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Pottery vessels and alcohol consumption at the late Neolithic Shuanghuaishu site in Central China

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During the late Neolithic, the number of pottery cups unearthed in the Central Plains of China increased, yet their function remained unclear. This study investigates the functions of pottery vessels from the Shuanghuaishu site, dating to the late Yangshao to early Longshan periods (*ca*. 5200–4500 cal BP), using starch grain, phytolith, fungal, and organic acid analyses. The results suggest that *jiandiping* were not typical vessels for brewing or consuming alcohol, while the emerging pottery cups were used for drinking alcoholic beverages. Ingredients used in brewing included millets, rice, Job's tears, Triticeae, tubers, and legumes. The form and function of the cups may have been influenced by the Dawenkou Culture and introduced to support feasting and ritual activities. These findings reveal a significant phase in drinking practices in the Central Plains around 5000 BP, reflecting both intensified regional interaction and growing ritual needs of complex societies during the late Neolithic.

The Central Plains is a vital birthplace of Chinese civilization. Broadly defined, the Central Plains region includes the Guanzhong Basin (central and eastern Shaanxi), central and western Henan, southern Hebei, and southern Shanxi (Fig. 1). During the late Neolithic, spanning the Yangshao Culture (7000–4800 BP) and the Longshan Culture (4800–4000 BP), the societal structure in the Central Plains underwent a significant transition from simplicity to complexity[1–4]. In the early Yangshao Culture period (7000–5800 BP), settlements and cemeteries exhibited egalitarian social structures; In the middle Yangshao Culture period (5800–5300 BP), evidence of wealth disparity and social stratification began to emerge; In the late Yangshao Culture period (5300–4800 BP), large central settlements such as Shuanghuaishu exhibited early urban characteristics, including triple moats, uniformly planned architectural complexes, designated residential zones, and cemeteries, alongside smaller surrounding satellite settlements; In the early Longshan Culture period (4800–4300 BP), regional interaction intensified—evident in the adoption of pottery styles and funerary customs from the Dawenkou Culture (6000-4500 BP) in the east—indicating the emergence of broader, more diverse regional complex societies[4]. These transformations were particularly pronounced in the heartland of the Central Plains, which corresponds to central and western Henan[5].

In recent years, scholars have increasingly focused on the significance of alcoholic beverages and drinking practices as indicators of social and cultural transformation in prehistoric China[6–8]. Corresponding to each of the cultural phases outlined above, the brewing and consumption of alcohol offer valuable insights into changing social dynamics. During the early and middle periods of Yangshao Culture (Fig. 1: Lingkou, Banpo, Jiangzhai, Dingcun, and Yangguanzhai sites), the important and traditional vessel type for production and consumption of alcoholic beverages in the Central Plains was *jiandiping* (尖底瓶), a pottery vessel with a small mouth, pointed base, and an egg-shaped body, similar in shape to amphorae[9–12]. Microwear analysis and ethnographic data indicate that *jiandiping* was used by a group of individuals who sat around it, using straws to share the alcoholic beverages it contained[13]. Thus, *jiandiping* is considered a typical vessel reflecting collectivism and social cohesion. In contrast, during the late Yangshao Culture period, although *jiandiping* continued to be used in drinking practices in two Shaanxi sites (Fig. 1: Xinjie and Mijiaya sites)[14,15], large vats and a painted pottery bottle were found in elite burials in central and western Henan (Fig. 1: Xipo and Qingtai sites)[16,17]. These findings suggest the emergence of competitive feasting activities and the use of elaborate drinking vessels to display individual social status, reflecting an

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intensification of social stratification. However, for the critical transition from the late Yangshao to the early Longshan Culture in the Central Plains, research on alcohol-related practices remains limited. Acquiring this information is crucial for reconstructing the evolution of drinking practices in prehistoric China and understanding the social complexity in the Central Plains region.

