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Micro Plant Remains Reveal the Function of Grooved Pottery Vessels From the Late Neolithic Meishan Site in Central China

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From 6,000 calendar years before the present (cal BP) onward, grooved pottery vessels occurred in the lower and middle reaches of the Yangtze River in succession. After a thousand years, it was introduced into central China and became popularized there around 4,000 years ago. It has been proposed that the function of the grooved vessels was to process plant foods, replacing the previously used stone slabs and rollers in terms of ethnographic investigation, but there is a lack of solid and direct evidence although little evidence of starches has been provided. Here we report our study on the sherds of grooved vessels from the Meishan site in central China (late Longshan and Erlitou period). The combined starch and phytolith analyses were first used together to examine the residues on the sherds. Starches from geophytes, millets (*Setaria italica* and *Panicum miliaceum*), wheat (*Triticum aestivum*), and phytoliths from the glumes and leaves of these crops plus rice (*Oryza sativa*), seem to suggest that the grooved pottery vessels were likely to be used to grind geophytes and dehusk grain seeds. But, incorporating the extremely low proportion of grooved vessels to entire pottery tools at the site, we hypothesize that the invention of grooved vessels may have been related to the success of rice domestication and may have been used as tools to pound by-products of crops, leaves, and husks somehow.

Keywords: starch grain analysis, phytolith analysis, food processing, agricultural society establishment, Yangtze river

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INTRODUCTION

During the transition from the Paleolithic Age to the Neolithic Age, stone slabs and rollers were widely used in the world. By means of starch grain analysis, it has been demonstrated that these tools were used to process cereal grains and other edible plant foods (Liu et al., 2010a, 2010b, 2018; Piperno et al., 2004; Yang et al., 2009, 2012a). From the Neolithic Age onward, as staple crops were gradually domesticated and agricultural communities came to be established during the period of 6,000–5,000 cal BP (Zhao, 2019), the number of stone slabs and rollers decreased notably in China, and then almost disappeared by the stage of the Longshan culture around 4,000 years ago (Ding, 2007; Song, 1997; Zeng and Zhu, 2012).

