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Investigating the Plant Microremains on Ceramic *Li* Tripods to Ascertain Their Function and the Plant Resource Exploitation Strategies During the Lower Xiajiadian Culture Period in Chifeng, Northeast China

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In undertaking a functional study of ceramic *Li* tripods, a common archaeological artifact in Northeast China during the Bronze Age, this study provides a crucial insight into both the function of these ceramics, plant resource strategies and human diets during this period. The precise function of the *Li* tripod has to date been controversial due to a lack of direct contextual evidence. Hence, this paper presents analyses of 10 *Li* tripods from six sites in the Chifeng area of Northeast China, all of which can be dated from their excavation contexts to the Lower Xiajiadian cultural period (3,900–3,400 cal a B.P.). The interior and exterior surfaces of the tripods were analyzed using starch grain analysis, phytolith analysis and microfossil charcoal analysis. A total of 133 starch grains were recovered, of which 111 (83.46%) were found on 80% of the interior surfaces examined. Further analysis found that these starch grains had damage features specifically gelatinised characteristics, which were consistent with the starch grains that had been boiled in our cooking simulations. In addition, there were obvious soot traces on the surfaces of the tripods, 2,835 microfossil charcoal grains not completely burned were identified, and 70% of the exterior surface samples had a higher frequency of contact with fire. These findings serve to confirm that *Li* tripods were used in the cooking of food. Of the 133 starch grains found, only 62 could be identified to species level. These were foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum milliaceum*) and plants from Triticeae taxa, as well as roots and tubers. The 3,424 phytoliths recovered from the 10 tripods were found to belong to the Panicoideae and Pooideae genera, of which the husks from foxtail and broomcorn millets from the Panicoideae genus accounted for 6.19% of the total. These results indicate that millets, the Triticeae, roots, and tubers, in addition to plants from Panicoideae and Pooideae genera, were utilized in the Chifeng area of Northeast China during the Bronze Age. This study deepens our understanding of the local subsistence patterns and the social context of early Bronze age civilization in the region.

Keywords: chifeng area, lower xiajiadian culture, early bronze-age civilization, *Li* tripod function, plant resource use, starch grain, phytolith, microfossil charcoal

INTRODUCTION

The West Liao River Basin in Northeast China occupies an important role as the birthplace of the Chinese civilization, and it has been the home of several archaeological cultures since the Neolithic Age, including the Xiaohexi, Xinglongwa, Zhaobaogou, Hongshan, and Lower Xiajiadian cultures (Su and Yin, 1981; Xu et al., 2013; Jia et al., 2017a). Among them, the Lower Xiajiadian culture is represented by the Xiajiadian sites in Chifeng city, which ushered in the Bronze Age and spanned the Erlitou culture to the early Shang Dynasty (ca. 3,900–3,400 cal. B.P.) (Zhang et al., 1987; Li, 1990; Wang et al., 1993). The Lower Xiajiadian culture was widely distributed in Chifeng, and 1,321 Lower Xiajiadian culture sites have been discovered in the Aohan Banner alone (Han, 2010). The archaeological sites of this culture surpass those of any other period in terms of their quantity and density, and the stratum associated with the culture is thick and contains widespread ancient urban settlements (Li and Gao, 1984).

Compared with the cylindrical pottery found in Chifeng during the thousands of years between the Xiaohexi culture and the Xiaoheyan culture in the Neolithic Age, the Lower Xiajiadian culture is mainly characterized by ceramic pottery vessels with three feet that are referred to as *Li* tripods. It has long been acknowledged that *Li* tripods were used for cooking (Liu, 1989; The Palace Museum, 2014). In recent years, ancient books and records, archaeological typology, and residue analyses have provided important clues about the functions of *Li* tripods. For instance, according to a typological study of *Li* tripods in the Yellow River Basin of the Longshan Period, it is believed that the tripod-shaped containers developed in response to practical cooking requirements (Gao, 1996). Moreover, an analysis of the starch grains from the *Li* tripods of the Bronze Age unearthed at the Dongzhao site in Zhengzhou, Henan province indicates that they were used for cooking rice (*Oryza sativa*) and other crops (Sun, 2018). Although large numbers of *Li* tripods from the Lower Xiajiadian cultural period have been unearthed in Chifeng, studies on their functions are still limited. Most studies focus on determining their cultural period and origins (Lin, 1995; Zhao, 2005), e.g., the development of *Li* tripods in Chifeng is believed to have integrated the Hongshan culture and the Erlitou culture (Liaoning Provincial Museum et al., 1983; Li and Gao, 1984).

In terms of the functions of *Li* tripods, the carbonized hulled broomcorn millet (*Panicum milliaceum*) found in a *Li* tripod unearthed at the Sifendi Dongshanzui sites in Chifeng suggests that they were likely used for cooking. However, this does not exclude the possibility that they were used as storage vessels. Therefore, more direct evidence is required to clarify the functions of these tripods. In this respect, plant microremains (including starch grains and phytoliths) can be analyzed to study the functions of pottery (Yang et al., 2014) and accurately identify crop types (Yang et al., 2006), as they are preserved for extensive periods (Torrence and Barton, 2006) and in large quantities (Wang and Lu, 1993). For instance, identifying the phytolith of foxtail millet (*Setaria italica*) and broomcorn millet has provided detailed information about the crop species used (Lu et al., 2009a). In addition, it is possible that starch grains and phytoliths produced by different plant organs remain within artifacts that were used to process husked seeds, roots, and tubers, even when residual phytoliths were lacking (Wu et al., 2011). In recent years, microscopic analyses conducted to identify residues on the surface of pottery and determine the morphology and species of plants used have provided direct evidence that can be used to understand the functions of such artifacts, the ingredients used, and how plant resources were utilized (Yang et al., 2014; Wang et al., 2017). Moreover, scholars have also studied the history of the human use of fire and have reconstructed ancient vegetation using the microfossil charcoal method (Patterson et al., 1987; Innes and Simmons, 2000; Li et al., 2010). Furthermore, the surface of most cooking utensils has traces of soot left from burning. As a charcoal residue produced by incomplete combustion of plant tissue, soot provides a reference or indication of the cooking function of *Li* tripods.

To broaden our knowledge of the subsistence strategies and social landscape of people in the early Bronze Age, starch grain, phytolith and microfossil charcoal residues were extracted from the surfaces of *Li* tripods of the Lower Xiajiadian cultural period unearthed in Chifeng, Northeast China. These residues were then analyzed with the intention of better understanding the functions of *Li* tripods and how the ancient people of Lower Xiajiadian culture used edible plant resources.

MATERIALS AND METHODS

Sample Collection

To analyze plant microremains, samples were collected from the feet of 10 *Li* tripods (**Figure 1A**) that had been previously unearthed from six sites in Chifeng, Northeast China: Mount Aobao Beiliang, Hadagou Nanliang, Fangshen Xiliang, Tuanjie Yingzi Mount Tuzi, Dujiadi, and Gaojia Wazi. The 10 samples were similar in shape, and residues and soot on the surface were visible to the naked eye (**Figure 1B**). All samples were from the Lower Xiajiadian cultural period, and they have been preserved at the Wengniute Museum.

The extraction of residues on the pottery surfaces was undertaken according to the protocols of Yang et al. (2014) and Liu et al. (2014). Twenty samples were analyzed. As the selected samples had been preserved at the Wengniute Museum, the surface was cleaned prior to sampling, that is, both the interior and exterior were rinsed with ultrapure water. To dislodge adhering sediment and starch, the interior surface and exterior surface of each tripod foot were separately shaken in an ultrasonic bath for 10 min, and liquid samples were obtained. To prevent cross-contaminating the samples during sampling process and the experiment, all knives, pipettes, centrifuge tubes, and powder-free gloves used were disposable and none contained starch.