The Shuanghuaishu site is located in the heartland of the Central Plains, on a high plateau to the south of Shuanghuaishu Village, Gongyi City, Henan Province (113°5′12″E, 34°48′56″N, altitude 103.885 m, Figs. 1 and 2). It is the largest and most urbanized core settlement discovered to date during the critical stage of the origins of Chinese civilization in the Yellow River Basin[18,19], and is regarded as the political center of the Central Plains during the late Neolithic[5]. The site occupied five phases[19,20], spanning from the late period of Peiligang Culture to the early period of Longshan Culture (Table 1). Therefore, Shuanghuaishu site provides ideal material for studying drinking practices in the Central Plains from the late Yangshao to the early Longshan.

There are two noteworthy phenomena in the Central Plains: first, pottery cups were scarce during the early Yangshao period but gradually increased from the late Yangshao period onward[21,22]; second, *jiandiping* were widely used throughout the Yangshao period as a representative vessel type but largely disappeared thereafter, with only a few examples unearthed

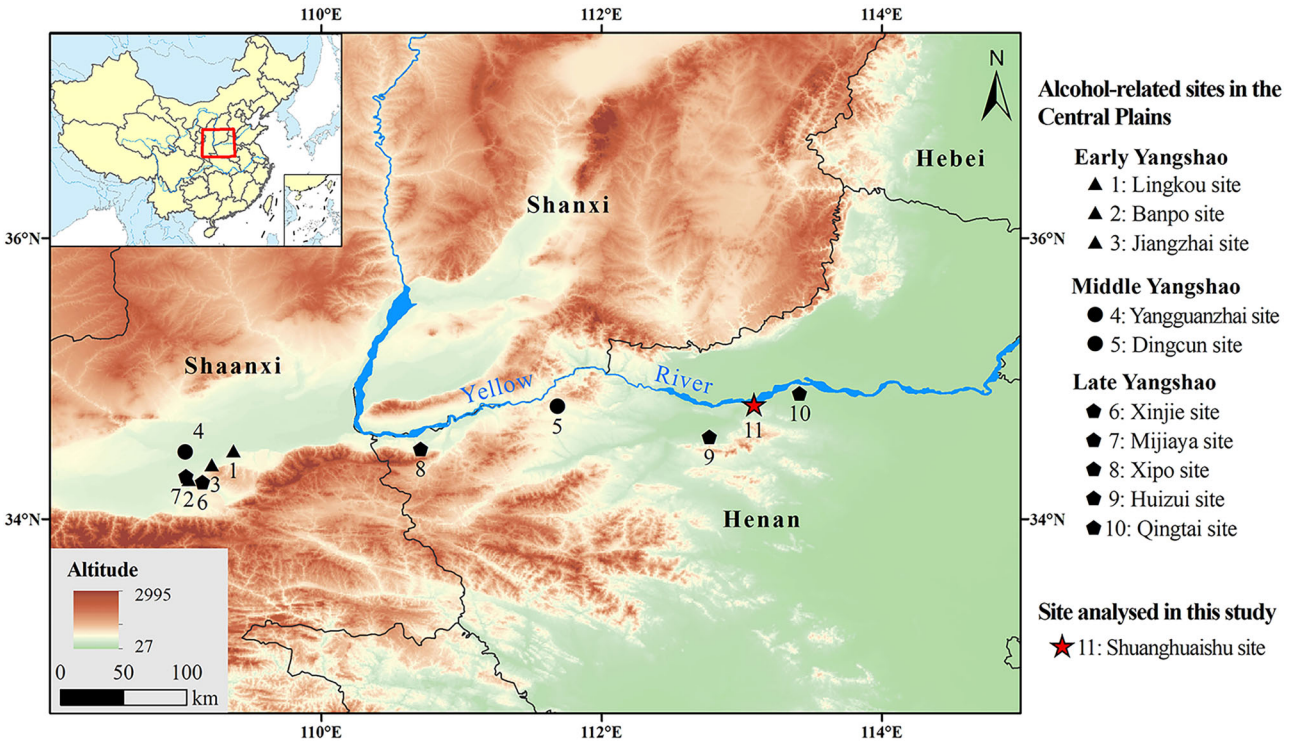

Fig. 1 | The geographical location of the Central Plains and distribution of sites mentioned in this study. 1–10: Sites with evidence of alcohol consumption in the Central Plains during the Yangshao period. 11: Shuanghuaishu site, analyzed in this study.