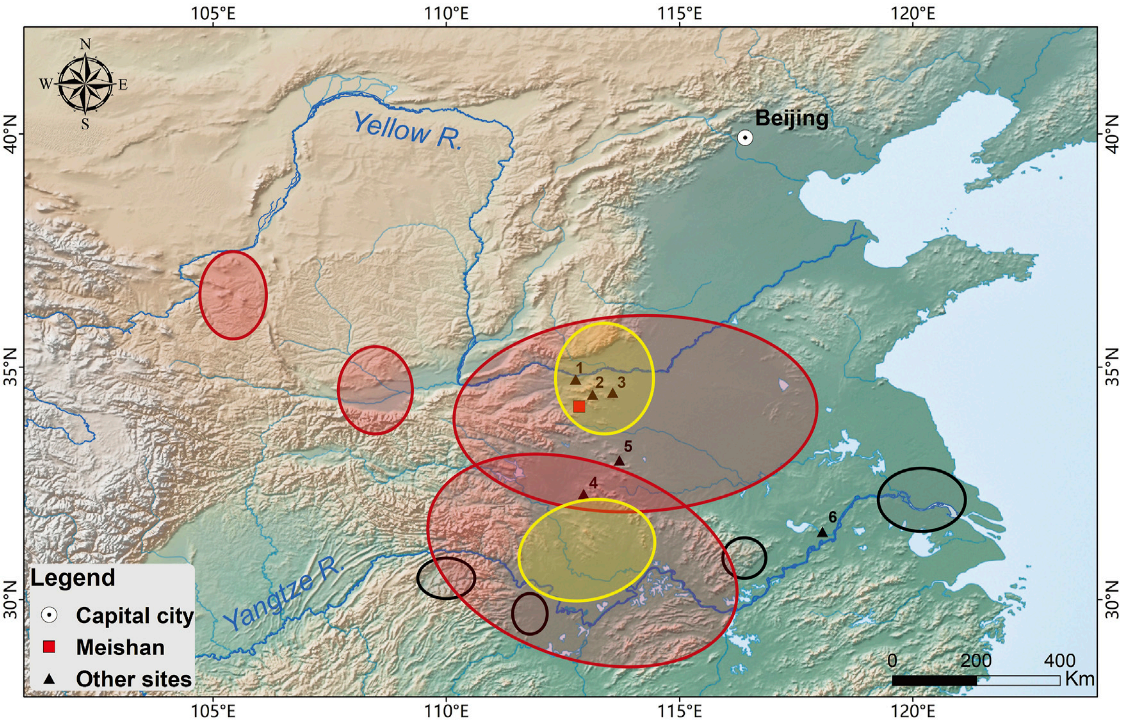

FIGURE 1 | Spatiotemporal distribution of grooved pottery vessels and location of the Meishan site and other archaeological sites mentioned in the text. Shadows with black circles indicate the initial area where the grooved pottery vessels appeared during the early phase of the Songze culture, shadows with yellow circles indicate the scenario during the mid-Songze culture, and shadows with red circles indicate the scenario at around 4,000 years ago. 1, Yanshi Shangcheng; 2, Wangchenggang; 3, Xinzhai; 4, Diaolongbei; 5, Yangzhuang; 6, Lingjiatan. The base map was obtained from the Natural Earth public domain map dataset (https://www.naturalearthdata.com/downloads/10m-raster-data/).

Since 6,000 cal BP, a type of pottery began to appear in the lower reaches of the Yangtze River, then immediately occurred in the middle Yangtze River regions and the middle reaches of the Yellow River, and was eventually popularized during the Erlitou culture (3,800–3,500 cal BP) (**Figure 1**) (Wang, 2019). After that, it showed signs of abating, although it still existed (An, 1986; Ding, 2007). This particular pottery is generally named *kecaopen* (刻槽盆in Chinese character), meaning grooved vessels. The features of this kind of ceramic are mostly like the pot from the same period but decorated with crisscross or radial grooves on the inner wall of the pots (**Figure 2**). Since the grooved vessels happened to occur as agricultural societies were established and as the number of the stone slabs and rollers decreased (Jin, 2013; Zhao, 2019), the hypothesis is that the function of grooved vessels was to replace stone slabs and rollers to grind or filter plant foods, in terms of ethnographic observation (An, 1986; Chen, 2005; Ding, 2007; Liu, 1991; Ye, 1989; Ye and Li, 1996; Zhang, 2017). Therefore, direct evidence is needed to verify this hypothesis.

As the studies on the function of stone slabs and rollers which were once suggested to be processing acorns, mineral pigments, animal skins, and so on (Xie et al., 1989; Zhao, 2005; Liu et al., 2010a), directly evidenced by the means of starch grain analysis to process cereal grains and other edible plants at least (Liu et al., 2010a, 2010b, 2018; Piperno et al., 2004; Yang et al., 2009, 2012a), starch recovered from the residues on the interior face of the grooved vessels can be tested for the aforementioned hypothesis. Previous studies on grooved vessel sherds from the Diaolongbei site and the Lingjiatan site in the middle and lower Yangtze River regions, respectively, were reported (Tao et al., 2009; Sun et al., 2019). Some unidentifiable starch grains were recovered from the residues on three 5000-year-old potsherds from the Diaolongbei site, and incorporating the evidence of the bright red color of stained starches with Congo red, it is deduced that grooved vessels at the Diaolongbei site were used for steaming or boiling some starchy foods, but the specific sources of the starches are not clear (Tao et al., 2009). Starches from the Lingjiatan site further revealed that wild resources, such as acorns and geophytes, were processed by using grooved vessels at 5,000 cal BP or so (Sun et al., 2019). A recent publication reported a similar study on 17 potsherds of grooved vessels from an early Bronze Age site, Yanshi Shangcheng, in central China, and raised a hypothesis that grooved vessels were perhaps used to dehusk seeds and make flour from dried roots and acorns, based on the morphological features of ancient starch grains from the residues on these potsherds (Reinhart, 2020).

Starches are usually contained in caryopses, geophytes, and palm piths, while phytoliths are usually produced in leaves and glumes. In fact, all human behaviors of dehusking, grinding, or cooking could cause starch residues to stick to the surface of the ware. Although the survival chances of phytoliths are much less

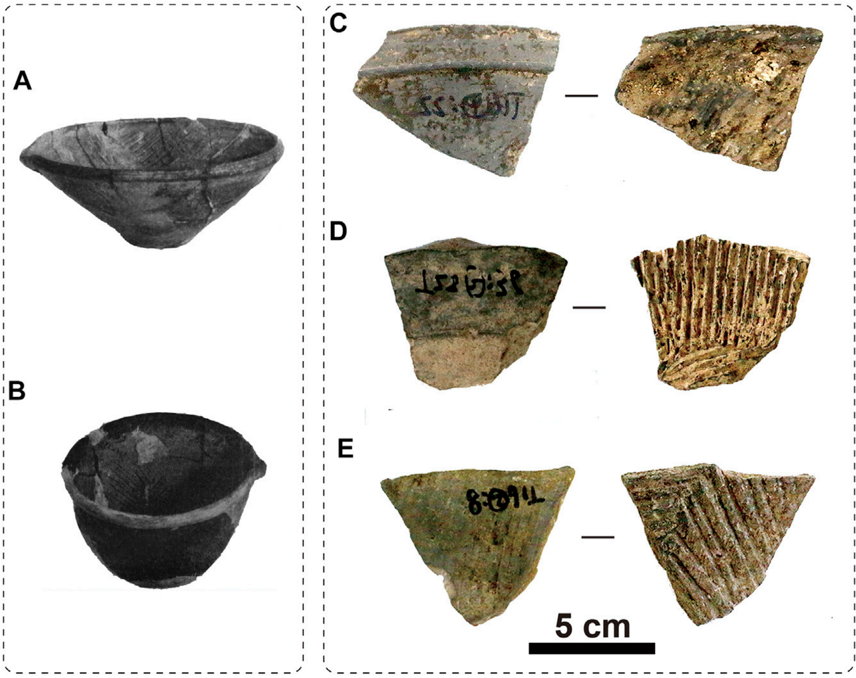

FIGURE 2 | Typical grooved pottery vessels and potsherds from the Meishan site. **(A,B)** Two types of the grooved vessels at the Meishan site, taken in the 1970s, without a scale bar (Fang, 1975). **(C,D)** Images for exterior (left) and interior (right) faces of three sampled potsherds in this study. **(C)** Potsherd with very shallow grooves. **(D)** Potsherd with deep grooves, ~0.2 cm in depth. **(E)** Potsherd bearing cross grooves, ~0.1 cm in depth.

than those of starches on the surface of the wares because of their non-sticky property, phytoliths from the glumes fortunately recovered from the residues would be a definite indicator for dehusking seeds.

Here we report our study on the residues adhering to the interior faces of grooved pottery vessels excavated from the Neolithic-Bronze Meishan site in central China using the analyses of both starch and phytoliths, to provide direct evidence for the function of this type of vessels.

MATERIALS AND METHODS

Meishan

The Meishan site (112.85°E, 34.15°N) is located in Ruzhou City of Henan Province in central China (**Figure 1**). It was found in 1958 and excavated during several seasons in 1970, 1975, 1987–1988, 1995, and 1997. Dwells, buries, pottery kilns, wells, pits, and other ruins were revealed, and stone tools of an axe, sickle, chisel, and knife, bone tools of arrowhead, awl, and hairpin, and pottery vessels of pots, steamer, plate, spinning wheels etc., were discovered, recording the evolution track of societies from the Longshan culture to the Erlitou culture in central China (Henan No. 2 team, Institute of Archaeology, Academy of Social Sciences, 1982; Yuan, 1991). Four AMS ^{14}C dating data obtained from bones put the occupation during the period of 4,000–3,500 cal BP (You et al., 2017).

Pottery Sherds of Grooved Vessels for Study

There are two types of grooved vessels excavated from the Meishan site. One is gray sand-tempered pottery with an inverted rim, whose upper part is trumpet-shaped and the lower part is cylindrical-shaped, with radiating grooves on the interior face (**Figure 2A**). The other type is gray clay pottery in the shape of a basin with an inverted rim and arc wall, of which the interior face is incised with oblique grooves and the exterior face is decorated with chopped basket patterns (**Figure 2B**). The sherds from the grooved vessels take up 3.3% of excavated potsherd assemblage at the Meishan site.

A total of 20 sherds of grooved potteries from the Meishan site are selected for this study (**Figures 2C–E**), that is, 14 sherds from the late Longshan period (~4,000 cal BP) and six from the early Erlitou period (~3,800 cal BP), which were excavated during the excavation seasons of 1995 and 1997 conducted by the Henan Provincial Institute of Archaeology. Half of the sherds are from gray sandy pottery, and the other half are from gray clay pottery. Of them, only one sherd, No. T19②b: 17, of the early Erlitou period, can be discerned from a vessel with a spout. Ancient starches from residues on both interior and exterior faces of the sherds were recovered, and then ancient phytoliths were recovered after starch extraction from six residue samples of the late Longshan and two residue samples from the early Erlitou (**Supplementary Tables S1, S2**).

Analyses of Starch and Phytolith

When we discuss the functions of a specific type of artifact, sources of residues on the surfaces are crucial. Usually, phytoliths and starches recovered from the residues on artifacts will be compared with those from sediments to confirm whether the artifacts were the primary source of these micro plant remains or not (Hart, 2011). However, the potsherds in our study were excavated more than 20 years ago, and contemporaneous sediments which are often used as contamination control samples are not available. Therefore, residues from the interior face can be compared with those from the exterior face of each potsherd based on an assumption that in the same taphonomic conditions, the contamination chances of both faces of the sherds are equal (Barton et al., 1998). If the quantity of micro plant remains on the exterior face of a sherd is more than or equal to that on the interior face, we think the recovered plant remains are sourced from the secondary deposition from the site's sediments after the tools were discarded, although we cannot rule out the possibility that plant residues on the exterior face are derived from the same plant-processing activity as the manipulator's hands touched both the foods and vessels at the same time, and the vessels must have been surrounded by the foods as they were processed. As a matter of fact, previous studies have demonstrated that few starches could be retrieved from sediment and soil (Li et al., 2010; Yang et al., 2012a; Ma et al., 2017).

To dislodge adhering residues, the interior face of the potsherds was submerged in ultrapure water and shaken in an ultrasonic water bath for 5–10 min, then the starches were isolated with heavy liquid flotation using a solution of CsCl at a density of 1.8 g/cm^3. The recovered residues were mounted in 10% glycerine and 90% water on a slide and examined with both white and cross-polarized light at a magnification of × 400. Starch grains were counted, analyzed for morphological features, and then recorded and compared with those from the modern reference collection. For a detailed protocol, refer to previous publications (Yang et al., 2009; 2012a, 2015). To identify the recovered starches, we compiled a modern reference collection of more than 260 species from 20 families of plants that are common in China, including crops and their wild related species, roots and tubers, tree seeds, and peas and beans (**Supplementary Figure S1**) (Wang et al., 2013; Wang et al., 2018; Yang and Perry, 2013; Yang et al., 2012b, 2013). Other published collections are consulted as well (Reichert, 1913; Piperno et al., 2000, 2004; Liu et al., 2010a, 2013, 2014).

Recovery of residues for the phytolith analysis followed that of sampling for starches. A heavy liquid of zinc bromide ($ZnBr_2$) at a density of 2.35 g/cm^3 was used to isolate phytoliths which were then mounted on a slide with Canada Balsam. Phytolith identification and counting were performed at × 400 magnification. Descriptions and nomenclature of the phytoliths followed the International Code for Phytolith Nomenclature (ICPN) 2.0 (Neumann et al., 2019). To identify phytoliths in the archaeological samples, published modern reference collections were consulted (Rosen, 1992; Wang and Lu, 1993; Piperno, 2006; Lu et al., 2009; Zhang et al., 2011; Gu et al., 2013; Ball et al., 2016; Ge et al., 2018).

RESULTS

Ancient Starches Recovered From the Residues

In total, 380 starch grains were recovered from all samples that can be classified into four groups (**Figures 3**, **4** and **Supplementary Table S1**).

Group A includes 238 starch grains in total, dominating the recovered starch assemblage. The grains are characterized by a polyhedral shape with central and open hila, and by Y-shaped or stellated fissures on occasion (**Figures 3A,B**). Sometimes, short lines radiating from the center to the edges on the surfaces of grains can be observed. The size of starch grains ranges from 7.2– 26.0 μm. Both the sizes and the morphological features of this group of starches are consistent with those of foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*) (**Supplementary Figures 1A,B**) (Ge et al., 2010; Yang et al., 2012b). Some granules larger than those from modern reference collections might be the result of grinding (Ma et al., 2019).

Group B includes 24 starch grains that are characterized by distinctive lenticular shapes and larger sizes between the range of 15.67~33.3 μm (**Figure 3C**). Pressure craters on the surface are apparent. They are identical to starch grains from the modern tribe Triticeae in which wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) are included (**Supplementary Figures 1C,D**) (Yang and Perry, 2013).

Group C includes 26 starch grains that have the shape of a partial sphere, hemisphere, or sphere, with facets (**Figures 3D,E**). The hilum is eccentric. Starch grains in this group are similar to geophytes (**Supplementary Figures 1E,F**), in which Chinese yams (*Dioscorea* spp.) could be identified at least.

Group D comprises unidentifiable starch grains because of their lack of typical morphological features or severe damage.

Ancient Phytoliths Recovered From the Residues

More than 7,000 phytoliths were recovered from the potsherds after the recovery of starches (**Supplementary Table S2**). A total of 265 typical bulliform phytoliths from rice leaves (**Figure 3F**), 253 double-peaked phytoliths from the glume of rice grains (**Figure 3G**), 89 Ω-type and 136 η-type phytoliths from glumes of foxtail and broomcorn millets (**Figures 3H,I**), and 34 phytoliths with wave patterns in conjunctions from glumes of wheat or barley are observed (**Figure 3J**), in addition to bilobate-scooped phytoliths usually extracted from the leaves of Paniceae and Oryzoideae (**Figures 3K,L**) (Piperno, 2006; Lu et al., 2009, 2017; Ball et al, 2016). The percentage of each type of phytolith is shown in **Figure 5**. It should be noted that the phytoliths from leaves, such as bulliform, bilobate, saddle, blocky, and rondel phytoliths, can reach up to half of the phytolith assemblage.

DISCUSSION

Plant Subsistence at the Meishan Site

From other contemporaneous sites of the Longshan culture in central China, such as the sites of Yangzhuang, Wangchenggang,

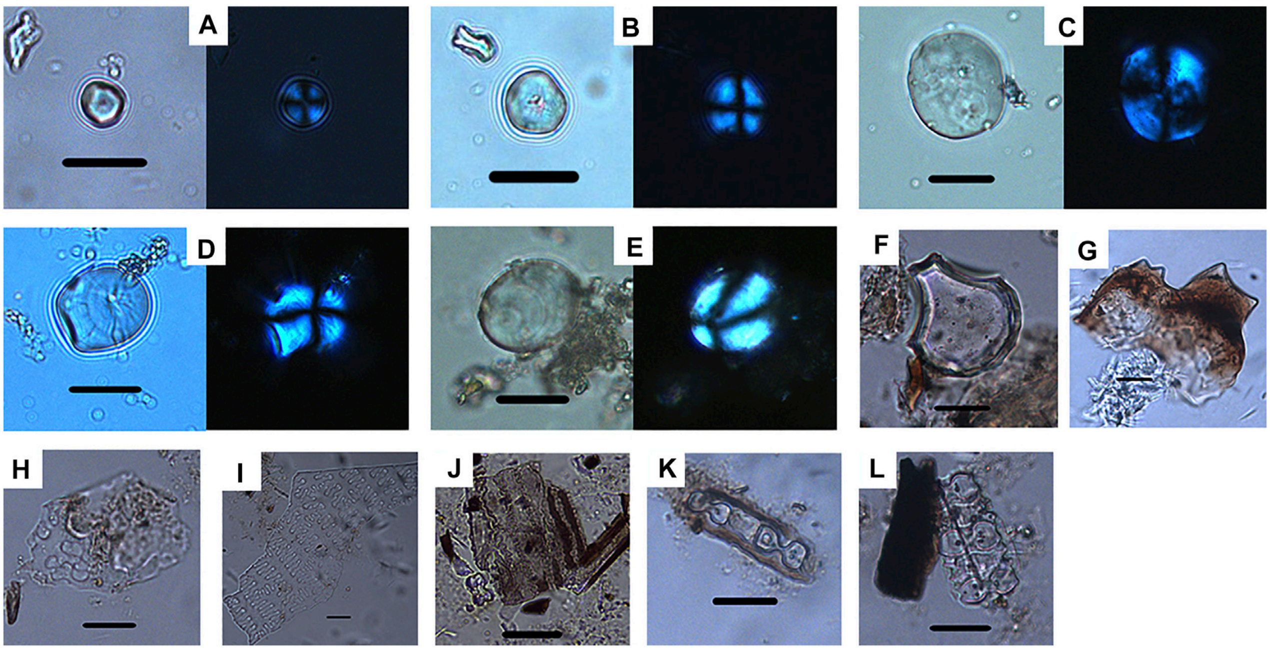

FIGURE 3 | Starch grains **(A–E)** and phytoliths **(F–L)** recovered from the residues on the grooved vessels from the Meishan Site. Each starch grain is shown in brightfield and polarized views. **(A,B)** Foxtail millet or broomcorn millets; **(C)** Triticeae; **(D)** geophytes; **(E)** possibly Chinese yam; **(F)** rice bulliform phytoliths from rice leaves with increased scale numbers; **(G)** double-peaked phytolith from rice husk; **(H)** Ω-type phytolith from foxtail millet husk; **(I)** η-type phytolith from broomcorn millet husk; **(J)** dendritic epidermal phytolith possibly from wheat or barley glumes; **(K)** bilobate-scooped phytolith from Oryzoideae; and **(L)** bilobate-scooped phytolith from Paniceae. Scale bar, 20 μm.

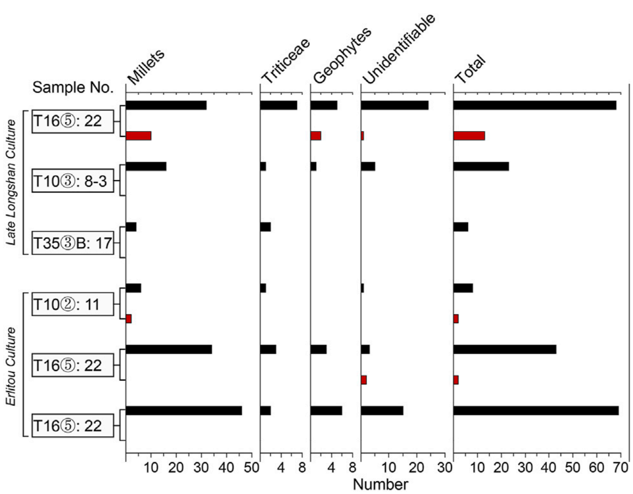

FIGURE 4 | Number of starch grains recovered from the residues on the grooved pottery vessels at the Meishan site. Black and red bars represent the samples from the interior face and exterior face, respectively. The results from possible contaminated potsherds have been excluded.

Xinzhai, etc., charred seeds of five grains which were staple crops in historical North China (Zhao, 2011), foxtail and broomcorn millets, rice, wheat, and soybean (*Glycine max*), were recovered by floatation (Jiang et al., 1998; Zhao and Fang, 2007; Zhong et al., 2016). Since barley was introduced in central China by the Shang and Zhou Dynasties (Guo and Jin, 2019), and the Meishan site should have the same plant subsistence as these contemporaneous sites, the phytoliths with wave patterns in the conjunctions and the starches identified to the tribe Triticeae recovered from the Meishan site should be from wheat. Therefore, multiple lines of evidence of both phytoliths and starches from the residues on the grooved vessels from the Meishan site comprise four grains except soybean which does not produce both phytoliths and characteristic starch grains. However, starches of geophytes from the Meishan site supplement archaeobotanical data from other contemporaneous sites of the late Longshan culture in central China.

Function of the Grooved Pottery Vessels

Phytoliths recovered from eight sherds show that the number of phytoliths on the interior face of each sherd is much higher than that on the exterior face, indicating phytoliths sourced from the use of vessels. But starch data are not ideal. The number of recovered starches is so small that there are 380 from 20 sherds in total for statistical analysis. Excluding the sherds of which both faces yield equal or approximately equal numbers of starches or those that their exterior faces yield more starches than the interior faces, in other words, excluding those sherds that might have a secondary deposition from contemporaneous sediments, only three sherds, T16⑤: 22, T10③: 8-3, and T35③B: 17 of the Longshan culture, and three sherds, T10②: 11, T16②: 8, and T10③: 8-1 of the Erlitou culture

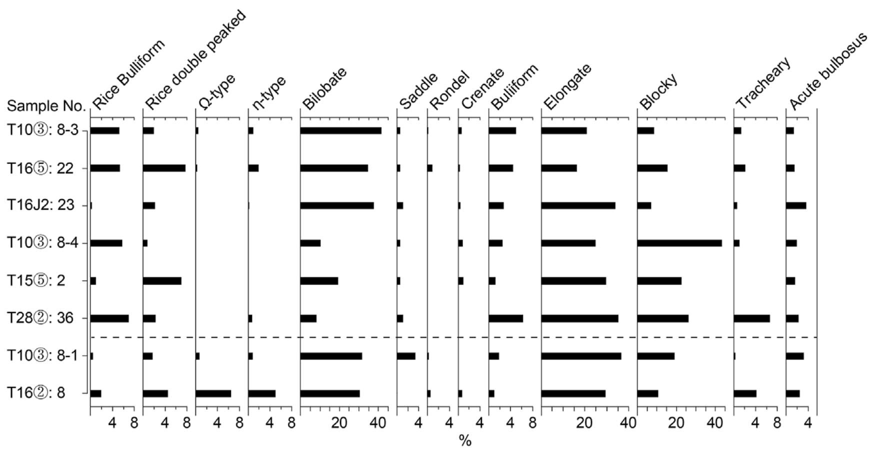

FIGURE 5 | Percentage of each type of phytolith recovered from the residues on the grooved pottery vessels at the Meishan site. The samples above the dashed line are from the late Longshan period, while the samples below the dashed line are from the Erlitou period.

remain useful for the discussion about the function of grooved vessels (**Figure 4**).

Both the phytoliths and starches from the residues confirm that grooved vessels were indeed used to process plants, as shown by previous studies at the sites of Lingjiatan and Yanshi Shangcheng (Sun et al., 2019; Reinhart, 2020). Wang (2019) summarized the studies on the grooved vessels in China and tends to agree that the principal function of the vessels was grinding geophytes. In our study, starch grains from Chinese yams and other geophytes were observed from residues on the interior faces of four sherds, providing evidence for the function of grinding geophytes again.

We recovered 7,595 phytoliths and 380 starch grains from the residues on 20 potsherds (**Supplementary Tables S1, S2**). The pattern of abundant phytoliths with a few starches from glumes and/or caryopsis of rice, foxtail millet, broomcorn millet, and wheat in this study seem to suggest that the grooved vessels were once used to dehusk seeds. But, two factors should be taken into consideration. One is the large number of phytoliths from leaves, taking up 54% of the phytolith population (**Figure 5**); the other is the small number of sherds from grooved vessels, taking up 3.3% of the pottery ware at the Meishan site. If the grooved vessels were used as principal tools to dehusk seeds, it could be difficult to cope with the work in an agricultural community using 3.3% pottery tools. The phytoliths from leaves may have been occasionally brought in when harvesting ears, so we cannot exclude the function of dehusking seeds. However, we prefer to hypothesize that they are the result of intentionally pounding leaves and husks for some reason. A few starch grains recovered from the potsherds might source the husks on which some starches had been left as dehusking. Rice leaves were once proved to be tempered in the ceramic mold for casting bronze ware during history (Lu et al., 1996). The reason for processing leaves and husks by the grooved vessels at the Meishan site needs further study.

We also noted that the function of grooved vessels is not related to the materials used for pottery manufacturing, because either sand-tempered sherds or clay sherds have the same starch and phytolith patterns in their residues. Since only one sherd is apparently from the vessel with a spout, we cannot distinguish the difference of functions between vessels with or without a spout, though we think the spout is a crucial factor in understanding the function.

Pottery Function and Agricultural Development

The function of early potteries from China, Japan, and Russia in East Asia has been proved to be used for cooking food by the residue analysis (Craig et al., 2013; Shoda et al., 2020; Yang et al., 2012a, 2014, 2015). Furthermore, millet starches recovered from charred residues on early potteries excavated from the sites of Nanzhuangtou, Donghulin, and Zhuannian indicated that the function of cooking plant food and that the invention of pottery manufacturing in the North China Plain may have been related to early farming activities around 10,000 years ago (Yang et al., 2012a, 2014, 2015). By the mid-Neolithic Age, the functions of pottery began to diversify with the establishment of the agricultural societies, and a variety of cooking utensils and containers were often discovered (Wang, 2005).

It is accepted that the middle and lower reaches of the Yangtze River are two centers of rice domestication. Rice was fully domesticated by around 8,000 cal BP in the middle regions after more than 2000 years of cultivation (Deng et al., 2015); however, in the lower regions, the process of rice domestication lasted for even 4,000 years and ended by around 6,000–5,500 cal BP (Fuller et al., 2009; Fuller, 2011; Gao, 2012; Ma et al., 2016, 2018). During the Yangshao Period, rice agriculture spread to central China, joining the millet agriculture (Qin, 2012; Zhang et al., 2012). It seems that the grooved vessel is highly relevant to rice agriculture. The earliest grooved pottery vessels were invented at the archaeological sites of the early stage of the Songze culture (6,000–5,300 cal BP) in the lower reaches of the Yangtze River (Wang, 2019), which happened to be consistent with the end of the process of rice domestication (Ma et al., 2018), and the technics first spread among the rice agricultural societies in the Middle Yangtze River regions during the mid-Songze culture, then was gradually introduced in central China by around 5,300 years ago where rice had been introduced, and local crops, two millets and wheat, were added to be processed as well.

Incorporating the rice phytoliths in a large number on the interior face of grooved vessels at the Meishan site (**Figure 5** and **Supplementary Table S2**), we hypothesize that the grooved pottery vessel might be invented to process by-products of rice for some reason, and to dehusk seeds and grind geophytes, probably. The hypothesis needs systematic residue analysis on the grooved pottery vessels from the lower Yangtze River regions to central China, from the earliest ones to the latest ones, in future studies.

CONCLUSION

Different from the previous studies based on the ethnographic investigation or single ancient starch evidence, we combine phytolith evidence in the study methods to conclude the function of the grooved pottery vessels, taking an example of the study on sherds excavated from the Meishan site, in central China. We studied the residues on the potsherds of grooved vessels at the Meishan site occupied during the period of 4,000–3,500 cal BP. In terms of starches from geophytes including Chinese yam and starches/phytoliths from glumes and leaves of rice, foxtail and broomcorn millets, and wheat, we demonstrate that the grooved pottery vessels were once principally used to pound leaves and husks for some reason, and to grind geophytes and dehusk crop seeds, possibly. In terms of the timing of rice domestication, we raised a hypothesis that the invention of grooved pottery vessels may have been related to the end of rice domestication in the lower reaches of the Yangtze River. This hypothesis needs further study.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

XY and JY designed the study. YZ, ZM, and XY performed microfossil analysis. TW, JY, YZ, XY, and GY analyzed the data. TW, JY, and XY wrote the manuscript with contributions from all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.832145/full#supplementary-material

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