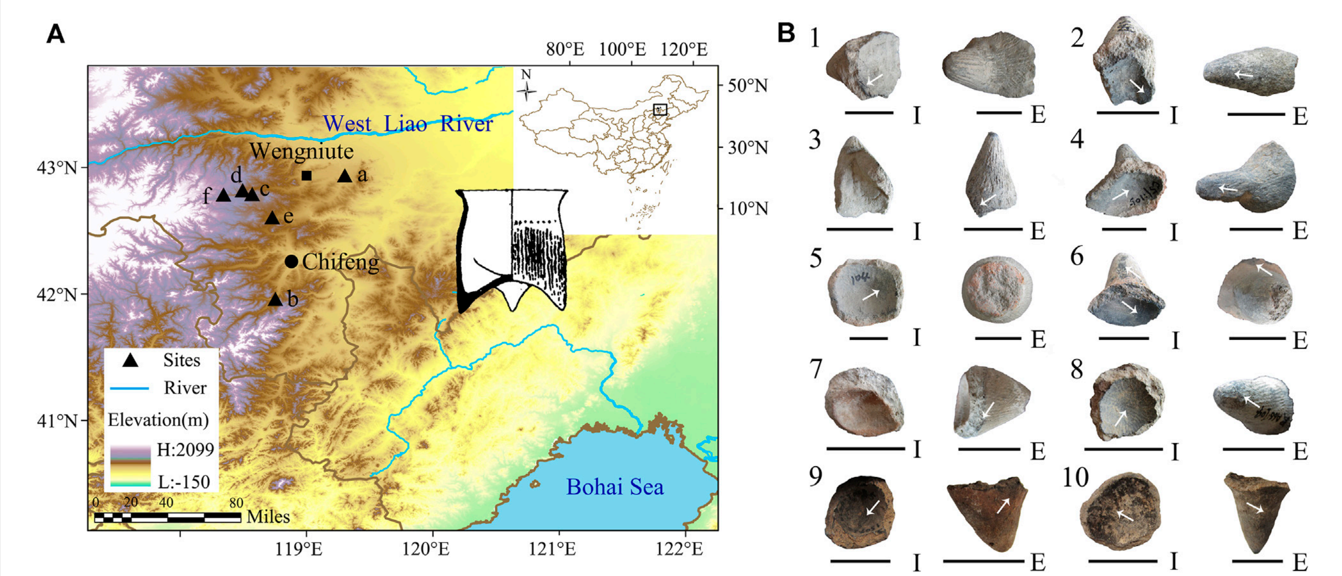

FIGURE 1 | Site locations from which artifacts were obtained and the samples subsequently analyzed. **(A)** Location of study region and archaeological sites: (a), Mount Aobao Beiliang site; (b), Hadagou Nanliang site; (c), Fangshen Xiliang site; (d), Tuanjie Yingzi Mount Tuzi site; (e), Dujiadi site; (f), Gaojia Wazi site. The sketch is of a basin-shaped *Li* Tripod, which is typical of an *Li* Tripod from the Lower Xiajiadian cultural period (Lin, 1995). **(B)** Tripod foot samples from the Lower Xiajiadian cultural period unearthed from Chifeng, Northeast China at the following sites: (1, 2), Mount Aobao Beiliang site; (3, 4), Hadagou Nanliang site; (5, 6), Fangshen Xiliang site; (7, 8), Tuanjie Yingzi Mount Tuzi site; (9) Dujiadi site, Specimen no. 150426-0230; (10) Gaojia Wazi site, Specimen no. 15046-0231. (I indicates the interior surface of *Li* tripods, E indicates the exterior surface of *Li* tripods, and the arrow indicates the sampling location of the residues. Scale bar: 5 cm).

In addition, although previous researchers have taken many images of starch grains from plants commonly used by ancient people, only a few studies have focused on starch grains damaged during processing. Therefore, we collected modern specimens of common Chinese crops (foxtail millet, broomcorn millet, and common wheat), Leguminosae, Liliaceae, and Fagaceae, and conducted processing simulation experiments. These samples were obtained *via* field acquisition and market purchase.

Starch and Phytolith Extraction

The plant microremains in the residues on the surfaces of tripod foot samples were extracted following steps previously reported (Lu et al., 2009b; Yang et al., 2012a; Yang et al., 2012b). Briefly, 6% H_2O_2 was added to the liquid samples of surface residue to break down some of the larger charred particles *via* oxidation and to release any starch grains potentially trapped within the particles or adhering to them. HCl (10%) was then added to remove calcium impurities. Then, the heavy liquid part of 1.8 g/cm^3 CsCl was added, mixed carefully, and centrifuged for 5 min at 2,500 rpm in order to extract the starch grains. The supernatant containing starch granules was then decanted into a fresh tube. Phytoliths were extracted from sediments remaining following starch grain extraction. For the second float, 2.35 g/cm^3 $ZnBr_2$ heavy liquid was added, mixed thoroughly, and centrifuged, and the supernatant containing the phytoliths was decanted into a fresh tube. Starch granule slides were prepared by mounting the recovered residue onto a slide in a solution of 25% glycerin and 75% ultrapure water. The slide was then sealed with neutral gum. Phytolith slides were prepared by mounting the recovered residue in neutral resin and then fixing it with a cover glass.

Analysis of Microfossil Charcoal

We detected microfossil charcoal together with the phytoliths and starch grains in the residue on the surface of the *Li* tripod feet. Next, we counted the total number of microfossil charcoal grains contained in the slides of the starch grains and phytoliths. Subsequently, following the conventions of microfossil charcoal analysis (Wang Z. S. et al., 2020), we randomly extracted 50 grains for each sample. Then we measured the length and width of the microfossil charcoal particles to calculate the length to width ratio (hereinafter referred to as the L/M ratio) for the identification of plant species. Ideally, 50 random grains were measured for the interior and exterior surfaces of each tripod foot sample, starting from the first grain identified. However, if less than 50 grains were identified, all of the grains were measured. Ultimately, we obtained a total of 772 sets of measurement data to determine the L/M ratio range and average L/M ratio for statistical analysis.

Grinding and Cooking Simulation Experiments

The seeds of modern foxtail millet, broomcorn millet, common wheat (*Triticum aestivum*), and lily (*Lilium Brownii*) bulbs were selected as samples. They were cleaned and dried after we confirmed that no traces of other species were present. To observe the influence of grinding on starch grains, 0.5 g of

TABLE 1 | Data of starch grains obtained from the surface residues of *Li* tripods of the Lower Xiajiadian cultural period unearthed from the Chifeng area, Northeast China (*n*).

Sample no		Location	Type I		Type II		Type III	Type IV	Total
			Intact	Damaged	Intact	Damaged			
Mount Aobao Beiliang Site	1	I	1	3	0	4	1	0	9
		E	0	0	0	0	0	0	0
	2	I	2	0	0	0	0	30	32
		E	0	0	0	0	0	0	0
Hadagou Nanliang site	3	I	2	3	0	0	0	20	25
		E	1	0	0	0	0	0	1
	4	I	1	0	0	1	0	6	8
		E	0	0	0	0	0	0	0
Fangshen Xiliang site	5	I	2	0	0	0	0	8	10
		E	0	0	0	0	0	0	0
	6	I	1	6	0	1	0	5	13
		E	0	0	0	0	0	1	1
Tuanjie Yingzi Mount Tuzi Site	7	I	0	0	0	1	0	0	1
		E	0	0	0	0	0	0	0
	8	I	1	2	0	4	0	0	7
		E	0	0	0	1	0	0	1
Dujiadi Site	9	I	2	0	0	1	0	0	3
		E	0	0	0	0	0	0	0
Gaojia Wazi Site	10	I	5	11	2	2	1	1	22
		E	0	0	0	0	0	0	0
Total		—	18	25	2	15	2	71	133
		—	43		17		—	—	—

(I indicates the interior surface of Li *tripods, E indicates the exterior surface of* Li *tripods).*

each sample was placed into a mortar and ground for 2–5 min, thus obtaining four samples for the grinding simulation experiment. The ground samples were then added to a centrifuge tube with 5 ml of ultrapure water and placed in a low-temperature environment for 1 h. To observe the effect of cooking on the starch grains, 0.5 g of each sample was added to a centrifuge tube with 5 ml of ultrapure water for 5–30 min of cooking in a water bath. The timer was started when the water began to boil, and with intervals of 5 min, 24 samples (six groups) were obtained for the cooking simulation experiment. The appropriate amount of starch suspension generated during the grinding and cooking simulation experiment was extracted with a disposable pipette, and a few drops of it were then added to a glass slide before 25% glycerin was added, and the slide was then sealed with neutral gum.

The prepared slides of starch grains and phytoliths were dried at ≤40°C for 48 h. The samples were then observed, identified, photographed, and counted using a Leica DM 750 microscope at ×400 magnification. The analyses were completed at the Environmental Archaeology Laboratory of Northwest University. The identification and classification of starch grains were mainly conducted by referring to the accumulated modern starch grain database of the laboratory and relevant study results (Yang et al., 2010; Wan et al., 2012; Yang andPerry, 2013; Ma et al., 2014). To identify and describe phytoliths and microfossil charcoal, they were compared with published pictures and materials (Wang and Lu, 1993; Lu and Liu, 2003; Piperno, 2006; Zhang and Lu, 2006; Lu et al., 2009a). All starch grains, phytoliths and microfossil charcoal on glass slides were evaluated and C2 v1.7.3 (Juggins, 2003) software was used to process data and obtain the percentage contents of phytoliths.

RESULTS

Starch Grains From Residues on the Surfaces of *Li* Tripod Foot Samples

Starch grains were identified from the interior surfaces of all 10 tripod foot samples. Starch grains were identified in only three samples from the exterior surfaces of the tripod feet. A total of 133 starch grains were extracted from the residues found on the interior and exterior surfaces of the tripod feet. Of these, 71 starch grains were seriously damaged and identification was not possible, these were classified as Type IV. The remaining identifiable 62 starch grains were classified into Types I–III based on their shapes and grain sizes. Of the 62 identifiable starch grains, 40 showed slight damage (**Table 1**). There were 111 damaged starch grains in total, accounting for 83.46% of all extracted starch grains. The definitions of grain types and associated findings are as follows.

