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An Interplay of Dryland and Wetland: Millet and Rice Cultivation at the Peiligang Site (8000–7600 BP) in the Middle Yellow River Valley, China

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Abstract: The Peiligang culture (ca. 9000–7000 cal. BP) represents the first Neolithic settlements in the middle Yellow River Valley, marking the beginning of millet and rice farming in the region. While previous studies have focused primarily on identifying cultivated cereals, less attention has been given to plant harvesting and processing practices or environmental conditions. To address this gap, we present new phytolith data from the Peiligang site (8000–7600 cal. BP) to make three key contributions. First, we show that the Peiligang people utilized two microhabitats: hillslopes for dryland millet cultivation and alluvial plain for wetland resources. Second, we combine our findings with other archaeological evidence to reconstruct the environmental conditions of the Peiligang site, suggesting that it was a water-rich habitat. Finally, by analyzing phytolith remains of plant processing waste in middens, we reconstruct how people harvested and processed millets and rice at the site. This study sheds light on the plant-based subsistence strategies employed by the Peiligang people and offers insights into the environmental factors that contributed to the development of early farming in the middle Yellow River Valley.

Keywords: Peiligang; phytolith analysis; crop harvesting and processing; North China

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1. Introduction

Early farming in China can be broadly divided into two groups: the northern tradition, centered around the cultivation of millet (foxtail millet *Setaria italica* and broomcorn millet *Panicum miliaceum*) in the Yellow River Valley, and the southern tradition in the Middle and Lower Yangtze Valley, focused on rice (*Oryza sativa*) cultivation [1]. The domestication of rice and millet occurred during the early Holocene, approximately between 10,000 and 8000 BP [1–3]. Despite their distinct growth patterns and ecological preferences, the distribution of fertile loess soil in North China and the expansion of East Asian monsoons allowed for the cultivation of both crops beyond their natural habitats. Around 8000 BP, a vast region characterized by mixed millet and rice farming began to develop, spanning the areas between the Yellow River and Yangtze River valleys [4,5]. The development of multi-cropping systems during the Neolithic period likely coincided with population movements and demographic expansions, eventually laying the foundation for the emergence of Bronze Age state societies in China.

While previous research has primarily focused on the temporal and spatial distribution patterns of early millet and rice cultivation, there has been relatively limited study on how these communities adapted their cultivation practices within different local environmental niches, as well as how they organized their crop harvesting and processing activities. These aspects likely varied across the region, as each site was influenced by distinct microclimate and ecological conditions. To address these gaps, we focused our study on the Peiligang site, located in the Middle Yellow River Valley, dating to 8000–7600 cal. BP. The Peiligang culture (ca. 9000–7000 cal. BP) represents the first Neolithic settlements in the Middle Yellow River Valley, showing the earliest evidence of millet and rice cultivation in the region. This study aims to answer three questions: (1) What plant resources were utilized by the Peiligang people? (2) How did they harvest and process plant crops at the site? (3) What was the microenvironmental condition at the Peiligang site? To answer these questions, we conducted a phytolith analysis of soil samples from the middens and environmental deposits. Middens are ideal sources for such analyses as they contain residues from daily activities, offering insights into the routines of daily life. Additionally, the environmental deposits, located in the periphery of the site and lacking evidence of residential structures, provide us with evidence to reconstruct the site's environmental surroundings.

Phytolith analysis is an effective method for reconstructing paleoenvironments and understanding past subsistence strategies. Phytoliths are plant silica bodies formed through the deposition of soluble silica from groundwater into plant tissues [6]. They have distinct shapes that allow for the identification of plant taxa at the family or even species level [7]. In comparison to macrobotanical remains, phytolith analysis provides a unique advantage in detecting plant parts such as leaves and stalks, which are often absent or underrepresented in macrobotanical remains. This expands the range of research questions that can be addressed. For example, previous studies have used phytolith remains to distinguish between locally grown crops and those obtained through trades [8], to identify cereal processing activities at settlements [9], and to investigate labor mobilization associated with cereal processing [10]. Phytolith remains have also been used to examine spatial distributions in plant-related activities at archaeological sites [11]. We will apply these approaches to study similar issues at the Peiligang site.

2. Environmental and Archaeological Background

Beginning around 9000 BP, the East Asian monsoon reached its peak, leading to an increase in temperature and precipitation in North China [12,13]. The climatic shift transformed the previously semiarid regions into warm-temperate ones characterized by deciduous forests, which in turn facilitated the flourishing of early Neolithic settlements along the Liao River and the Middle and Lower Yellow River Valleys. During this time, early Neolithic sites began to appear in mountainous basins and floodplains. In the Middle Yellow River Valley, the Peiligang culture sites (ca. 9000–7000 cal. BP) emerged on hilly lowlands near rivers and floodplains. Many of these sites comprised both residential structures and burials, suggesting increased sedentism.