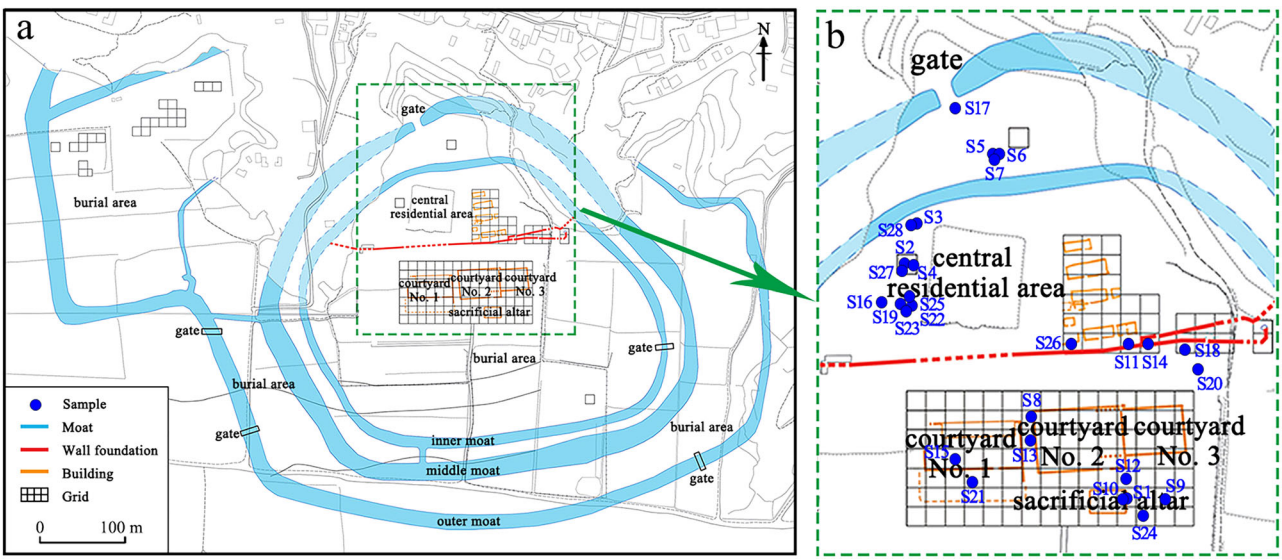

Fig. 2 | Plan map of Shuanghuaishu site and 28 samples distribution, redrawn after Gu et al.[19]. **a** The structure of the Shuanghuaishu site, which mainly consists of three moats, four burial areas, one central residential area, one sacrificial altar, and three courtyards. **b** The location of 28 pottery samples analyzed in this study.

during the early Longshan period[23]. However, the reasons behind the decline of *jiandiping*, the increase in pottery cups, and the specific functions of these cups remain unclear. A similar pattern is observed at the Shuanghuaishu site, where pottery cups were mainly unearthed in Phases IV and V, and *jiandiping* was found in Phases II, III, and IV[18]. The cups at Shuanghuaishu can be categorized into traditional local forms, such as cylindrical-bodied cups, and forms likely introduced from other regions, including *gu*-shaped cups (with a trumpet-shaped body), ring-shaped cups (with a circular ring-shaped base). Notably, bronze *gu* and *jue* were two of the most important ritual vessels for alcohol in ancient Chinese dynasties, and their precursors can be traced back to various types of pottery cups from the late Neolithic period[24,25]. Previous studies have shown that by the late Longshan period (*ca.* 4100–3800 BP) and the early Bronze Age (*ca.* 3750–3450 BP), drinking practices in northern China commonly involved pottery cups, and pottery/ceramic pitchers such as *jue*, *he*, and bottle[26,27]. In addition, alcohol production typically involved large pottery jars, while various pitchers were used for serving, indicating a complex and evolving system of alcohol-related vessel functions[28].

