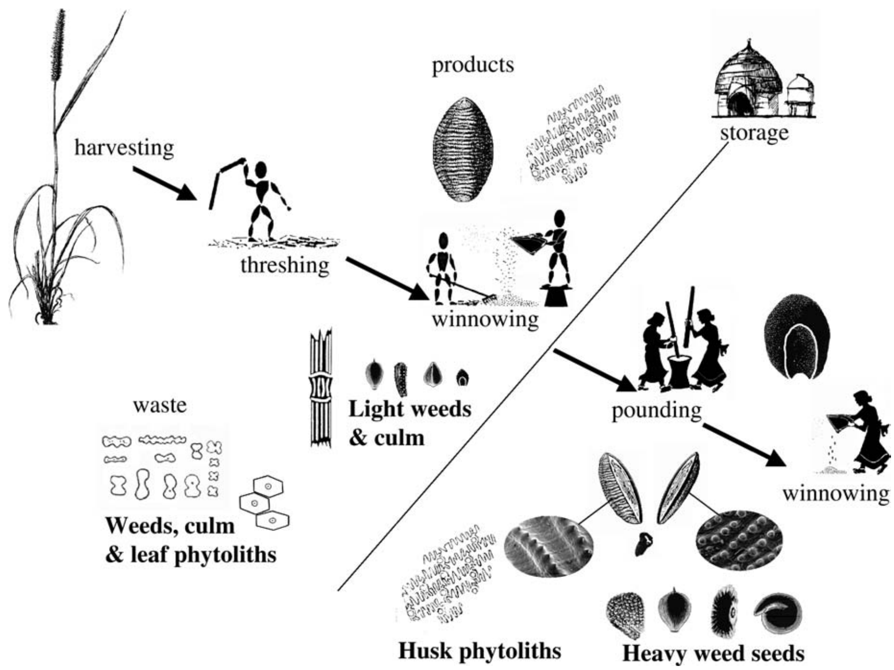

Fig. 5. Schematic representation of the major processing stages for millets showing the products and waste produced by each process. Phytoliths are in white and macro-remains in black.

specimens indicating that these grains must have entered the fire with husks intact. While rice husks are somewhat more robust and are recovered in charred and silicified form in some macro-remains assemblages, these too are likely to be underrepresented due to charring bias. In phytolith form, however, these husks should preserve in the form of distinctive inflorescence morphotypes, such as the double-peaked husk cell of rice (actually from lemma and paleas). Similarly we should expect pappilate cells of millet husks, as well as the highly undulate long-cells characteristic of grass infloresences and often identifiable to genus, or even species, when comparative studies have been made (as is the case with wheat [3,4,55]). These husk phytoliths will be preserved whether they go through the fire and enter ash, or whether they are simply disposed on-site and allowed to decompose. These also might be used as animal feed and therefore incorporated into dung-derived phytolith assemblages.

Dehusking is aided if grains are dry, and this is sometimes affected by exposure to fire (parching). Therefore, one potential pathway to preservation is parching of spikelets to remove the husk. Amongst ethnographic studies of wheat and barley, parching is sometimes used but not necessary [27,49:41]. Similarly parching is not necessarily employed with rice or millets. Thompson [69] suggests rice may be underrepresented in the archaeological record because parching is not required for separating grains from their husks and there are also fewer chances of accidental charring. Preparation of particular dishes, such as Thai *khao mao* (a toasted pounded rice mixed with coconut), require parching. Reddy [54] (unpublished PhD dissertation, 1994) reports parching is used more frequently for processing of hulled millets. The absence of parching, however, does not remove the production of dehusking waste in and around domestic space. As the routinely produced waste product, this may be disposed of in fire regularly or sporadically and through this route to archaeological preservation. Consequently, the absence of parching should not be simplistically equated with the absence of charred macroscopic plant remains. The presence of phytolith evidence for processing waste, however, may be the first step to understanding why certain macro-remains categories are absent or underrepresented, and thus may be crucial to a more complete behavioural interpretation of archaeobotanical assemblages.

Phytolith remains of rice and millet crop processing have potentially more chance of survival in the archaeological record than their equivalent macro-remains. This is due to the vagaries of contact with fire and destruction through charring. This indicates that phytoliths can be used to infer the processing stage and check the deductions based only on macro-remains. This has vast potential also for sites that lack organic plant remains. Furthermore, using phytoliths in conjunction with macroscopic plant remains provides the potential to explore the distribution of crop-processing residues, whether burnt or unburnt, across sites and between sites, and provide a more robust basis for considering the organisation of post-harvest agricultural labour and the utilization of agricultural products and by-products.

Sample number	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Pulses	0	0	0	0	0	0	0	0	0	1	0	0	1	7	2	0
Millets	7	1	1	0	0	0	0	0	1	0	0	0	0	1	0	3
Barley	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Wheat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rice	0	0	0	0	0	0	0	0	1	1	0	3	0	0	4	1
Total seeds	9	4	1	0	0	5	0	0	4	10	2	3	2	11	10	4

Sample number	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Pulses	2	1	8	0	5	5	2	11	4	4	0	0	2	10	0	0
Millets	3	3	1	5	1	2	0	0	0	0	0	2	1	5	0	0
Barley	0	0	1	4	0	0	0	0	1	0	1	0	1	2	0	0
Wheat	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Rice	2	2	10	8	0	1	4	8	1	3	1	0	1	0	0	1
Total seeds	7	6	43	17	6	11	20	27	8	7	2	2	7	26	0	1

Fig. 6. Summarized results for macro-botanical remains of the main seed crops at Mahagara.

5. The application of the rice ethnographic model to a phytolith study of a North Indian Neolithic site

A clear example of how phytoliths can be used to assist in the interpretation of agricultural practices can be demonstrated at Mahagara, a Neolithic site in North Central India, which may be an early centre for the cultivation of domesticated rice in India [17:299–300,63]. The macroscopic remains from the original excavations are relatively poor but have produced a number of rice grains, which are thought to be of domestic type [63]. Rice was also used as a temper for pottery at Mahagara and this included rice husks in particular and some grains but there is no mention of other processing waste such as stem fragments or leaves. This suggests the use of mortar waste from dehusking for ceramic temper. The site produced evidence of small huts focused around a central cattle pen, and thus we might expect dung-derived material to be incorporated into site deposits even if it was not burned. Due to the limited number of grains and lack of other macro-remains, we are left with little possibility of inferring how rice processing and agriculture was organized, whether rice was just part of a broader agricultural strategy, or even consumed by a predominantly forager group, perhaps obtained by trade from elsewhere. The role of rice by-products in the overall economic strategy of the site, e.g. as fuel or cattle fodder, is also unknown.

In order to address these issues, phytolith samples and flotation samples for macro-remains were taken at Mahagara by Dr Fuller in 2001 from a section through occupation deposits of predominantly midden material, as well as the nearby site of Koldihwa [23]. Analysis of the macroscopic plant remains has revealed rice grains as found in previous excavations but this was not the only crop plant present (Fig. 6). Initially, small millet grains are also present and then later some pulses (*Vigna* cf. *radiata*, *Vigna* cf. *mungo*, *Lens culinaris*, *Cajanus cajan* and *Lathyrus sativus*), wheat, and barley are added to the crop repertoire. However, all these crops are only present in the form of grains. Does this mean that there is no cultivation happening at Mahagara? Are all these crops imported? If we just had the analysis from macro-remains, and if we applied conventional archaeobotanical producer-consumer models (as followed by Reddy [53,54:133] and Thompson [69:141–142]), this would be the suggested interpretation.