The Peiligang site is the type site of the Peiligang culture, covering 5–6 hectares on an alluvial plain bounded by rivers and close to small hills (Figures 1 and 2B). The site comprises residential and burial areas, with the western section primarily serving as a cemetery area. Excavations in 1977–1979 focused on the western section, revealing important materials related to Peiligang burial rituals [14,15]. In 2018–2019, new excavations were conducted in the residential area, which included large middens that we are focusing on in this paper. The area was initially a low-lying area created by people digging for soil and, over time, became a dumpsite for trash, forming large middens with numerous ceramics, lithic, animal, and botanical remains. In the southeast corner of the site, excavations also revealed green-gray soil layers with sedimentation characteristics, suggesting a marshy depression likely representing a pond. Radiocarbon dating from seven carbonized fruit shell samples indicated a calibrated range of 5978–5678 BCE, suggesting the site being occupied for about 300 years in total [16] (Figure 2D).

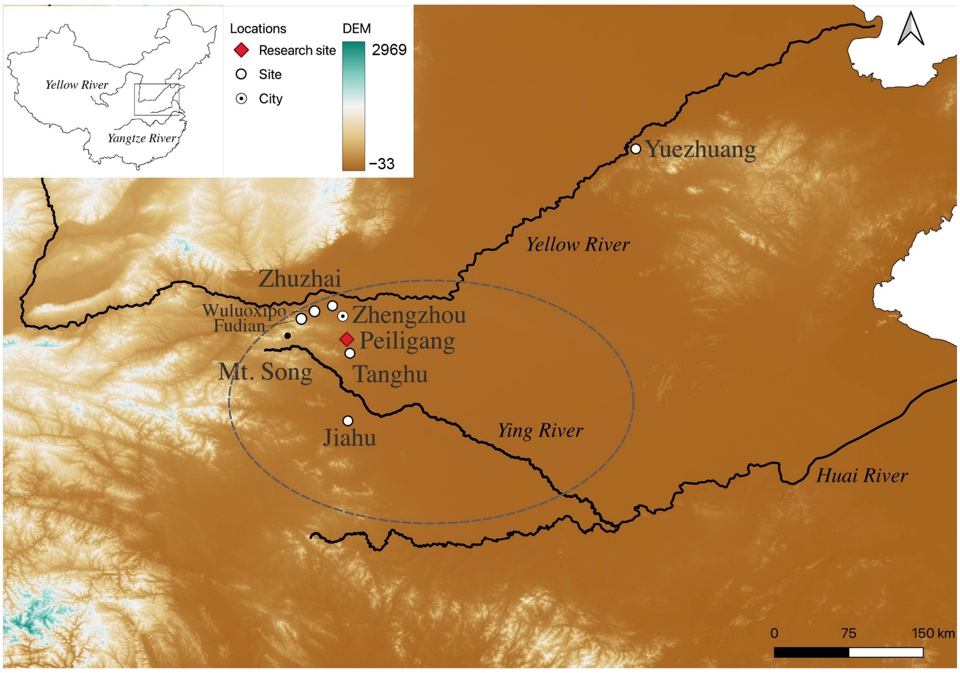

Figure 1. The location of Peiligang and other sites discussed in this study. Circle indicates the spatial distribution of the Peiligang culture.