Table 1 | Five occupation phases at the Shuanghuaishu site

Phase	Chronology (archeology culture)	Date
I	Late Peiligang[a]	*ca.* 7500–7000 BP
II	Late Yangshao	*ca.* 5300–5200 cal BP
III	Late Yangshao	*ca.* 5200–5100 cal BP
IV	Late Yangshao	*ca.* 5100–4850 cal BP
V	Early Longshan	*ca.* 4850–4500 cal BP

[a]Peiligang Culture: An early Neolithic archeological culture distributed in the Central Plains, dating to 9000–7000 BP, earlier than the Yangshao culture. The late Peiligang period is ~7500–7000 years old.

Given this context, the increasing presence of pottery cups in the Central Plains from late Yangshao period raises several key questions: Were the cups at the Shuanghuaishu site used for drinking alcohol? Were *jiandiping* and other pottery vessel types, such as jars and bottles, also associated with drinking practices? To explore these issues, this study employs starch grain, phytolith, fungal residue, and organic acid analyses to investigate the functions of pottery vessels and alcohol-related practices at the Shuanghuaishu site from the late Yangshao to early Longshan period.

Methods

Materials

Based on previous research, *jiandiping*, jar, and bottle have been determined to be the pottery vessels associated with production and consumption of alcoholic beverages within the Yangshao Culture area[8,17]. For this study, a total of 28 pottery samples potentially related to alcoholic vessels were collected from Phases III to V of the Shuanghuaishu site, including 15 cups, six *jiandiping*, six jars, and one bottle (Figs. 2, 3 and Table 2).

As shown in Fig. 2, the residential structures and the altar at the Shuanghuaishu site were located within the inner moat, which constitutes the core zone of the settlement. Accordingly, all pottery vessels sampled in this study were collected in or near the inner moat area, where alcohol-related activities may have occurred. Specifically, 24 of 28 samples were collected within the inner moat area; these included samples from nine ash pits, two ash ditches, and 12 grid layers. The other four samples were collected in two ash pits between the inner and middle moats area. We did not collect samples from the burial area, this is because there are no burial objects unearthed at the Shuanghuaishu site.

Methods

Food processing can cause damage to starch grains, and different processing methods may create similar damage patterns[29]. Therefore, interpreting ancient food processing techniques based on starch grain