Type I starch grains (n = 43) were polyhedron-shaped with centric hila and linear, transverse, star, or Y-shaped fissures

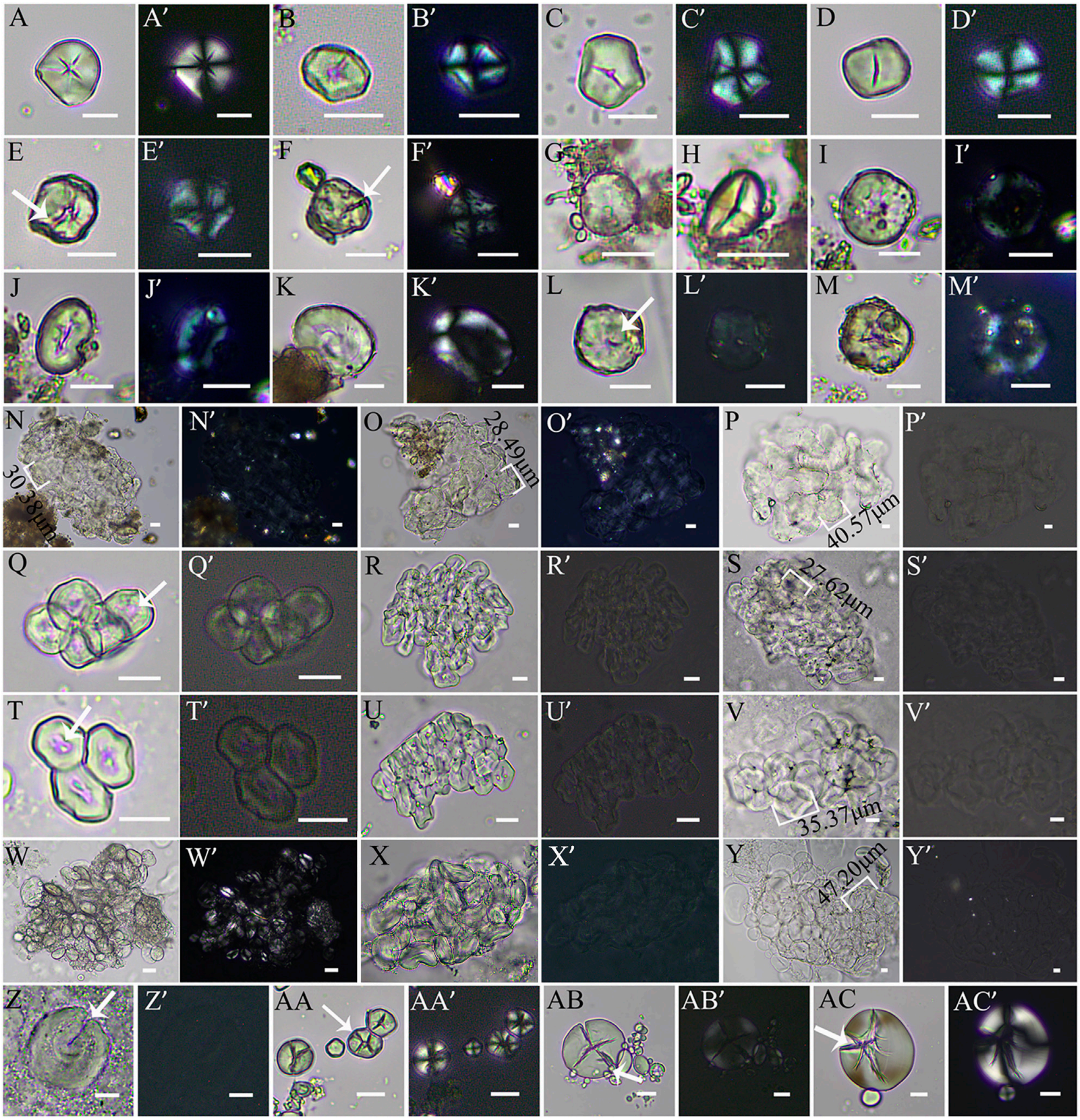

FIGURE 2 | Starch grains extracted from the surface residues of *Li* tripods of the Lower Xiajiadian cultural period unearthed from Chifeng, Northeast China, and starch grain specimens from simulation experiment. **(A–D′)** Type I intact starch grains and **(E–F′)** Type I damaged starch grains. **(G)** Polar view of type II starch grains, **(H)** lateral view of type II starch grains, and **(I–J′)** Type II damaged starch grains. **(K,K′)** Type III starch grains. **(L–O′)** Type IV starch grains. **(P,P′)** Thermally damaged lily starch grains after 5 min of heating. **(Q–S′)** Modern foxtail millet starch damaged by heating: **(Q,Q′)** heated for 5 min, **(R,R′)** heated for 15 min, and **(S, S′)** heated for 30 min **(T–V′)** Modern broomcorn millet starch damaged by heating: **(T,T′)** heated for 5 min, **(U,U′)** heated for 15 min, and **(V,V′)** heated for 30 min **(W–Y′)** Common wheat starch damaged by heating: **(W,W′)** heated for 5 min, **(X,X′)** heated for 15 min, and **(Y–Z′)** heated for 30 min **(AB,AB′)** Common wheat starch damaged by grinding; **(AA,AA′)** modern foxtail millet starch damaged by grinding; and **(AC,AC′)** lily starch damaged by grinding. **(A,A′–F, F′; I,I′–AC,AC′)** Each group of photos was taken separately under bright field (left) and cross-polarized light (right). (Arrows indicate the damage characteristics of starch grains, Scale bar: 10 μm)

through the hila of most grains. Extinction crosses were mostly "+"-shaped with straight arms (**Figures 2A–D′**). The maximum lengths ranged from 9.8 to 20.1 μm, with a mean length of 14.8 ± 2.7 μm. The extinction crosses of 25 starch grains were unclear in polarized light (**Figures 2E–F′**) and there were cracks on the surfaces of four grains (**Figures 2E,F**). According to the identification criteria established by Yang et al. (2010), which are based on data analysis of starch grain shapes of Chinese northern modern foxtail and broomcorn millets, and other close wild species, Type I grains were considered to belong to millet, because the surfaces were smooth and the grain sizes were larger than average. The results thus suggest that the starch grains were most likely from foxtail and broomcorn millet crops.

Type II starch grains (n = 17) were characterized by biconvex shapes and a centric hilum. The starch grains were olivary and possessed a longitudinal dent when rotated (**Figures 2G,H**). The extinction crosses of two starch grains were X-shaped in polarized light, and those of the remaining 15 starch grains partially disappeared in polarized light (**Figures 2I–J′**). The grain lengths ranged from 12.9—35.9 μm with a mean of 23.1 ± 4.6 μm. According to the identification criteria established by Piperno et al. (2004) and Yang and Perry (2013) based on the study of such starch grains, it was determined that Type II starch grains were from the tribe Triticeae.

Type III starch grains (n = 2) were oval with an extremely eccentric hilum. There were no cracks, and the arms of extinction crosses were slightly bent (**Figures 2K,K′**).The grain lengths were 19.53 and 30.31 μm, respectively. In modern specimen banks, the grain sizes of roots and tubers are relatively large, and the hilum is skewed to one end (Wan et al., 2011). Therefore, it was determined that Type III starch grains originated from roots and tubers.

Finally, the extinction characteristics of Type IV starch grains (n = 71) were not visible. The surfaces of most were unclear, in an aggregated state, overlaid, and lacked an independent outline (**Figures 2N–O′**). The central parts of some of the starch grains were sunken or hollow, but the basic outline was identifiable (**Figures 2L–M′**). They were classified as Type IV because the species could not be identified.

Starch Grains Obtained From Grinding and Cooking Simulation Experiments

The results of the grinding simulation experiments of modern foxtail and broomcorn millet, common wheat, and lily starch grains are consistent with that of our previous study (Ma et al., 2019). The observational and statistical results identify the following. 1) Grinding caused physical and mechanical damage to some starch grains, resulting in morphological alterations. The main manifestations were that the relatively smooth surface of the starch grains became coarse, the edges became cracked and broken, and/or the central areas on the extinction crosses became dark (**Figures 2AA–AC′**). 2) The grinding strength was positively correlated with the content of the damaged starch grains. 3) After grinding, the extinction crosses of the starch grains were distorted, but the position of the hilum remained unchanged.

The results of starch grains from the cooking simulation experiments are consistent with that of previous studies (Ge et al., 2010; Hong et al., 2013; Lu et al., 2014; Chen et al., 2021). The crystal structure of the starch grains was thermally damaged and their central parts became sunken. The starch molecules gradually became transparent as they expanded and became deformed. As the heating duration increased, the number of small visible grains declined and the number of large grains increased. The average size of the foxtail millet starch grains increased to 15.18, 20.57, and 27.85 μm after being heated for 5, 15, and 30 min, respectively (**Figures 2Q–S′**). This indicates that the grain size of foxtail millet doubled throughout the cooking procedure and became similar to that of broomcorn millet (**Figures 2T–V′**). The starch grain size of common wheat increased to 21.14 and 41.20 μm after being heated for 5 and 30 min, respectively (**Figures 2W–Y′**). The starch grain size of lily increased to 40.88 μm after being heated for 5 min, which is close to its size after being heated for 30 min (48.87 μm; **Figures 2P,P′**).

There was a positive correlation between heating duration, moisture content, and gelatinization of the starch grains. Observations of the seed samples showed that the starch grains became transparent and the extinction crosses were unclear after heating for 5 min (**Figures 2Q,Q′,T,T′,W,W′**). After heating for 15 min, the starch grains were in an aggregated state with increased transparency, and although the extinction crosses had completely disappeared, their basic outlines were maintained (**Figures 2R,R′,U,U′,X,X′**). After heating for 30 min, the independent outline was lost, the starch grains were almost completely transparent, and the extinction characteristics disappeared (**Figures 2S,S′,V,V′,Y,Y′**). Lily starch granules were seriously damaged and their identification characteristics were lost after being heated for 5 min (**Figures 2P,P′**). Finally, grinding damage and cracks were observed in some of the starch grains (**Figures 2Z,Z′**).

Results of Phytolith Analysis

A total of 3,424 phytoliths were extracted from the study samples, of which 107 were damaged and could not be identified. **Figure 3** shows the main phytolith shapes, which include 17 types. There were 692 pointed phytoliths, and they had the highest total phytolith content of 20.21% (**Figure 3O**), followed by smooth elongates (15.13%; **Figure 3M**), sinuate elongates (12.44%; **Figure 3N**), bilobates (11.33%; **Figure 3I**), rondel-shaped phytoliths (10.86%; **Figure 3G**), square phytoliths (8.82%; **Figure 3P**), epidermal cells (3.45%; **Figures 3S,T**), trapezoid phytoliths (1.31%; **Figure 3H**), fan-shaped phytoliths (0.50%; **Figure 3Q**), cross-shaped phytoliths (0.18%; **Figure 3L**), cylindrical polylobate phytoliths (0.09%; **Figure 3K**), silicified stomata (0.09%; **Figure 3R**), and dumbbell-shaped phytoliths arranged vertically (0.06%; **Figure 3J**). In addition, η-type phytoliths from the husks of broomcorn millet (5.46%; **Figures 3B**), *O*-type phytoliths from the husks of foxtail millet (0.73%; **Figure 3A**), and phytoliths from the husks of the family Poaceae (6.22%; **Figures 3C–F**) were extracted from the study samples.

(I indicates the interior surface of *Li* tripods, E indicates the exterior surface of *Li* tripods).

Results of Microfossil Charcoal Analysis

Microfossil charcoal grains were identified on both the interior and exterior surfaces of the 10 *Li* tripod foot samples, and a total of 2,835 grains were detected (**Table 2**).

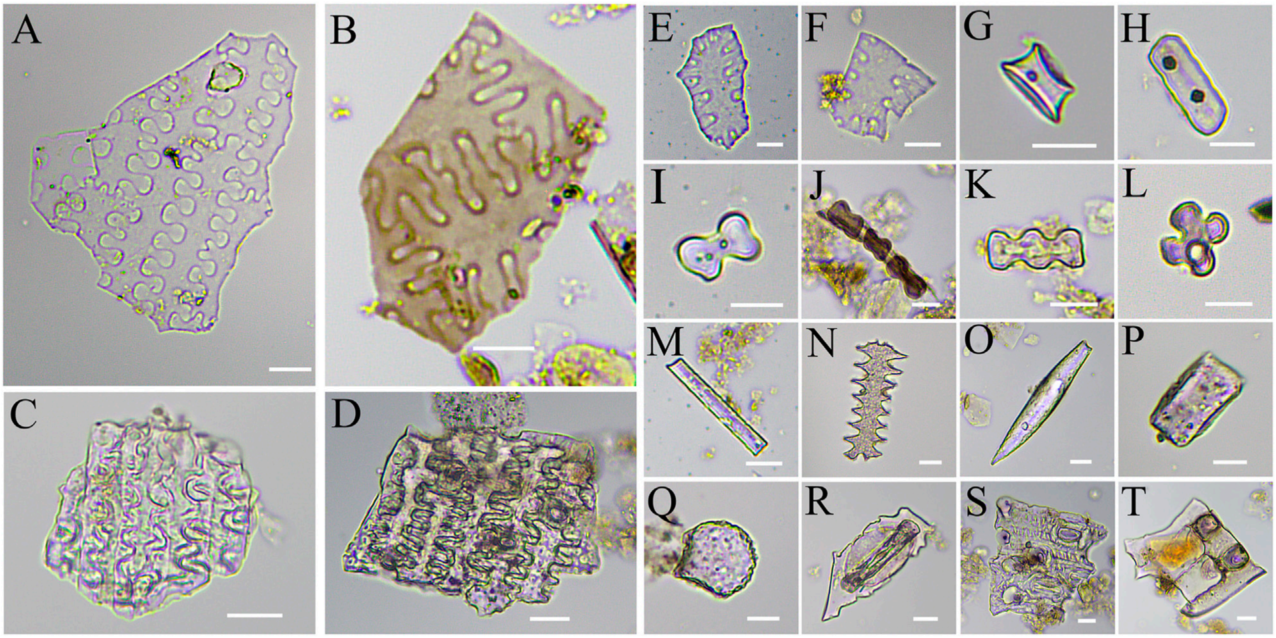

FIGURE 3 | Phytoliths extracted from the surface residues of *Li* tripods from the Lower Xiajiadian cultural period unearthed in Chifeng, Northeast China. **(A)** Ω type phytoliths extracted from the husks of foxtail millet, **(B)** η type phytoliths extracted from husks of broomcorn mille. **(C–F)** Grain shells of the family Poaceae: **(C)** Phytoliths that are most likely from the husks of Pooideae; **(D–F)** Phytoliths that are most likely from the husks of Panicoideae. **(G)** Rondel, **(H)** Trapezoid, **(I)** Bilobate, **(J)** Dumbbell-shaped phytolith arranged vertically, **(K)** Cylindrical polylobate, **(L)** Cross, **(M)** Smooth-elongate, **(N)** Sinuate-elongate, **(O)** Pointed, **(P)** Square, **(Q)** Fan, **(R)** Silicified stomata, and **(S,T)** Epidermal cells. (Scale bar: 10 μm).

TABLE 2 | Quantitative statistics and measurement data of microfossil charcoal.

Sample no		Location	Number of microfossil charcoal grains	Number of measurements	Range of L/W ratio	Average L/W ratio
Mount Aobao Beiliang Site	1	I	5	5	1.10–2.00	1.55
		E	52	50	1.07–5.79	1.78
	2	I	58	50	1.00–5.26	1.87
		E	251	50	1.00–3.48	1.73
Hadagou Nanliang site	3	I	52	50	1.01–3.97	1.98
		E	217	50	1.00–4.75	1.95
	4	I	58	50	1.04–5.33	1.95
		E	78	50	1.01–3.81	1.77
Fangshen Xiliang site	5	I	9	9	1.34–3.14	2.03
		E	110	50	1.01–4.54	1.84
	6	I	928	50	1.09–3.87	1.86
		E	30	30	1.00–5.17	1.95
Tuanjie Yingzi Mount Tuzi Site	7	I	13	13	1.15–3.02	1.91
		E	114	50	1.07–4.66	2.00
	8	I	12	12	1.00–5.57	2.35
		E	212	50	1.05–4.43	1.88
Dujiadi Site	9	I	232	50	1.01–3.69	1.91
		E	3	3	1.16–1.84	1.50
Gaojia Wazi Site	10	I	216	50	1.02–3.98	1.99
		E	185	50	1.00–4.96	1.90
Total		—	2835	772	1.00–5.79	1.89

(I indicates the interior surface of Li *tripods, E indicates the exterior surface of* Li *tripods, L/M ratio indicates the ratio of length to width of microfossil charcoal).*

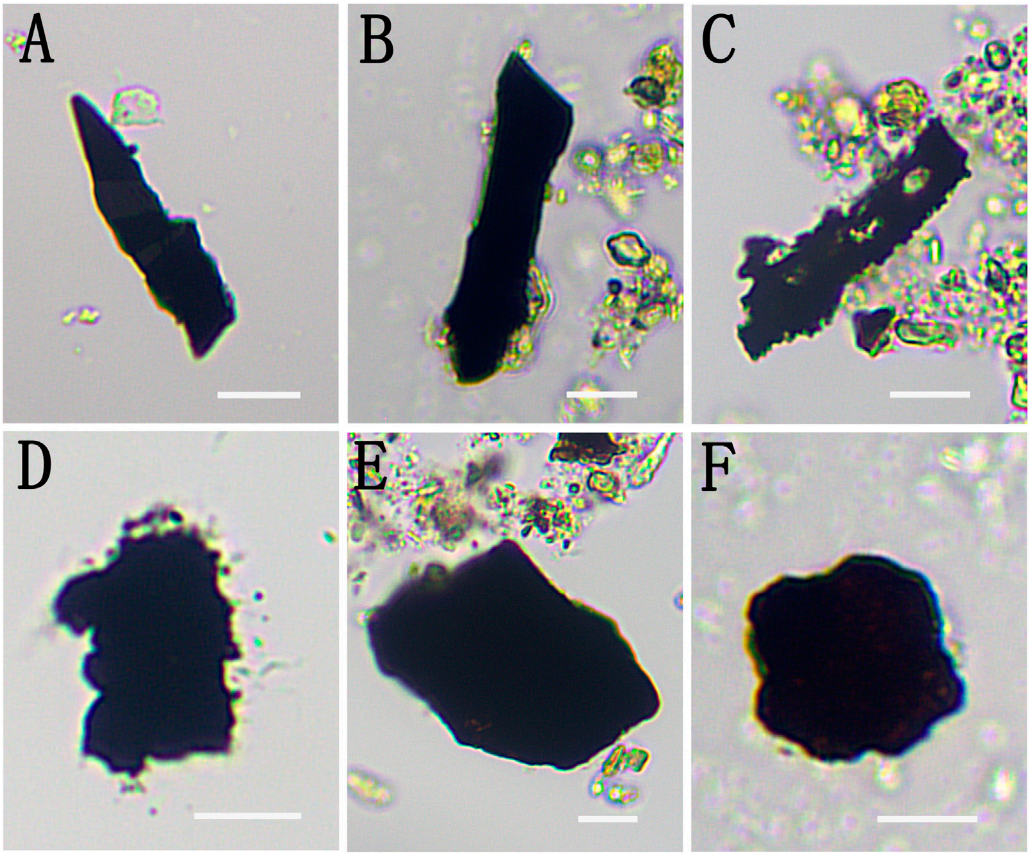

FIGURE 4 | Morphology of microfossil charcoal. **(A–C)** Possible microfossil charcoal from grasses, **(D–F)** Possible charcoal from woody plants. (Scale bar: 10 μm).

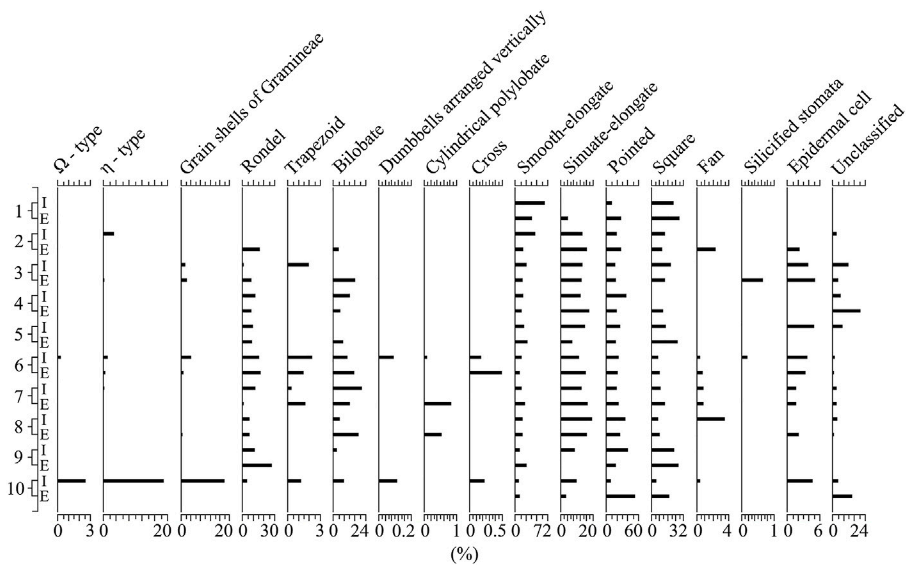

FIGURE 5 | Changes in percentages of phytolith types extracted from the surface residues of *Li* tripods from the Lower Xiajiadian cultural period unearthed in Chifeng, Northeast China.

Microfossil charcoal analysis revealed three main microfossil charcoal shapes: the strip shape, square shape, and approximately circular shape (**Figure 4**. The longitudinal edge and transverse fracture of the strip-shaped charcoal fossils were relatively straight, with many pore structures (**Figures 4A–C**). The square and approximately circular shaped charcoal fossils were relatively dense, with few pores, and the edges were irregular (**Figures 4D–F**). The length of the microfossil charcoal ranged from 5.49 to 148.59 μm, with an average length of 22.26 μm. The L/M ratio ranged from 1 to 5.79 μm, with an average of 1.89 μm (**Table 2**).

According to criteria for the identification of plant species, based on morphological characteristics and the L/M ratio proposed by Zhang and Lu (2006), strip-shaped microfossil charcoal may originate from grasses, while square-shaped or approximately circular specimens may derive from woody plants. After oscillation and centrifugation in the laboratory, the average L/M ratios of microfossil charcoal for grasses and woody plants were 3.90 ± 0.1 μm and 1.8 ± 0.1 μm, respectively. For the microfossil charcoal residue on the surface of the tripod feet, the average L/M ratio was similar to that of microfossil charcoal from woody plants. In the 772 sets of measured data, only 16 microfossil charcoal grains had a length-width ratio greater than 3.90 μm, which accounted for 2.07% of the total measured grains.

DISCUSSION

The tripod foot samples had been preserved in a museum, and the chance of contamination from deposits in the surrounding environment would have been equal for all the tripod surfaces. We therefore extracted samples from both the interior and exterior surfaces of each tripod foot and compared the quantities and assemblages of starch grains and phytoliths separately to determine the possibility of contamination from surrounding deposits. **Table 1** and **Figure 5** show the absolute quantity and appearance frequency of starch grains (n = 130; 100%) and phytoliths (n = 2,388; 100%) that were extracted from the interior surfaces of *Li* tripod foot samples. It is evident that the amounts are considerably greater than those collected from the exterior surfaces (only three starch grains and 1,036 phytoliths were collected). The discrepancies between the numbers thus suggests that most of the starch grains and phytoliths collected from the tripod feet were directly related to the use and behavior of people from the ancient culture.

Functions of *Li* Tripods

A total of 111 damaged starch grains were identified in the residues on the surfaces of the 10 tripod foot samples (**Table 1**). They accounted for 83.46% of the total grains, and they appeared on 80% of the interior surfaces. This result suggests that the starch grains were damaged during processing. To explore processing methods and obtain specimen images for comparison with ancient, damaged starch grains, we referred to previous research (Crowther, 2012; Ge et al., 2020; Chen et al., 2021). Ancient food processing methods are classified into two major types: dry cooking (e.g., roasting and baking) and wet cooking (e.g., boiling). Comparative studies indicate that when the dry cooking method was adopted, the extinction cross characteristic of starch granules may have been lost, but that the limited amount of water absorption involved may have restricted their morphological deformation (Bradbury and Holloway, 1988; Babot, 2003; Chandler-Ezell et al., 2006). In extreme circumstances, since no water is involved, starch granules can be heated to 200°C without any measurable change occurring (Wang et al., 1991; Jang and Pyun, 1996). The form of the starch grains found in the residues left on the interior surfaces of the tripod feet examined in our study is closer to that of the contemporary starch grain samples used in our cooking simulation experiment. These results indicate that the starch grains in the residues on the surfaces of the tripod feet were mainly subjected to thermal (boiling) damage (n = 111) and mechanical (grinding) damage (n = 4).

The degree and rate of starch gelatinization mainly depend on the moisture and temperature (Crowther, 2012). On one hand, when the starch moisture content falls below 60%, heating under normal pressure may fail to cause total gelatinization (Wang et al., 1991). Additionally, the water content of different plant storage organs varies considerably. For example, the water content in fresh roots and tubers (approximately 70–80%) is far higher than that of cereals (approximately 20–30%) (Hoover, 2001; Crowther, 2012). If cooked under the same conditions, the gelatinization speed of roots and tubers is considerably faster than that of cereals, so it is less likely that starch granules in roots and tubers survive and recover (Crowther, 2012). On the other hand, the temperature range from the start of gelatinization to its conclusion is usually 5–20°C. Thus, the extinction cross characteristic of starch granules that are not completely gelatinized within this interval may be retained (Lu et al., 2014). These findings indicate that even when the cooking mode is the same, the survival, recovery and recognition probability of starch granules from different plants or the same plant vary.

Starch grains with mild gelatinization (**Figures 2E–F′,I–J′**) were from foxtail millet, broomcorn millet, and the tribe Triticeae, but it was not possible to identify grains that underwent extreme gelatinization (**Figures 2L–O′**). The shapes and sizes of grains were compared with those from the surface of the tripod, and it was found that those from the tripod feet were closer to the those of the foxtail and broomcorn millets from the cooking simulation specimens (**Figures 2Q,Q′,S,S′,T,T′,V,V′**). In addition, a handful of starch grains were subjected to mechanical damage (**Figure 2Z**) during the cooking simulation experiments, even though grinding was not used, and the mechanical force applied was mainly that of stirring. It was thus inferred that the four damaged starch grains (**Figures 2E,F**) with cracks that were obtained from the residues on the surface of the tripod feet were likely subjected to stirring and squeezing during cooking, or they were from grains that broke during hulling. The identification of gelatinized starch grains in the residues on the surfaces of tripod feet further proves that at least one of the *Li* tripod functions was cooking plant-based food. It also demonstrates that the starch grains extracted from the experiments were mainly associated with processed cooked food rather than surrounding contamination.

According to previous research (Zhang, 2015) and relevant practical knowledge, if a *Li* tripod was used as a cooking vessel, there should be traces of incomplete burning of firewood on its surface as a result of cooking, such as common soot or charcoal residue. An analysis of the microfossil charcoal found on both the interior and exterior surfaces of 10 *Li* tripod foot samples identified different numbers of each. In seven of the samples, the grains detected on the exterior surfaces were far higher than on the interior surfaces (**Table 2**), indicating that the exterior surfaces had a higher frequency of contact with fire. As for the other three samples, the reasons why the microfossil charcoal grains on the interior surfaces were more numerous than on the exterior surfaces is not clear. However, microfossil charcoal remains were found on the interior surfaces of all the samples, and the corresponding species were likely to include woody plants and grasses. Possible reasons for this phenomenon are as follows. 1. Mostly, a *Li* tripod without cover was placed on the fire directly for boiling, and the charcoal grains produced by fuel during cooking were very likely to fall into the *Li* tripod by air. 2, Due to the limited tools available to ancient people for cleaning the tripods, charcoal grains on the outer surface of some *Li* tripods might have become attached to cleaning tools and thus transferred to the inner surface. The *Li* tripod foot was likely not easy to clean for space narrowness, and thus, the charcoal grains likely precipitated and became stuck. The analysis results of microfossil charcoal are consistent with the finding that many starch grains were damaged by boiling, as mentioned above. The residue of incompletely burnt charcoal on the surfaces of *Li* tripods provides further evidence of their cooking function. However, the identification of microfossil charcoal plant species in this study was limited to exploratory experiments, and thus more fundamental experimental studies are required.

In summary, we believe that the *Li* tripods from the Lower Xiajiadian cultural period unearthed in Chifeng were likely used for cooking foxtail and broomcorn millets as well as plants from the tribe Triticeae. Thus, the food processing methods used by this ancient culture at such sites are revealed. The plant microremains obtained support the use of *Li* tripods as an important food processing tool during the Lower Xiajiadian cultural period, and it appears likely that they were typically used as cooking utensils.

Plant Resources Revealed by Ancient Plant Microremains

The results suggest that *Li* tripods of the Lower Xiajiadian cultural period unearthed in Chifeng were used as cooking utensils. The plant microremains on their surfaces signify the food that people used in their recipes. Starch grains of foxtail millet, broomcorn millet, and the tribe Triticeae; roots, and tubers, and phytoliths from the grain husks of foxtail millet and broomcorn millet; and one piece of phytolith that was probably from the husks of Pooideae (**Figure 3C**) were identified in the surface residues of 10 tripod foot samples. The tribe Triticeae belongs to the Pooideae of the Poaceae subfamily. Furthermore, the phytoliths also included bilobate and cross-shaped phytoliths from the leaves of Panicoideae, trapezoid and rondel-shaped phytoliths from Pooideae leaves, and elongate phytoliths and fan-shaped phytoliths from the family Poaceae (Ge, 2016). Therefore, the analytical results of the starch grains and phytoliths are relatively consistent.

The phytoliths from the husks of foxtail and broomcorn millets and those from the husks of Pooideae were mainly extracted from the interior surfaces of the *Li* tripods; hence, these crop husks (6.07% of the total) and the phytoliths of the stems and leaves of the Poaceae are quite likely to represent the limited grain processing techniques of the period. The stems, leaves, and husks of foxtail and broomcorn millets and other grains required separation prior to grinding and cooking (Wang Q. et al., 2020). A previous study simulated the processing methods in prehistoric society using modern grain processing tools. The results indicate that using mortars, pestles, slabs, and mullers as dehusking and grinding tools could not fully hull the grains: the highest dehusking rates achieved in the experiments were 99 and 97.9%. Meanwhile, the husked grains were not 100% intact (Wang et al., 2013). In addition, the apparent soot on the outer surface of the tripod feet analyzed likely contained phytoliths that remained following the process of burning plants. The ancients usually used seeds as food and straw as firewood (Wang and Chai, 2010), hence the influence of the residual phytoliths of foxtail and common millet after burning during the heating process cannot be completely ruled out.

The edible plant resources of the ancient people in the Lower Xiajiadian cultural period included foxtail and broomcorn millets, plants from the tribe Triticeae, roots, and tubers. With respect to their absolute quantities and appearance frequencies, the starch grains and phytoliths from the husks of crops extracted from the residues on the interior surfaces of the tripod feet were mainly millets (starch grains: $n = 42$; 90%, and phytoliths: $n = 208$; 40%). There were comparatively fewer starch grains from the tribe Triticeae ($n = 16$; 70%) and from roots and tubers ($n = 2$; 20%). These results are consistent with those of previous research that suggest that the dry farming structure during the Lower Xiajiadian cultural period was dominated by foxtail and broomcorn millets (Sun et al., 2014; Jia et al., 2016a; Jia et al., 2016b; Ma et al., 2016; Jia et al., 2017b; Jia et al., 2021).

Starch granules from the tribe Triticeae appeared relatively frequently in the residues from the surfaces of the tripod feet. Triticeae has approximately 20 genera and 330 species globally, of which 13 genera and 175 species are found in China, and they are mainly distributed in northern China throughout diverse ecological environments (Liu Y. P. et al., 2013). In addition, Triticeae has been found in many Neolithic Age sites in Northeast China (Ma, 2014; Wu et al., 2018), which indicates that it was universally bred, cultured, and utilized by the ancient people of this region. Furthermore, recent research shows that Triticeae is closely related to human life and plays an important role in wheat crops and fodder (Culman et al., 2013; Pugliese et al., 2019).

A handful of starch grains from roots and tubers were also identified, which indicates that roots and tubers were also utilized in Chifeng during the Lower Xiajiadian cultural period. Roots and tubers are rich in starch and are abundant in the wild. Furthermore, compared with gramineous plants, they have more edible parts. As such, they have been an important edible plant resource since the late Paleolithic period (Liu L. et al., 2013; Yang et al., 2014). It is evident that the selection of multiple plant resources provided choice for these people, which further reduced risks associated with food scarcity from single crop failures.

CONCLUSION

We analyzed starch grains, phytoliths, and microfossil charcoal from residues found on the surfaces of 10 *Li* Tripods from the Lower Xiajiadian cultural period, which were previously unearthed from six sites in Chifeng, Northeast China. In combination with the identification of gelatinized starch grains, the soot traces on *Li* tripod surfaces, and the evidence indicating that 70% of the exterior surface samples had a higher frequency of contact with fire, our results provide further evidence that the *Li* tripods were used for cooking foxtail and broomcorn millets and plants from the tribe Triticeae. In addition, the starch grain and phytolith analyses results suggest that the edible plant resources of the ancient people of Chifeng during the Lower Xiajiadian cultural period included foxtail and broomcorn millets, plants from the tribe Triticeae, roots and tubers. Of these, foxtail and broomcorn millets were dominant. This study provides physical evidence of the functions of *Li* Tripods from the Lower Xiajiadian cultural period, as well as direct evidence of the plant resource exploitation strategies and agricultural patterns of the ancient people of this era, which in turn further promotes knowledge about their subsistence patterns and the social context of early Bronze-Age civilization.

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 authors.

AUTHOR CONTRIBUTIONS

ZM and SL designed the study and wrote the manuscript. SL collected the samples and conducted the experiments. SL and ZM analyzed the data. XJ, YS, and ZM contributed to the discussion and approved the final manuscript.

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REFERENCES

Babot, M. d. P. (2003). "Starch Grain Damage as an Indicator of Food Processing," in *Phytolith and Starch Research in the Australian-Pacific-Asian Regions: The State of the Art*. Editors D. M. Hart and L. A. Wallis (Canberra: Pandanus Press), 69–81.

Bradbury, J. H., and Holloway, W. D. (1988). *Chemistry of Tropical Root Crops: Significance for Nutrition and Agriculture in the Pacific*. Canberra: Australasian Centre for International Agricultural Research, 39–133.

Chandler-Ezell, K., Pearsall, D. M., and Zeidler, J. A. (2006). Root and Tuber Phytoliths and Starch Grains Document Manioc(Manihot Esculenta), Arrowroot(Maranta Arundinacea), andLlerén (Calatheasp.)at the Real Alto Site, Ecuador. *Econ. Bot.* 60 (2), 103–120. doi:10.1663/0013-0001(2006)60[103:ratpas]2.0.co;2

Chen, T., Hou, L., Jiang, H., Wu, Y., and Henry, A. G. (2021). Starch Grains from Human Teeth Reveal the Plant Consumption of Proto-Shang People (C. 2000-1600 BC) from Nancheng Site, Hebei, China. *Archaeol Anthropol. Sci.* 13, 153. doi:10.1007/s12520-021-01416-y

Crowther, A. (2012). The Differential Survival of Native Starch during Cooking and Implications for Archaeological Analyses: a Review. *Archaeol Anthropol. Sci.* 4 (3), 221–235. doi:10.1007/s12520-012-0097-0

Culman, S. W., Snapp, S. S., Ollenburger, M., Basso, B., and DeHaan, L. R. (2013). Soil and Water Quality Rapidly Responds to the Perennial Grain Kernza Wheatgrass. *Agron.j.* 105 (3), 735–744. doi:10.2134/agronj2012.0273

Gao, T. L. (1996). A Study of the Pottery *Li* Tripod of the Longshan Period in the Yellow River valley. *Acta Archaeol. Sin* 4, 399–442. in Chinese.

Ge, W., Liu, L., Chen, X. C., and Jin, Z. Y. (2010). An Experimental Study on Starch Grain Damage during Food Processing and the Application in Archaeology. *Archaelogy* 7, 77–86. in Chinese.

Ge, W., Liu, L., Zhao, C. C., and Jin, Z. Y. (2020). Analysis of Starch Grain Residues in Utensils Unearthed from Xishan Site. *Archaeol Cult. Relics* 4, 111–119. in Chinese.

Ge, Y. (2016). Phytoliths in Common Modern Plants of China: Morphology and Implication. [Ph.D. Dissertation]. [Beijing]: The university of Chinese Academy of Sciences (In Chinese).

Han, M. L. (2010). A Study on Settlements and Environment of Prehistoric Times in the West Liaohe River valley. *Acta Archaeol. Sin* 1, 1–20. in Chinese.

Hong, J., Zheng, X. L., and Liu, C. (2013). Study on Particle and Gel Properties of Total, A-type, B-type Starch with Different thermal Damage Degrees. *Cereals & Oils* 26 (8), 8–12. in Chinese.

Hoover, R. (2001). Composition, Molecular Structure, and Physicochemical Properties of Tuber and Root Starches: a Review. *Carbohydr. Polym.* 45 (3), 253–267. doi:10.1016/S0144-8617(00)00260-5

Innes, J. B., and Simmons, I. G. (2000). Mid-Holocene Charcoal Stratigraphy, Fire History and Palaoecology at North Gill, North York Moors, UK. *Palaeogeo Palaeocl* 164 (1-4), 151–165. doi:10.1016/S0031-0182(00)00184-X

Jang, J. K., and Pyun, Y. R. (1996). Effect of Moisture Content on the Melting of Wheat Starch. *Starch/Stärke* 48 (2), 48–51. doi:10.1002/star.19960480204

Jia, X., Lee, H. F., Zhang, W., Wang, L., Sun, Y., Zhao, Z., et al. (2016b). Human-environment Interactions within the West Liao River Basin in Northeastern China during the Holocene Optimum. *Quat. Int.* 426, 10–17. doi:10.1016/j.quaint.2016.01.011

Jia, X., Sun, Y. G., Yang, J. G., and Zhao, Z. J. (2017b). Floating Selection Carbonized Plants Result and Analysis of the Upper Xiajiadian Cultural Period of West Liao River Region, Northeast China. *Agric. Archaeol* 6, 33–39. in Chinese.

Jia, X., Sun, Y., Wang, L., Sun, W., Zhao, Z., Lee, H. F., et al. (2016a). The Transition of Human Subsistence Strategies in Relation to Climate Change during the Bronze Age in the West Liao River Basin, Northeast China. *The Holocene* 26 (5), 781–789. doi:10.1177/0959683615618262

Jia, X., Wang, S., Sun, Y., Li, Y., Jiao, Y., Zhao, Z., et al. (2021). Charcoal Evidence for Environmental Change Ca. 3.5 Ka and its Influence on Ancient People in the West Liao River Basin of Northeastern China. *Quat. Res.* 102, 1–11. doi:10.1017/qua.2020.120

Jia, X., Yi, S., Sun, Y., Wu, S., Lee, H. F., Wang, L., et al. (2017a). Spatial and Temporal Variations in Prehistoric Human Settlement and Their Influencing Factors on the South Bank of the Xar Moron River, Northeastern China. *Front. Earth Sci.* 11 (1), 137–147. doi:10.1007/s11707-016-0572-5

Juggins, S. (2003). C2 User Guide: Software for Ecological and Palaeoecological Data Analysis and Visualisation. *Newcastle upon Tyne, UK*. Newcastle: University of Newcastle, 7–72.

Li, B. Q. (1990). *Peking University*. Beijing: Cultural Relics Press, 56–79. in Chinese."A Study of the Lower Xiajiadian Culture," in *Collected Works for the Thirtieth Anniversaryof the Archaeology Speciality of Peking University (1952-1982)*, Compiled by the Department of Archaeology

Li, G. D., and Gao, M. X. (1984). A Study on Several Issues Concerning the Lower Xiajiadian Culture. *J. Liaoning Univ. (Philosophy Soc. Sci. Edition)* 5, 50–56. in Chinese.

Li, Y., Wu, J., Hou, S., Shi, C., Mo, D., Liu, B., et al. (2010). Palaeoecological Records of Environmental Change and Cultural Development from the Liangzhu and Qujialing Archaeological Sites in the Middle and Lower Reaches of the Yangtze River. *Quat. Int.* 227 (1), 29–37. doi:10.1016/j.quaint.2010.05.015

Liaoning Provincial MuseumJuu Uda League Cultural Relic Work StationChifeng Cultural Center (1983). A Preliminary Report on Trial Excavation at the Sifendi Dongshan Site, Chifeng County, Inner Mongolia. *Archaelogy* 5, 420–429. in Chinese.

Lin, X. J. (1995). A Study on *Li* Tripod Families in Northeast Region. *J. Liaohai Cult. Relics.* 1, 72–81. in Chinese.

Liu, L., Bestel, S., Shi, J., Song, Y., and Chen, X. (2013b). Paleolithic Human Exploitation of Plant Foods during the Last Glacial Maximum in North China. *Proc. Natl. Acad. Sci.* 110 (14), 5380–5385. doi:10.1073/pnas.1217864110

Liu, L., Ma, S., and Cui, J. (2014). Identification of Starch Granules Using a Two-step Identification Method. *J. Archaeological Sci.* 52, 421–427. doi:10.1016/j.jas.2014.09.008

Liu, X. L. (1989). Source of Food of Chinese Prehistoric People and the Processing. *Agric. Hist. Chin.* 4, 29–37. in Chinese.

Liu, Y. P., Su, X., Chen, K. L., La, B., and Ke, J. (2013a). Current Taxonomic Status and Major Existing Problems in Triticeae (Poaceae). *J. Biol.* 30 (2), 77–83. in Chinese. doi:10.3969/j.issn.2095-1736.2013.02.077

Lü, H., Li, Y., Zhang, J., Yang, X., Ye, M., Li, Q., et al. (2014). Component and Simulation of the 4,000-Year-Old Noodles Excavated from the Archaeological Site of Lajia in Qinghai, China. *Chin. Sci. Bull.* 59 (35), 5136–5152. doi:10.1007/s11434-014-0663-1

Lu, H. Y., and Liu, K-B. (2003). Morphological Variations of Lobate Phytoliths from Grasses in China and the South-Eastern United States. *Divers. Distrib* 9 (1), 73–87. doi:10.1046/j.1472-4642.2003.00166.x

Lu, H., Zhang, J., Liu, K.-b., Wu, N., Li, Y., Zhou, K., et al. (2009b). Earliest Domestication of Common Millet (Panicum Miliaceum) in East Asia Extended to 10,000 Years Ago. *Proc. Natl. Acad. Sci.* 106 (18), 7367–7372. doi:10.1073pnas.090015810610.1073/pnas.0900158106

Lu, H., Zhang, J., Wu, N., Liu, K.-b., Xu, D., and Li, Q. (2009a). Phytoliths Analysis for the Discrimination of Foxtail Millet (*Setaria Italica*) and Common Millet (*Panicum Miliaceum*). *PLoS ONE* 4 (2), e4448. doi:10.1371/journal.pone.0004448

Ma, Z. K. (2014). *The Process of Millet Domestication and Dispersal*. [Ph.D. dissertation]. Beijing: University of Chinese Academy of Sciences (in Chinese.

Ma, Z., Li, Q., Huan, X., Yang, X., Zheng, J., and Ye, M. (2014). Plant Microremains Provide Direct Evidence for the Functions of Stone Knives from the Lajia Site, Northwestern China. *Chin. Sci. Bull.* 59 (11), 1151–1158. doi:10.1007/s11434-014-0174-0

Ma, Z., Perry, L., Li, Q., and Yang, X. (2019). Morphological Changes in Starch Grains after Dehusking and Grinding with Stone Tools. *Sci. Rep.* 9 (1), 2355. doi:10.1038/s41598-019-38758-6

Ma, Z., Yang, X., Zhang, C., Sun, Y., and Jia, X. (2016). Early Millet Use in West Liaohe Area during Early-Middle Holocene. *Sci. China Earth Sci.* 59 (8), 1554–1561. doi:10.1007/s11430-015-5257-5

Patterson, W. A., Edwards, K. J., and Maguire, D. J. (1987). Microscopic Charcoal as a Fossil Indicator of Fire. *Quat. Sci. Rev.* 6 (1), 3–23. doi:10.1016/0277-3791(87)90012-6

Piperno, D. R. (2006). *Lanham MD*. Altamira Press.Phytolith: a Comprehensive Guide for Archaeologist and Paleoecologists

Piperno, D. R., Weiss, E., Holst, I., and Nadel, D. (2004). Processing of Wild Cereal Grains in the Upper Palaeolithic Revealed by Starch Grain Analysis. *Nature* 430 (7000), 670–673. doi:10.1038/nature02734

Pugliese, J. Y., Culman, S. W., and Sprunger, C. D. (2019). Harvesting Forage of the Perennial Grain Crop Kernza (*Thinopyrum Intermedium*) Increases Root Biomass and Soil Nitrogen Cycling. *Plant Soil* 437, 241–254. doi:10.1007/s11104-019-03974-6

Su, B. Q., and Yin, Z. W. (1981). The Issues Concerning the Types of Archaeological Areas in Archaeological Culture. *Cult. Relics* 5, 10–17. in Chinese.

Sun, Y. G., Zhao, Z. J., Cao, J. E., Sun, J. S., and Dang, Y. (2014). 2009 Floating Selection and Analysis Report on Erdao Jingzi Ruins of Inner Mongolia. *Agric. Archaeol.* 6, 1–9. in Chinese.

Sun, Y. N. (2018). *Plant Food Sources and Pottery Function at the Site of Qingtai and Dongzhao from Yangshao Period to the Bronze Age Based on Starch Grain Analysis*. Master's thesis (Hefei: University of Science and Technology of China (in Chinese).

The Palace Museum. (2014).*A Study On the Families of Chinese Li Tripods*. Beijing: The Forbidden City Publishing House (In Chinese).

Torrence, R., and Barton, H. J. (2006). *Ancient Sarch Research*. Walnut Creek: Left Coast Press, 1–256.

Wan, Z. W., Yang, X. Y., Ge, Q. S., and Jiang, M. X. (2011). Morphological Characteristics of Starch Grains of Root and Tuber Plants in south China. *Quat. Sci.* 31 (4), 36–745. doi:10.3969/j.issn.1001.74lO.2011.04.18

Wan, Z. W., Yang, X. Y., Li, M. Q., Ma, Z. K., and Ge, Q. S. (2012). China Modern Starch Grain Database. *Quat. Sci.* 32 (2), 371–372. doi:10.3969/j.issn.1001-7410.2012.02.24

Wang, C. X., Cheng, J. T., Cao, J. E., Ta, L., Xiong, Z. L., and Guan, Y. (2017). Diet and Related Issues Revealed by Starch Grain Analysis on Pottery Unearthed from the Weijiawopu Site, Inner Mongolia. Acta Anthropol. *Sin* 36 (3), 406–414. in Chinese. doi:10.16359/j.cnki.cn11-1963/q.2017.0055

Wang, L. X., Qi, X. G., and Xiao, B. G. (1993). A Tentative Discussion of the Origin of Lower Xiajiadian Culture. *North. Cult. Relics.* 2, 5–16. in Chinese.

Wang, Q., Kamijyou, O., and Luan, F. S. (2013). The Study of Stone Saddle Querns and Rollers at Beiqian Site, Jimo, Shandong Province. *Dongfang Archaeology* 1, 154–179. in Chinese.

Wang, Q., Ma, Z. K., Chen, Q. H., Ma, Y. C., Yang, X. Y., Ruan, Q. R., et al. (2020b). Microbotanical Remains Provide Direct Evidence for the Functional Study of Stone Tools from Jartai Pass Site in Nilka County, Xinjiang. *Quat. Sci.* 40 (2), 450–461. doi:10.11928/j.issn.1001-7410.2020.02.15

Wang, S. S., Chiang, W. C., Zhao, B., Zheng, X. G., and Kim, I. H. (1991). Experimental Analysis and Computer Simulation of Starch-Water Interactions during Phase Transition. *J. Food Sci.* 56 (1), 121–124. doi:10.1111/j.1365-2621.1991.tb07990.x

Wang, X. G., and Chai, G. S. (2010). On the Types and Utilization of Biomass Energy in Ancient China. *Stud. Hist. Nat. Sci.* 29 (4), 421–436. in Chinese.

Wang, Y. J., and Lu, H. Y. (1993). *The Study of Phytolith and its Application*. Beijing: China Ocean Press (in Chinese.

Wang, Z. S., Zhao, Y. T., Miao, Y. F., Zou, Y. G., and Tang, G. Q. (2020a). Statistical Problem of Microcharcoal in Loess Sediments Based on the Pollen Methodology. *Arid Land Geo.* 43 (3), 661–670. in Chinese. doi:10.12118/j.issn.1000-6060.2020.03.12

Wu, W. W., Qing, G. L., and Jin, G. Y. (2018). Preliminary Analysis Results of Starch Granule Collected from Tabuobo Site in Inner Mongolia. *Huaxia Archaeology* 5, 52–58. 96 (in Chinese).

Wu, W. W., Yang, X. Y., and Jin, G. Y. (2011). The Application of Starch Analysis in Archaeology: Case Studies on Yuezhuang and Other Sites. *Dongfang Archaeology* 1, 330–348. in Chinese.

Xu, D., Lu, H., Wu, N., Liu, Z., Li, T., Shen, C., et al. (2013). Asynchronous marine-terrestrial Signals of the Last Deglacial Warming in East Asia Associated with Low- and High-Latitude Climate Changes. *Proc. Natl. Acad. Sci.* 110 (24), 9657–9662. doi:10.1073/pnas.1300025110

Yang, X., Ma, Z., Wang, T., Perry, L., Li, Q., Huan, X., et al. (2014). Starch Grain Evidence Reveals Early Pottery Function Cooking Plant Foods in North China. *Chin. Sci. Bull.* 59 (32), 4352–4358. doi:10.1007/s11434-014-0500-6

Yang, X., and Perry, L. (2013). Identification of Ancient Starch Grains from the Tribe Triticeae in the North China Plain. *J. Archaeological Sci.* 40 (8), 3170–3177. doi:10.1016/j.jas.2013.04.004

Yang, X., Wan, Z., Perry, L., Lu, H., Wang, Q., Zhao, C., et al. (2012a). Early Millet Use in Northern China. *Proc. Natl. Acad. Sci.* 109 (10), 3726–3730. doi:10.1073/pnas.1115430109

Yang, X. Y., Kong, Z. C., Liu, C. J., and Ge, Q. S. (2010). Morphological Characteristics of Starch Grains of Millets and Their Wild Relatives in North China. *Quat. Sci.* 30 (2), 364–371. in Chinese. doi:10.3969/j.issn.1001-7410.2010.02.13

Yang, X. Y., Lu, H. Y., and Xia, Z. K. (2006). The Application of Plant Starch Grains Analysis in Archaeology. *Archaeol Cult. Relics* 3, 87–91. in Chinese.

Yang, X., Zhang, J., Perry, L., Ma, Z., Wan, Z., Li, M., et al. (2012b). From the Modern to the Archaeological: Starch Grains from Millets and Their Wild Relatives in China. *J. Archaeological Sci.* 39 (2), 247–254. doi:10.1016/j.jas.2011.09.001

Zhang, H. M. (2015). The Relationship between the Primitive Pottery Product Design and the Food Culture of Li Tribe in Hainan Island. *Art Des.* 12, 112–114. (in Chinese). doi:10.17265/1539-8072/2015.12.012

Zhang, J. P., and Lu, H. Y. (2006). Preliminary Study of Charcoal Morphology and its Environmental Significance. *Quat. Sci.* 26 (5), 857–863. (in Chinese).

Zhang, Z. P., Kong, Z. S., Zhang, W. J., and Chen, Y. (1987). in *Analects Archaeological Culture (1)*. Editor B. Q. Su (Beijing: Cultural Relics Press), 58–78. in Chinese.*"Study of the Lower Xiajiadian Culture"*

Zhao, B. F. (2005). *Study on Archeology Culture of Xia Dynasty to Warring States in Northeast Region of China*. [Ph.D. dissertation]. Changchun: Jilin University (in Chinese.

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