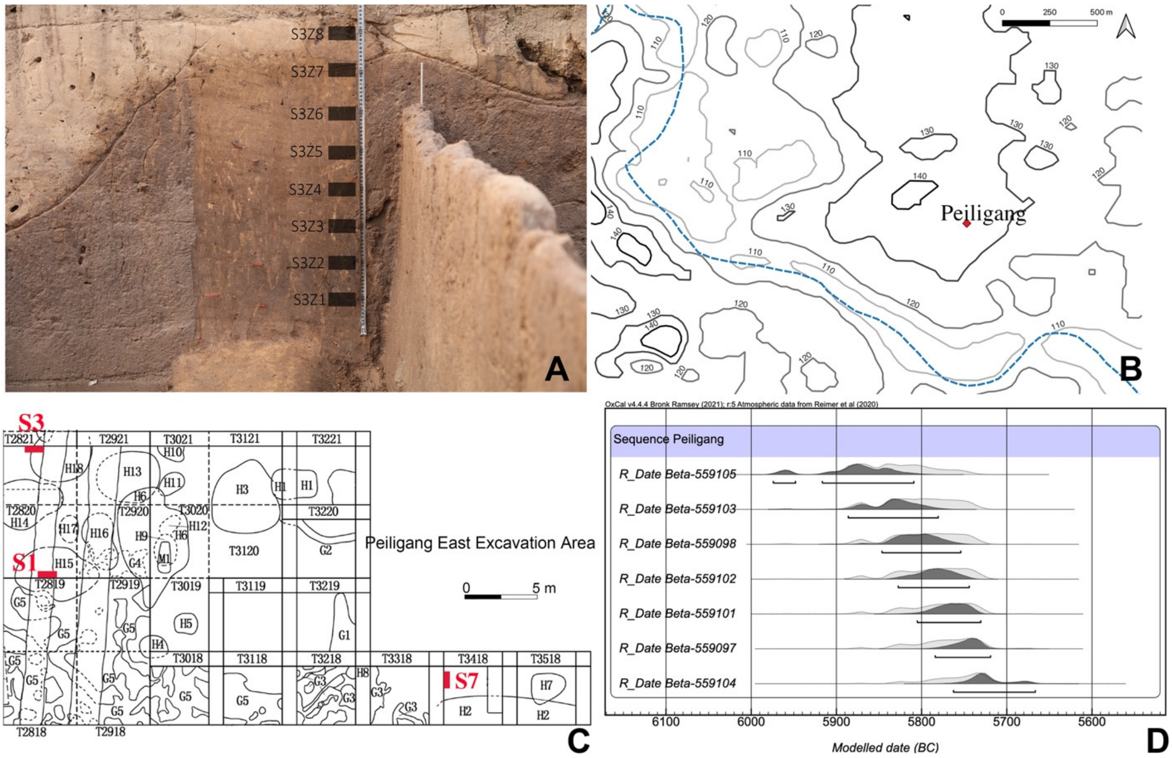

Figure 2. (**A**). Sampling locations of S3 Midden; (**B**) A contour line map showing the location of Peiligang and its surrounding elevations; (**C**) locations of S1, S3, and S7 samples at Peiligang; (**D**) calibrated 2σ probability distribution of AMS Radiocarbon dates on carbonized seeds from Peiligang.

Preliminary macrobotanical analysis at Peiligang suggests a subsistence economy based on low-level production [17]. Wild plants such as acorns, walnuts, jujubes, and other fruits are predominant, while cultigens like broomcorn millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), and rice (*Oryza*) were found in small quantities [16]. This result suggests that the Peiligang people practiced broad-spectrum subsistence strategies, in which food production played a minor role in the overall subsistence economy [18].

3. Materials and Methods

A total of 29 samples were collected for phytolith analysis from two different types of locations, as shown in Figure 2A,C. Among them, 20 samples were obtained from two large middens (H15, H18) that were likely made up of waste from daily activities, including Peiligang culture style pottery and stone tools. Twelve S1 samples labeled as S1Z1–S1Z12 were collected from midden H15, consisting of dark brown soils and charcoals, while eight S3 samples labeled as S3Z1–S3Z8 were collected from midden H18, with a soil condition similar to S1. Additionally, nine samples were collected from the western profile of trench T3418, which was located near the marshy depression (H2) in the southeastern corner of the site. The deposits in this location were yellow-brown in color and contained relatively few artifacts, suggesting their association with natural deposits that better reflect the site's environmental conditions. Samples were collected at 10 cm intervals from the bottom to the top at all three locations (Figure 2). Samples from top layers (S1Z12, S3Z8, and S7Z9) were also collected and analyzed for comparative purposes, as they represent recent loess deposits.

Phytolith extraction followed an established method, as detailed in the Supplementary Material Text S1 . The procedure generally involved deflocculating the samples with 5% Calgon solution (sodium hexametaphosphate) and warm water centrifuging, treatment with 10% hydrochloric acid (HCl) and 30% hydrogen peroxide (H_2O_2), and separation using sodium polytungstate (density 2.35 g/mL). The processed samples were then mounted on slides using 50% glycerol. Phytolith counting and identification were conducted using a Zeiss Axio Scope 5 microscope at 400× magnifications. We counted all or at least 300 identifiable phytoliths, with identification made by comparing samples with reference materials from our lab and published sources [19–21]. Phytoliths were recorded based on the International Code for Phytolith Nomenclature 1.0 [22]

Additionally, previous studies have developed models to assess water availability based on phytolith types. One such study by Weisskopf et al. [4] used the ratio of fixed-to-sensitive grass phytoliths to detect water availability from cultivated rice fields in wet and dry conditions, following the model for C3 plants proposed by Madella et al. [23]. However, a more recent study by D'Agostini et al. [24] has challenged this ratio as a proxy for water availability, especially for sites with C4 plants like millets. Instead, they suggest that higher proportions of sensitive morphotypes, such as bulliforms, long cells, and stomata, indicate well-watered conditions. We applied D'Agostini et al.'s model to calculate the proportions of sensitive-type phytoliths in the Peiligang samples.