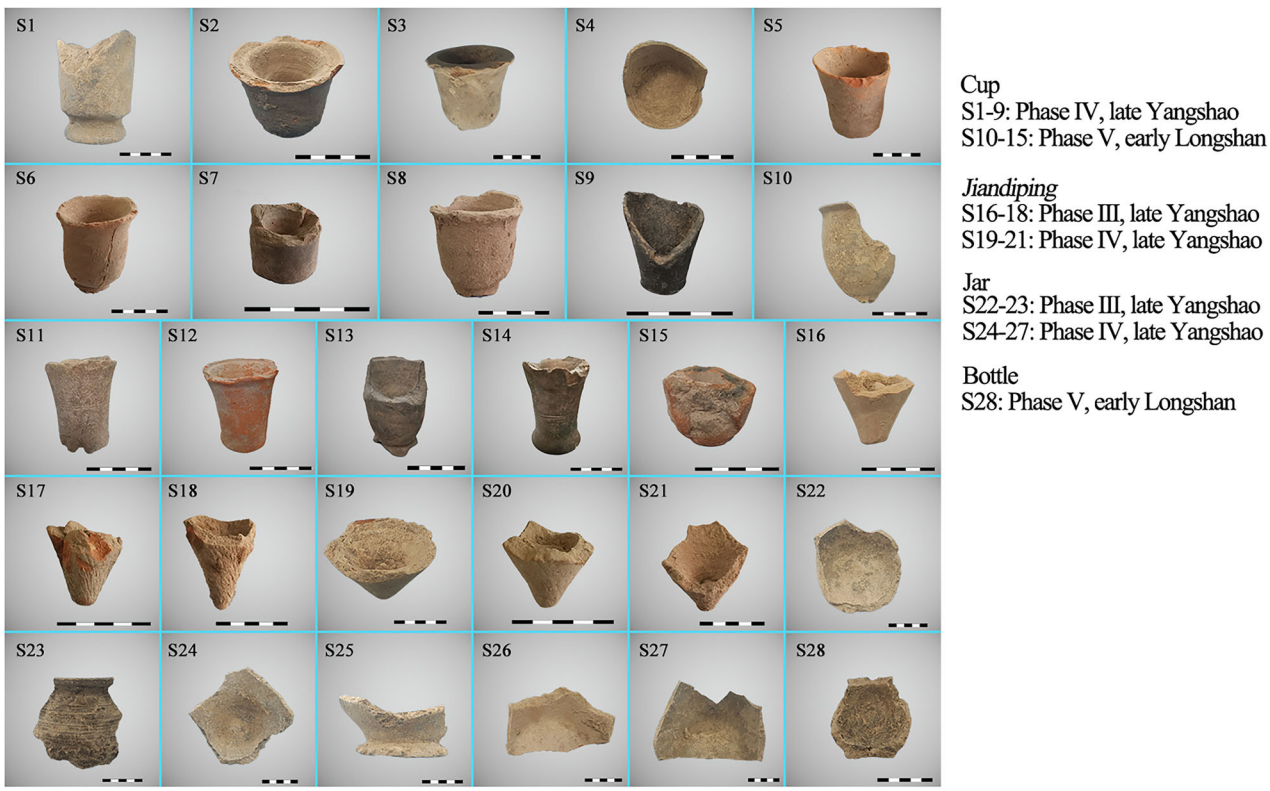

Fig. 3 | Photographs of 28 pottery samples collected at the Shuanghuaishu site and their associated periods (scale bar: 5 cm). S1, S3, S6, S8, S10, and S13 are ring-footed cups. S2, S4, and S7 are cylindrical-bodied cups. S5, S9, S11, S12, and S14 are *gu*-shaped cups. S15 is a cup (cannot be identified vessel type due to damaged). S16–S21 are *jiandiping*. S22–S27 are jars. S28 is a bottle.

Table 2 | Pottery samples analyzed at the Shuanghuaishu site

Lab No.	Artifact No.	Pottery	Phase	Culture age	Date (cal. BP)
S1	2018HGSIT2645H739:1	Ring-footed cup	IV	late Yangshao	*ca.* 5100–4850
S2	2018HGSIT3832H696:4	Cylindrical-bodied cup	IV	late Yangshao	*ca.* 5100–4850
S3	2017HGSIT4033⑦	Ring-footed cup	IV	late Yangshao	*ca.* 5100–4850
S4	2017HGSIT3832H696	Cylindrical-bodied cup	IV	late Yangshao	*ca.* 5100–4850
S5	2016HGSIT4338H324	*Gu*-shaped cup	IV	late Yangshao	*ca.* 5100–4850
S6	2016HGSIT4338H324	Ring-footed cup	IV	late Yangshao	*ca.* 5100–4850
S7	2016HGSIT4338H324	Cylindrical-bodied cup	IV	late Yangshao	*ca.* 5100–4850
S8	2018HGSIT3040⑥:1	Ring-footed cup	IV	late Yangshao	*ca.* 5100–4850
S9	2019HGSIT2647⑤	*Gu*-shaped cup	IV	late Yangshao	*ca.* 5100–4850
S10	2018HGSIT2645②	Ring-footed cup	V	early Longshan	*ca.* 4850–4500
S11	2018HGSIT3445G4	*Gu*-shaped cup	V	early Longshan	*ca.* 4850–4500
S12	2018HGSIT2745②H729	*Gu*-shaped cup	V	early Longshan	*ca.* 4850–4500
S13	2018HGSIT2940④	Ring-footed cup	V	early Longshan	*ca.* 4850–4500
S14	2018HGSIT3446G4:①	*Gu*-shaped cup	V	early Longshan	*ca.* 4850–4500
S15	2018HGSIT2836①	Cup	V	early Longshan	*ca.* 4850–4500
S16	2017HGSIT3632H717	*Jiandiping*	III	late Yangshao	*ca.* 5200–5100
S17	2018HGSIT4636H825	*Jiandiping*	III	late Yangshao	*ca.* 5200–5100
S18	2019HGSIT3450②	*Jiandiping*	III	late Yangshao	*ca.* 5200–5100
S19	2018HGSIT3632④	*Jiandiping*	IV	late Yangshao	*ca.* 5100–4850
S20	2019HGSIT3349②	*Jiandiping*	IV	late Yangshao	*ca.* 5100–4850
S21	2018HGSIT2743③	*Jiandiping*	IV	late Yangshao	*ca.* 5100–4850
S22	2018HGSIT3632④:1	Jar	III	late Yangshao	*ca.* 5200–5100
S23	2018HGSIT3632④:2	Jar	III	late Yangshao	*ca.* 5200–5100
S24	2018HGSIT2546②:2	Jar	IV	late Yangshao	*ca.* 5100–4850
S25	2018HGSIT3632H714:2	Jar	IV	late Yangshao	*ca.* 5100–4850
S26	2018HGSIT3442H594:2	Jar	IV	late Yangshao	*ca.* 5100–4850
S27	2018HGSIT3832H716	Jar	IV	late Yangshao	*ca.* 5100–4850
S28	2017HGSIT4033H710③	Bottle	V	early Longshan	*ca.* 4850–4500