However, phytolith analysis offers a different view of the economic system at Mahagara. Results for rice phytoliths can be seen in Fig. 7 (MGR-02-1 is the earliest deposit), while the representation of rice in

Rice phytolith type	MGR -02-1	MGR -02-2	MGR -02-3	MGR -02-4	MGR -02-5	MGR -02-6	MGR -02-7	MGR -02-8	MGR -02-9	MGR -02-10
Double-peaked husk cell	17	0	33	65	40	153	68	0	0	0
Multi-cell husk	2	27	283	111	40	102	99	0	0	0
'Scooped' bilobe	13	0	66	108	40	77	136	0	0	0
Fan shaped bulliform	10	0	66	86	40	77	113	0	0	0
Total phytoliths	1141	5524	12700	9395	17427	14082	9764	2165	1935	1566

Fig. 7. Rice phytoliths from Mahagara in number of phytoliths per gram of sediment.

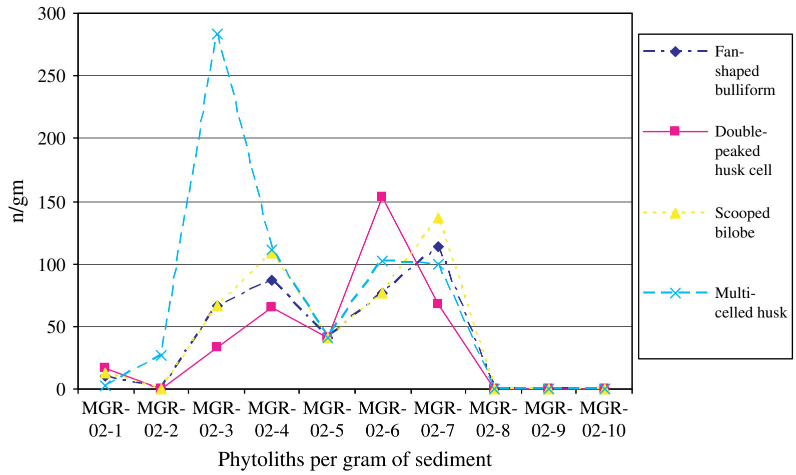

Fig. 8. Graph showing number of different rice phytolith types per gram of sediment.

macro-remains is summarized in Fig. 6. In the majority of samples, all the identifiable rice phytoliths are represented in fairly equal quantities (see Figs. 8 and 9). This demonstrates that there are roughly equal amounts of each plant part of rice in each sample. The presence of leaf phytoliths indicates the early stages of crop processing. Two samples (MGR-02-2 and -3) do not follow this trend and both have higher numbers of multi-celled husks than other phytolith types. These samples indicate greater input of by-products of the later stages of crop processing because little or no stem or leaf phytoliths are present.

Millet phytoliths are also present but particular identifications can not be made (see Fig. 10). They are all present in very small numbers and probably represent weeds of the rice crop but some may have also been consumed. There are a substantial amount of wild grass husk phytoliths, which probably include small millets that cannot be identified at present. There seems to be little correlation between the rice phytoliths and the millets. This may suggest that some of the millets come from a different source to the rice crop and are likely to be the waste from dehusking of the millet crop but some

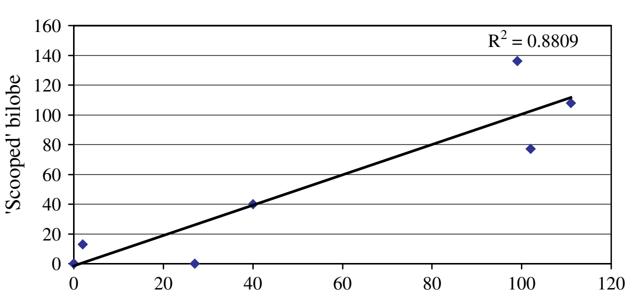

Fig. 9. Graph comparing "scooped" bilobes and multi-celled husks from rice.

of the lack of correlation may be more a result of the lack of identification criteria presently available. The wild grass husks, however, have a strong correlation with rice husks and therefore indicate that they are the likely weeds of the rice crop.

Wheat and barley phytoliths are not present in the assemblage but there are a few grains. This evidence strongly suggests that these are minor components of subsistence. While it may be that these were grown locally, the evidence for their crop-processing residues is absent implying that they were not processed on a routine basis, and their by-products did not play an important role as fuel or animal feed. This may be because they were special crops, rather than staples, or it could be that they were received in trade from some other region. In this respect it is intriguing to note that during the late third millennium BC a parallel trend is seen in South India where wheat and barley appear in small quantities in some sites. This coincides with other indications of ceramic change from pottery and it has been argued that this was a period of use of these species as a socially valued element in cuisine (or beverages) [18]. However, wheat and barley have become important crops of the Ganges valley and have high ubiquities across sites by the second millennium BC [17,60]. It may be that their original adoption in the late Neolithic period was on a small scale for reasons that were not specifically subsistence.

The application of crop processing models to the phytolith assemblage at Mahagara has revealed a different picture of the economy. Phytolith analysis has determined that this site was a producer site for rice and probably small millet crops during the Neolithic. The later introduction of winter crops on to the site brought either a new agricultural system, which did not have routine on-site processing or these crops were procured through trade. This is a very different conclusion to the one that would have been drawn from the analysis of the

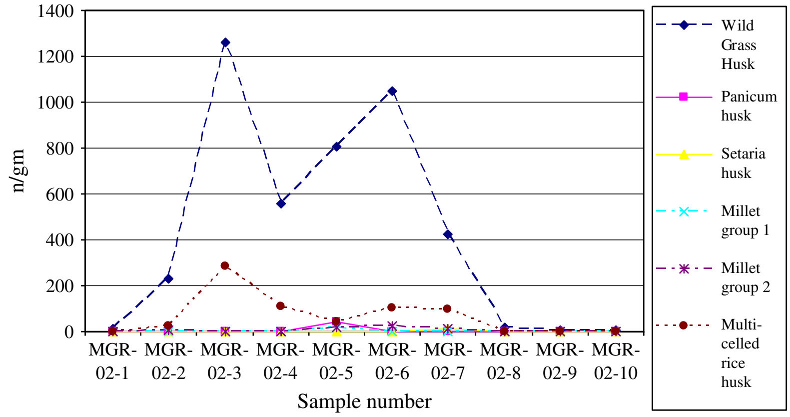

Fig. 10. Graph showing number of different possible crop phytoliths and wild grass husk phytoliths.

macro-remains solely and demonstrates the need for phytolith analysis to complement other forms of archaeobotanical investigations.

6. Conclusions

Traditional crop processing models used with macroscopic remains provide good interpretations of past agricultural schemes when there is sufficient material available. This examination of rice and millet crop processing methods has highlighted the problem that macro-remains representing important stages may be lacking due to the vagaries of preservation. By contrast, phytolith assemblages are sensitive to the original vegetal input without being reliant on charring for preservation. In addition, phytoliths may be available when carbonized remains are not present.

At present, applying phytolith analysis to such studies is limited by the level of species identification. For most crops, identification is not at the stage for this type of application. However, as is demonstrated here, the identification of rice is sufficiently advanced to attempt the recognition of crop processing stages and should also be applicable to wheat and barley. Nevertheless in conjunction with macro-remains, providing evidence for the presence of a particular cereal crops, phytolith suites may be used to infer concentrations of plant parts corresponding to straw, husks, and other key components of crop-processing by-products. Another aspect that limits phytolith studies is sampling procedures. Phytoliths need to be sampled in a similar manner to macroscopic remains so that they can be used to this end. Sampling a number of different features and replicate sampling needs to be carried out to gain an adequate number of samples for detailed data analysis but at present this is not normally conducted. Phytolith analysis should be a routine part of any archaeobotanical study especially in regions where organic preservation is poor.

Although the example from Mahagara had a limited number of samples, hopefully it has demonstrated that the application of phytolith analysis to the question of determining crop processing stages is an exciting prospect. This technique could potentially have a startling effect on the interpretations of sites, such as those in South Asia, that have poor charred assemblages and also add to existing knowledge of crop husbandry practices where only macro-remains have been used previously. The combination of phytoliths and macrobotanical analysis offers the surest way of interpreting crop processing stages allowing preservational biases and behavioural patterns to be fully understood.

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