4. Results

A total of 4736 phytoliths were recorded from archaeological deposits, along with the presence of freshwater sponge spicules in seven archaeological soil samples, as detailed in Figure 3 and Table S1. Among the three modern samples analyzed, one sample (S3Z8) reveals 236 phytoliths, predominantly consisting of common bulliforms from grass leaves, with no evidence of crops. Two other modern samples did not yield phytoliths.

The phytolith assemblages recovered from Peiligang soil samples included three major types of plant resources: crops, wetland and weedy grasses, and woody species. The crop phytoliths include rice (*Oryza*, double-peak and Oryza-type bulliform, Figure 4A,B), broomcorn millet (*Panicum miliaceum*, η type, Figure 4C), foxtail millet (*Setaria italica*, Ω type, Figure 4D), and possible Job's tears (*Coix lacryma-jobi*, large Variant-1 cross, Figure 4F). Phytoliths of wetland weedy grasses include tabular scrobiculate and tabular conical, from Cyperaceae inflorescence and leaf/culm, respectively, as well as *Phragmites*-type bulliform from common reeds (Figure 4G–I). Wood phytoliths include tracheary and elongate scalloped/granuate types that are likely from broad-leaved trees in the region (Figure 4J) [25].

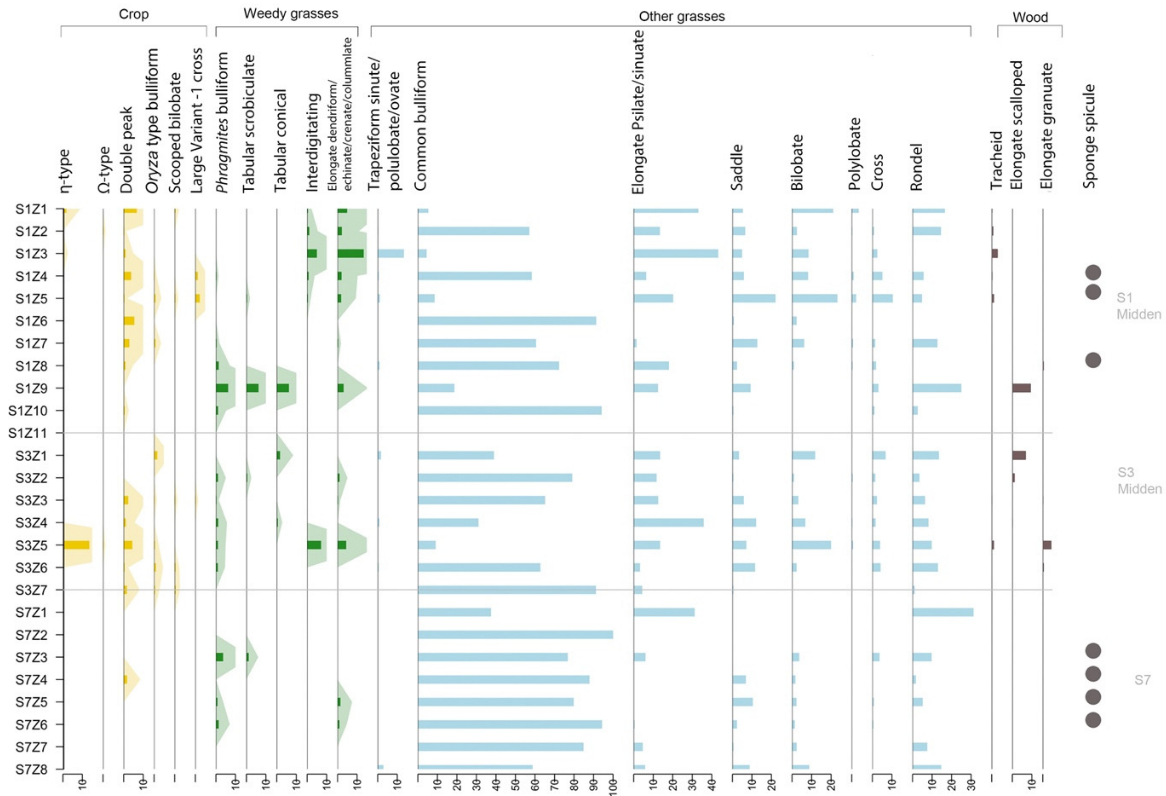

Figure 3. Percentage diagram of the major phytolith morphotypes from Peiligang. The shaded areas of lighter color represent ×5 exaggerated values.