damage requires support from contextual archeological information, a representative number of samples, and complementary lines of evidence[29]. Previous brewing simulation studies have demonstrated that saccharification and fermentation tend to leave morphological changes on starch grains, including small pits and cracks, missing edges, hazy extinction crosses, enlarged fissures, expansion of the central depression, and ring-shaped structures[17,30,31]. These damage types are typical of brewing and distinguishable in a well-documented context. To further strengthen our interpretations, we compared the archeological starch grains with modern reference collections obtained through our brewing experiments (Fig. 4). In addition, the analysis of biomolecules preserved in archeological artifacts, using chromatographic and mass spectrometric techniques, is a powerful but controversial approach[32]. It is now widely accepted that the identification of ancient alcoholic beverages through organic residue analysis can be strengthened by archaeobotanical evidence and archeological context[33–35]. Moreover, residual evidence of fungi and husk phytoliths may indicate brewing and filtration techniques[17,31]. Based on this framework, our study integrates archaeobotanical analysis with organic residue analysis to investigate alcohol-related practices at the Shuanghuaishu site.

What is more, previous studies have identified the ingredients of Neolithic alcoholic beverages in China as cereals (such as millets, rice, Triticeae, and Job's tears), tubers, fruits, and honey[8,36]. At Shuanghuaishu, charred macrobotanical remains of foxtail millet, common millet (*Panicum miliaceum*), rice, Fabaceae, wild soybean (*Glycine soja*), Nepalese hog plum seed (*Choerospondias axillaris*), sour jujube seed (*Ziziphus jujuba* var. *spinosa*), jujube seed (*Ziziphus jujuba*), melon seed (*Cucumis melo*) and other plant foods have been recovered[37], providing suggestive evidence of cereal and fruit consumption.

Therefore, starch grains were first extracted from all 28 samples, as brewing-damaged starch provides the most direct archaeobotanical evidence of alcohol production. Based on the presence of such damage, only those samples exhibiting diagnostic brewing-related starch morphologies were selected for subsequent analyses of husk phytoliths, fungal residues, and organic acids. To test for potential contamination, we collected control samples by gathering dust and soil from the surfaces of the pottery vessels. In addition, blank controls were established by processing empty samples (i.e., without any archeological material) through the same procedures used for the extraction of starch grains, husk phytoliths, fungal residues, and organic acids. Detailed procedures for starch grains, husk phytoliths, fungi, and organic acids analyses are listed in the Supplementary Material.

We referenced the organic acid profiles of cereal-, fruit-, and honey-based fermented beverages[38–43] and selected nine common organic acids from these beverages as the analytical targets for this study (Table 3). These nine acids include lactic acid, succinic acid, fumaric acid, malic acid, tartaric acid, citric acid, pyruvic acid, acetic acid, and oxalic acid. The organic acid analysis in this study aims to identify the presence of organic acids in the pottery vessels as supporting evidence for the brewing damage observed in starch grains, rather than analyzing their concentrations.

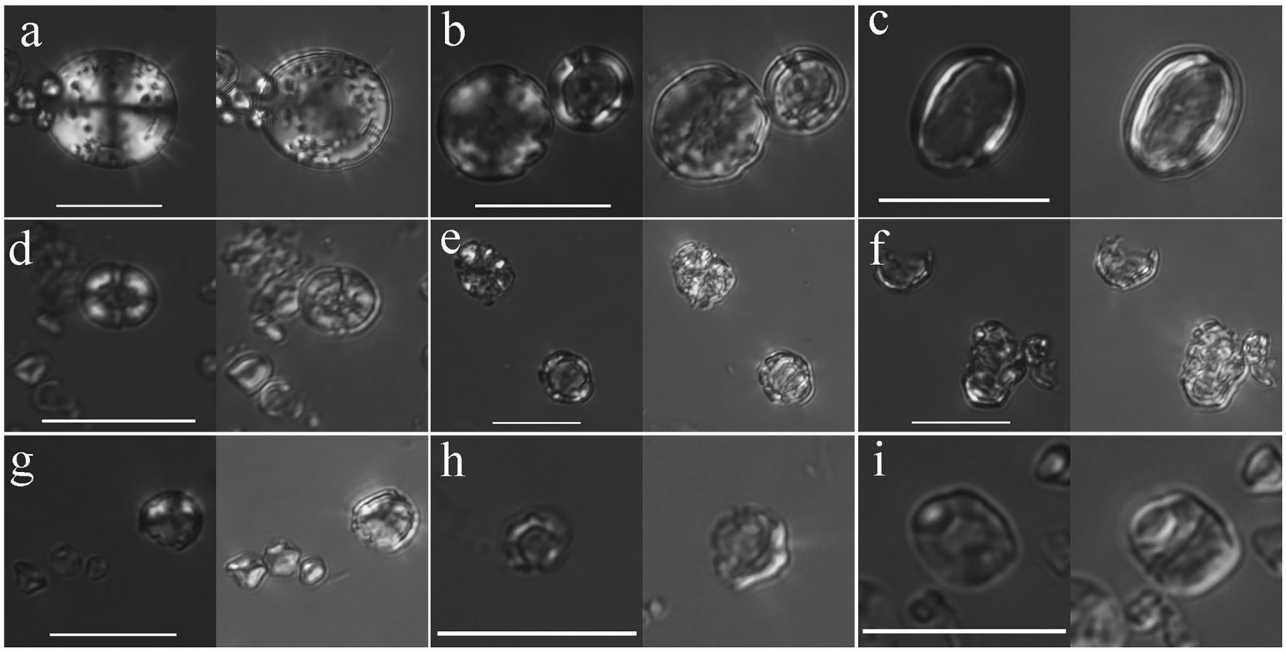

Fig. 4 | Representative examples of brewing-damaged starches from brewing simulation experiments (scale bar: 20 μm). **a** Wheat (*Triticum aestivum*) starch grain showing small pits on the surface; **b** Wheat starch grains—left: with missing edges and weakened birefringence; right: with a central depression forming a ring-shaped structure; **c** Wheat starch grain with central depression forming a ring-shaped structure; **d** Foxtail millet (*Setaria italica*) starch grains with central depression and enlarged fissures; **e**, **f** Foxtail millet starch grains showing swelling, melting, missing edges, and ring-shaped structures; **g** Rice (*Oryza sativa*) starch grains with missing edges and weakened birefringence; **h**, **i** Rice starch grains showing swelling, melting, and central depression.

Table 3 | Common organic acids in fermented beverages.

Type	Common organic acids	Reference
Huangjiu[a]	Lactic acid, Succinic acid, Fumaric acid, Malic acid, Pyruvic acid, Tartaric acid, Acetic acid	40
Beer	Lactic acid, Succinic acid, Fumaric acid, Malic acid, Pyruvic acid, Citric acid, Oxalic acid, