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Towards improved detection and identification of crop by-products: Morphometric analysis of bilobate leaf phytoliths of *Pennisetum glaucum* and *Sorghum bicolor*

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ABSTRACT

Better detection and taxonomic identification of cereal leaves is expected to result in a better understanding of the presence and function of crop products at archaeological sites. Therefore, this paper focuses on bilobate phytoliths from leaves of *Pennisetum glaucum* (L.) R. Br and *Sorghum bicolor* ssp. *bicolor* (L.) Moench, which are two important crop plants that regularly co-occur at archaeological sites in Africa and the Indian subcontinent. These two taxa are further compared with *Panicum miliaceum* L. and *Setaria italica* (L.) P. Beauvois, which is of relevance for agricultural sites in prehistoric South Asia, Eastern Asia, Africa, and part of Eurasia where the four crops certainly or presumably co-occur.

Leaves of *Pennisetum glaucum* and *Sorghum bicolor* were systematically sampled to explore the variation of short cells and to collect 27 morphometric variables of 3100 bilobate phytoliths with newly developed open-source software. This study provides new information on the occurrence of cross-like and notched (nodular) bilobate short cells in leaves of pearl millet and trilobates in sorghum, which is of relevance for taxonomic distinction. The morphometric variables of the bilobates phytoliths do not allow for taxonomic classification between *P. glaucum* and *S. bicolor*. Possibilities for taxonomic distinction between the leaves of these taxa should thus be searched in other directions than bilobate phytolith morphometry. The obtained morphometric data are nevertheless important since they allow for future comparison with other taxa. Indeed, morphometric analysis allows for distinction between *Pennisetum glaucum*/*Sorghum bicolor*, *Panicum miliaceum* and *Setaria italica*.

Furthermore, one *P. glaucum* population that was grown in a rather different climate than the others also shows different bilobate morphometry results. This difference between *P. glaucum* populations points to phytolith morphometry possibly being influenced by environmental settings. Moreover, it has implications for sampling strategies of similar research and the validity of morphometric identification criteria based on data from few reference populations or reference populations from a single region.

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1. Introduction

1.1. *The need for the development of identification criteria for plants based on phytoliths*

Archaeobotany applied to agricultural societies mostly focuses on understanding crop domestication and cultivation practices, *i.e.* on food production. However, many cultivated crops and especially cereals can supply not only food but also secondary products such as straw, hay and chaff, derived from culms, leaves and inflorescences. Ethnographical studies demonstrate that these non-dietary, secondary products are of fundamental importance in the economy of traditional societies (*e.g.* Hillman, 1984; Jones, 1984; Grubben and Partohardjono, 1996; D'Andrea et al., 1999; Peña-Chocarro et al., 2009), and imply that this was also the case in prehistoric societies. Indeed, some archaeological studies of sites with exceptional good preservation conditions have demonstrated that secondary products always played a fundamental role, supplying fuel, animal fodder and components for construction

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material (Cappers, 2006; Ryan, 2011; Van Doosselaere et al., 2014). Generally speaking, however, archaeobotanical studies tend to overlook secondary crop products.

Non-dietary, secondary crop products are created during harvest and crop processing (Hillman, 1984; Jones, 1984). Crop processing concerns the separation of edible grains from non-edible secondary products and arable weeds. It generally consists of an initial stage of processing nearby the arable field, the storage of the semi-cleaned crop products (possibly after trade and/or transport), and the final processing on a day-to-day basis at consumer sites. The technical, organizational, temporal and spatial details of these processes depend partly on the anatomy of plants, and partly on socio-economic aspects of the relevant communities and societies (Van der Veen and Jones, 2006; Fuller et al., 2014a). The study of secondary crop products in archaeological sites will thus not only provide a more thorough understanding of both dietary and non-dietary functions of crop plants, but will also lead to better knowledge of prehistoric crop processing and reveal the underlying socio-economical aspects of past societies.

The overlooking of secondary crop products in the archaeological record can be related to a bias in the current research approach (Young and Thompson, 1999; Harvey and Fuller, 2005). Effectively, the study of archaeobotanical assemblages is routinely based on plant macroremains (primarily seeds and fruits). These remains are less suited to study plant parts that do not relate to inflorescences. Also, organic plant material, once deposited, generally decays when in contact with oxygen, while material that is most commonly preserved is carbonised material. Fire, however, is not regularly involved in the processing of crops. Furthermore, fire tends to destroy all but the most resilient parts of the crop plant (seeds and some chaff). Finally, in the rare event that the fragile plant organs (culms, leaves and fragile chaff) carbonise, they are extremely sensitive to mechanical destruction after burial. As a result, secondary crop products are underrepresented in the archaeobotanical record and are only incidentally recovered and/or recognised. From these problems concerning the survival and post-depositional history of plant parts other than seeds, the necessity arises to develop a distinct approach to study the full spectrum of archaeobotanical evidence of crop plants and crop plant utilization.