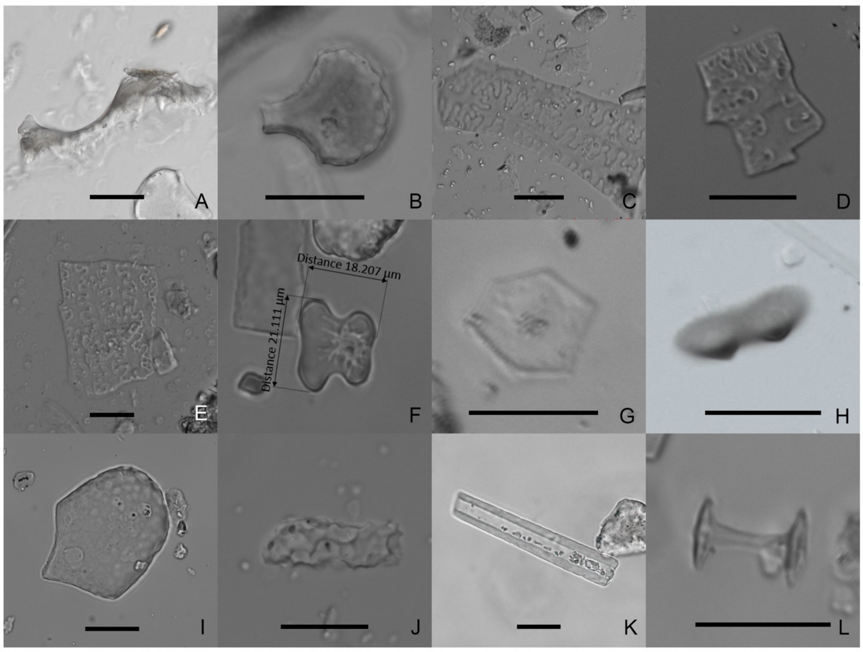

Figure 4. Phytoliths and sponge spicules recovered from Peiligang. (**A**) Double peak (rice husk); (**B**) *Oryza*-type bulliform (rice leaf); (**C**) η-type (broomcorn millet inflorescence); (**D**) Ω-type (foxtail millet inflorescence); (**E**) interdigitating type (Panicoideae inflorescence); (**F**) large Variant-1 cross (Job's tears leaf/culm); (**G**) tabular scrobiculate (Cyperaceae achene); (**H**) tabular conical (Cyperaceae leaf/culm); (**I**) *phragmites* bulliform (common reed leaf); (**J**) elongate scalloped (woody species); (**K**,**L**) sponge spicules; scale bars = 25 μm.

The presence of rice and millet phytoliths suggest that the Peiligang people practiced a mixed dryland and wetland cultivation strategy alongside their foraging activities. In the following, we discuss the plant use and diversity, paleoenvironmental conditions, and crop harvesting and processing practices through a detailed analysis of phytolith types. We also connect our findings to the broader development of multi-cropping cultivation in prehistoric China.

5. Discussion

5.1. Peiligang Plant Resources

Among the diagnostic plant phytoliths recovered from Peiligang, rice phytoliths show the highest ubiquity (55.2%), followed by common reeds (44.8%), sedges (17.2%), and Job's tears (10.3%). These plants were commonly found in the wetland environments. Phytoliths from dryland crops, including broomcorn millet (10.3%) and foxtail millet (6.9%), are also present but less ubiquitous.

The presence of rice phytoliths, including *Oryza*-type bulliform cells and scooped parallel bilobate short cells from rice leaves, as well as double-peaked phytoliths from rice husk, indicate that rice was cultivated locally rather than obtained through trade. These findings are further supported by the identification of phytoliths from *Oryza* crop weeds such as Cyperaceae, along with accompanying sponge spicules indicating the presence of freshwater environments (Figure 4K,L). Peiligang is located north to the natural range of the wild ancestor of domesticated rice, suggesting that the cultivation of rice at this site represents a northward expansion from the Yangtze River Valley, where rice domestication originated [2]. Due to the limited quantity of recovered *Oryza*-type bulliforms, we are unable to determine the domestication status of Peiligang rice. Nevertheless, given the earlier evidence of rice domestication from the Lower Yangtze River, the results of charred rice remains from Yuezhuang and Zhuzhai [26,27], as well as analyses of rice phytoliths from Tanghu and Jiahu [28–30], rice domestication was already underway in both the Middle and Lower Yellow River regions around 8000 BP.

The phytolith assemblages also include Variant-1 crosses larger than 18 µm in width, a morphotype consistent with those from Job's tears and not produced by other Panicoideae grasses in East Asia (Figure 4F) [20]. Job's tears is believed to be native to tropical and subtropical regions of Asia, typically growing near streams and in marshy valleys. While macroremains of Job's tears have only been reported from three Neolithic sites along the Yangtze River Valley, including Hemudu [31], Chengtoushan [32], and Baodun [33], evidence from an ancient starch analysis suggest that Job's tears has a longer history in temperate regions of China [34]. The discovery of Job's tears phytoliths at Peiligang supports previous analyses, suggesting that this crop may have been cultivated as part of early Neolithic farming practice in China, particularly in moist microenvironments such as areas near lakes and swamps.

Reeds (*Phragmites* sp.) and sedges (Cyperaceae) are plant species commonly found in wetlands and are often considered as weeds in rice fields. These plants also have economic and subsistence significance for humans due to their nutritional qualities and their ability to attract fauna. Besides their edible roots and seeds, their leaves and culms could be used for various cultural purposes, including raw materials for thatching, floor covering, matting, and bedding [35,36]. These uses have been well documented in the ethnographic and historical records in China [37].

Millet cultivation played a minor role in the overall subsistence strategy at Peiligang. Millet phytoliths accounted for only 1.2% of all recorded phytoliths, with a ubiquity of 15.4%, lower than that of wetland species. The presence of abundant fruit and nut remains in the macrobotanical assemblages further indicates an environment with ample edible resources [16]. Therefore, millet cultivation likely remained at a low level, requiring less labor investment in terms of field management. Among the millet phytoliths, broomcorn millet was the predominant type, while foxtail millet was represented by only two Ω-type phytoliths. This finding is consistent with preliminary macrobotanical analysis conducted at the site [16], indicating that broomcorn millet was the primary millet cultivated at Peiligang. Similar millet cultivation patterns have been reported from other contemporary millet farming sites in the Yellow River Region, including Tanghu [28], Zhuzhai [27], Yuezhuang [26], and other Peiligang sites such as Fudian and Wuluoxipo [38]. It was not until the Yangshao culture, around 6000 BP, that foxtail millet began to replace broomcorn millet as a staple food crop [1].

5.2. The Environmental Condition at Peiligang

The phytoliths obtained from the S7 location suggest a wetland environment (Figures 3 and 5A). The presence of sedges, reeds, and a significant abundance of bulliforms from grass leaves suggests vegetation typical of moist areas, potentially suitable for rice cultivation. The ubiquitous presence of freshwater sponge spicules in S7 also provides additional evidence, as they are commonly found in wetlands and lakes [39]. The location of S7, situated on the periphery of the site near a depression and away from trash pits, is consistent with the vegetation and environmental characteristics found there.

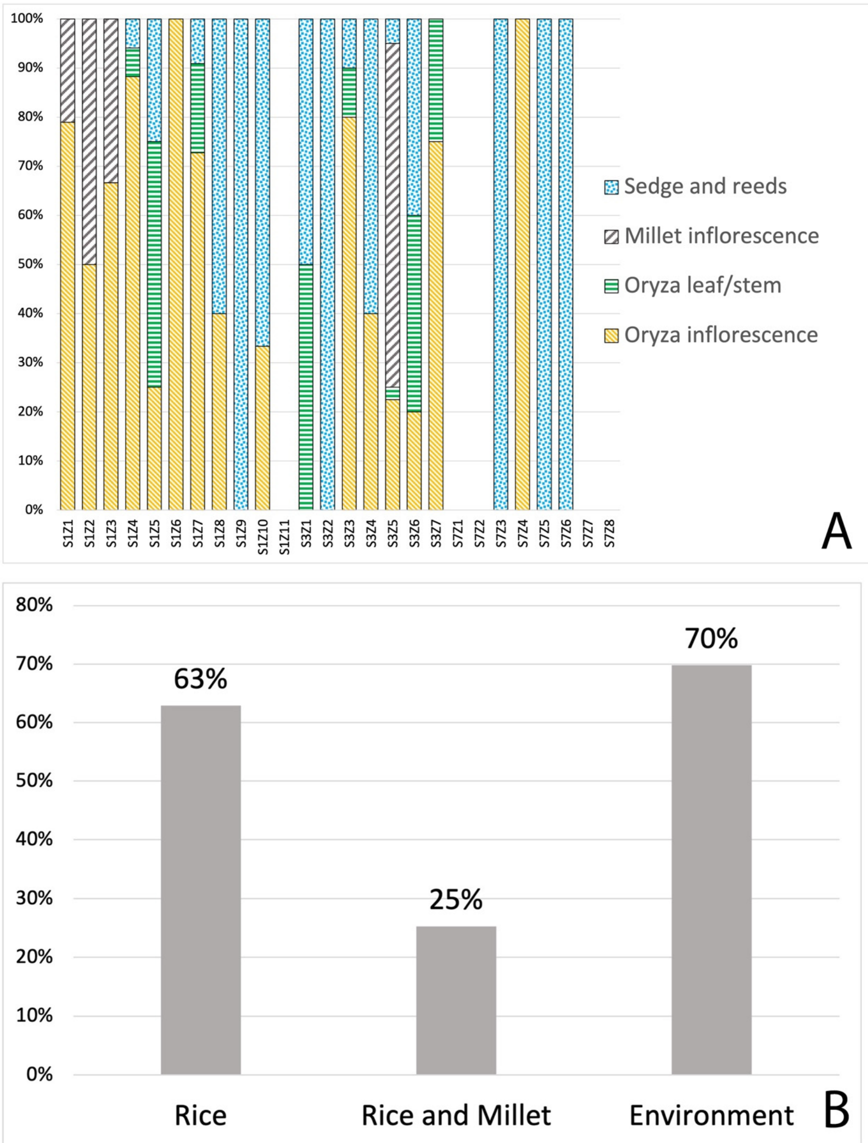

Figure 5. (**A**) Ratios of crop and weedy type phytoliths; (**B**) ratios of sensitive types: total phytolith types from rice processing waste, rice and millet processing waste, and environmental deposition.

Applying D'Agostini et al.'s model [24], we calculated the proportions of sensitive type phytoliths in the Peiligang samples (Figure 5B). We categorized the samples into three groups based on the presence of rice and millets: (1) samples with only rice phytoliths, likely representing rice processing wastes; (2) samples with both rice and millets, probably resulting from processing both crops; and (3) samples with no crops, mostly from the S7 location representing environmental deposition. Our results indicate that both rice processing samples and environmental samples contain significantly more water, with 63% and 70% sensitive types, respectively. In contrast, phytoliths from millet processing wastes contain only 25% sensitive types, indicating less water availability. These findings suggest that the Peiligang people resided near low-lying wetland areas suitable for rice cultivation, while millets were more likely grown in dryland areas further away from the site. People likely made use of the ecological niches, predominantly including different water and topographic conditions around the site, to manage the cultivation of millets and rice in separate areas.

5.3. Harvesting and Processing of Rice and Millet

Crop harvesting and processing activities played a significant role in shaping labor organization and seasonality scheduling in the past [40,41]. In the case of Peiligang, the phytolith assemblages recovered from middens mainly consist of crop and weed husks and leaves, resembling remnants from crop processing activities. The composition of these phytoliths reveals two significant patterns related to crop harvesting and processing.

First, the phytolith data suggest different patterns in the processing of millet and rice. While rice phytoliths were found in 15 of 18 midden layers, millet phytoliths were more sporadic but concentrated. Notably, a significant majority (88.7%) of the millet phytoliths were recovered from a single midden layer, in contrast to the distribution of rice across most midden layers. The disparity may be attributed to the site's environmental conditions and potential variations in labor organization during food processing. Peiligang was located on an alluvial plain bounded by rivers, providing favorable conditions for rice cultivation in close proximity. During the early stages of rice domestication, rice plants likely had asynchronous flowering and fruiting over a protracted period throughout the fall season [42]. As a result, rice harvesting at Peiligang probably extended over a considerable duration, with on-site processing activities such as winnowing and dehusking carried out routinely and in small portions. In contrast, millet cultivation required well-drained soils located further away from the settlement, possibly on the small hills located approximately 200 m from the current site location (Figure 2B). The Peiligang people likely harvested millets during the summer when they matured and processed them before the onset of rice harvesting and processing. It is also plausible that certain millet processing activities occurred outside the immediate settlement area, leaving sporadic millet phytoliths in the middens.

Second, the presence of abundant phytoliths derived from rice leaves and light weed husks suggest that the Peiligang people harvested rice by cutting stalks near the base (Figure 5). Ethnographic and experimental studies indicate at least two harvesting methods: low cutting of the stalks using a sickle or uprooting, and harvesting only the panicles at the top using finger knives [43,44]. The abundance of bulliform and weed phytoliths, along with the discovery of denticulate sickles at the site, suggests that Peiligang people likely utilized sickles for rice harvesting. This harvesting method is commonly practiced in Asia and believed to have been used by early rice cultivation communities around 8000 BP. A similar pattern has been observed at Jiahu, another Peiligang culture site located in the Huai River Valley, where a significant number of denticulate sickles appeared in Phase III (ca. 8000–7500 BP) [45]. Residue and use-wear analyses have further confirmed that some of these sickles were used to harvest rice and other Poaceae plants [46,47]. Comparable evidence has been reported from Hehuashan in the Lower Yangtze Valley (ca. 8000–7000 cal. BP), where chipped flakes from the Kuahuqiao culture were utilized as sickles for rice harvesting [48]. However, the specific methods of millet harvesting remain unclear, as no diagnostic phytoliths from millet leaves have been identified [25]. Addressing this question requires a more systematic analysis of macrobotanical remains at the site.