Phytoliths, microscopic bodies that consist of opal silica and that are formed in living plants, offer an excellent alternative research approach to solve some of the problems on the preservation of secondary crop products. They can be retrieved from a wide range of archaeological sites and contexts because their preservation is independent of fire (until 950°Celsius), they do not require specific settings to be incorporated in the sediment and they survive over a relatively long time in most sedimentary environments. Moreover, they allow for the identification of plant parts since they have the anatomical characteristics of the original plant cells and tissues. The grass family, which includes all cereal crops, is particularly suitable for phytolith analysis because grasses produce abundant phytoliths in different anatomical locations. Furthermore, phytoliths from inflorescences and leaves of grasses are often diagnostic at genus/species level (Piperno, 2006).

Notwithstanding phytoliths being the subject of continuing research developments in the field and becoming an increasingly important part of the retrieved archaeological record, their potential for investigating non-dietary crop products has rarely been taken into consideration (Piperno, 2006, 78). Phytolith analysis has been very useful to identify early domestication of maize and rice (Piperno and Pearsall, 1993; Pearsall et al., 1995, 2003; Gu et al., 2013), the fruits of plants that rarely leave behind carbonised parts such as squashes, gourds and banana (Bozart, 1987; Mbida et al., 2000; Ball et al., 2006; Chandler-Ezell et al., 2006; Piperno, 2009), and major economic crops like oat, wheat, barley, common millet and foxtail millet (Rosen, 1992; Portillo et al., 2006; Ball et al., 2009; Lu et al., 2009; Madella et al., 2014a). However, the majority of these taxonomic studies mostly focus on the inflorescences/fruits because these plant parts are primarily expected to end up in archaeological sites and have a specific archaeological interest, and because their phytoliths, such as the ones from grass inflorescences, are considered to be highly diagnostic. The potential of phytoliths for the investigation of secondary products has been highlighted (Harvey and Fuller, 2005) and there indeed are some published examples demonstrating the effectiveness of this method (*e.g.* Madella, 2001, 2007; Bates, 2011; Ryan 2011; Di Lernia et al., 2012; Lancelotti and Madella, 2012). For cereals, there are some (preliminary) studies on einkorn and rice (Ball et al., 1993; Gu et al., 2013).

In order to fill this gap, the main aim of this study is to investigate phytoliths from leaves of two species of big millets: sorghum – *Sorghum bicolor* ssp. *bicolor* (L.) Moench – and pearl millet – *Pennisetum glaucum* (L.) R. Br. They both belong to the subfamily Panicoideae of the Poaceae, though representing different tribes (Andropogoneae and Paniceae respectively). These taxa were selected because they are major crops co-occurring in Africa and South-East Asia since prehistory (e.g. Fuller and Madella, 2002; Fahmy, 2008; Crowther et al., 2014; Pokharia et al., 2014). The details of the domestication history of these crops are still to be discovered (De Wet et al., 1976; Tostain and Marchais, 1989; De Alencar Figueiredo et al., 2008; Oumar et al., 2008; Fuller et al., 2014b). Domesticated pearl millet is present in West-Africa from c. 2500 BC (Manning et al., 2011; Clotault et al., 2012; Ozainne et al., 2014) and became widespread in Africa from the first half of the second millennium BC, as indicated by finds in India from c. 2000 BC onwards. Sorghum was presumably domesticated in Africa before the second millennium BC (Fuller, in press; Zohary et al., 2012), but details are unknown. Interestingly, ethnography shows that apart from the parts of interest for human consumption also the non-edible plant parts have multiple economic functions, such as use of stalks for thatching, building, fencing, brooms, fuel, temper, and the use of the leaves as cattle, sheep and goat fodder (Grubben and Partohardjono, 1996; National Research Council, 1996; Reddy, 1998; Dahlberg et al., 2011). This makes the development of identification criteria highly relevant.

An additional aim of this paper is to compare the results of phytoliths of pearl millet and sorghum leaves with similar phytoliths of common millet, *P. miliaceum* L., and foxtail millet, *S. italica* (L.) P. Beauvois, both members of the Poaceae, subfamily Panicoideae, tribe Paniceae. These two crops were also of high economic importance in prehistory and occasionally co-occur with sorghum at archaeological sites in South Asia, Eastern Asia and Africa (Bale, 2001; Fuller and Madella, 2002; Fuller, 2003, 2004; Fuller and Boivin, 2009; see further Discussion 4.5). Morphometric data of the bilobates of these species' leaves (N = 2000 + 2000) have been collected according to the same protocol as for pearl millet and sorghum. Comparison of common and foxtail millet phytoliths by means of a discriminant function results in 88% correct identification, thus showing that taxonomic distinction is possible (Out and Madella, 2015).

1.2. Taxonomic identification of pearl millet and sorghum by phytolith analysis

While various studies discussing silicification and phytolith production in pearl millet and sorghum (and closely related taxa) are available (Ponnaiya, 1951; Metcalfe, 1960; Lanning and Garabedian, 1963; Parry and Kelso, 1975; Sangster and Parry, 1976a,b,c; Renvoize, 1982; Lanning and Eleuterius, 1992; Hodson and Sangster, 1993; Sangster and Hodson, 1997; Lux et al., 2002;

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