5.4. Development of Multi-Cropping Cultivation System

The Peiligang culture shows considerable variations in settlement-subsistence systems, reflecting adaptations to diverse microenvironmental conditions over time and space. These sites can generally be classified into two types: those situated on the alluvial plains and those in hilly areas [49]. Recent archaeobotanical studies have shown distinct agricultural strategies employed by these two types of sites: mixed farming of millet and rice may have been limited to the alluvial plains, while sites in hilly regions focused solely on millet cultivation [50]. The results of this phytolith analysis support the observed spatial farming patterns and reveal a multi-cropping cultivation system that combines rice, broomcorn millet, and foxtail millet.

The beginning of multi-cropping practices was likely influenced by both environmental and social factors. In the Central Plains, multi-cropping first emerged in the Middle Yellow River and Upper Huai River regions, with the Peiligang culture representing the earliest example. The fertile loess provided well-drained soil suitable for millet cultivation, while the East Asia monsoon brought favorable temperature and precipitation conditions for rice cultivation [5,51]. Among the archaeobotanical remains of the three crops, rice holds the highest proportion, followed by broomcorn millet and foxtail millet, as evidenced in this research and studies at other sites [27]. The relative importance of rice may have been partly attributed to the Holocene Optimum, a period when temperature and precipitation levels reached their peak after 9000 BP [52]. Concurrently, the growing population and expansion of settlements also contributed to a more sedentary lifestyle, promoting multi-cropping practices.

Subsequently, around 8000 to 4000 years ago, the multi-cropping pattern of rice and millets intensified and expanded to the Middle and Lower Huai River valleys, exemplified by the sites of Shuangdun (7300–6800 cal. BP) and Wanbei (7600–4400 cal. BP) [53,54]. Similar to the Peiligang culture sites, rice remained dominant, with limited cultivation of broomcorn millet and foxtail millet. However, during the Yangshao period, around 6000 BP, the pattern of crop cultivation began to change in the Middle Yellow River valley. The proportion of rice declined, and foxtail millet replaced broomcorn millet as the dominant millet type. This shift was partially related to the weakening of the monsoonal climate, causing the frontal zone to retreat southward and resulting in declined temperature and precipitation in the Central Plains [55].

6. Conclusions

This research demonstrates that the Peiligang people adapted to the local environment by utilizing and cultivating a variety of plant resources. Located on an alluvial plain with abundant water and fertile soil, the Peiligang people cultivated and utilized rice, Job's tears, reeds, and sedges, in addition to foraging fruits, nuts, and other wild resources. Rice cultivation was likely concentrated near the settlement and involved continuous maintenance, processing, and year-round consumption. In contrast, millet cultivation required well-drained soil and was probably located further away from the site. It is important to note that the overall subsistence economy remained largely based on hunting and gathering. Plant food production began as a gradual addition to a primarily gathered food economy, with nuts and other wild resources serving as the main subsistence sources and cultivated cereals playing a minor role [18,27].

This study also opens up new directions for future research. One prominent aspect is the social dimensions of plants. As numerous scholars have demonstrated, plants held significant social roles in human life, in addition to being a subsistence source [56,57]. Excavations at Peiligang have revealed different functional zones, including burial and residential areas, along with various types of pottery and stone tools likely associated with plant processing and consumption. Understanding how people utilized plants in these social contexts requires a comprehensive contextual analysis. Another key question regards the location and condition of early rice cultivation. As demonstrated by the results in this study, rice was likely cultivated and processed locally, rather than from trade. However, the specific details of where and how the Peiligang people cultivated rice remain unclear and require further studies. To provide answers to these questions, future research may incorporate soil micromorphology, a stable isotope analysis of human and plant remains, and a systematic functional analysis of food artifacts. Such investigations will provide additional evidence to reconstruct the extent of plant food use and consumption and shed further insight onto the dynamics of human–environmental interactions during the early Neolithic period in the Yellow River Valley.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy13082130/s1, Table S1: Peiligang phytolith data; Text S1: Phytolith processing method.

Author Contributions: Conceptualization, J.W., L.L. and Y.L.; methodology, J.W.; formal analysis, J.W., Y.H. and Y.T.; resources, Y.L., X.C. and W.G.; data curation, J.W.; writing—original draft preparation, J.W; writing—review and editing, J.W., Y.H., Y.T., L.L. and Y.L.; visualization, J.W. and Y.T.; project administration, Y.L., X.C. and W.G.; All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The raw data of this research are available at Dartmouth College and can be accessed by contacting J.W.

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Conflicts of Interest: The authors declare no conflict of interest.

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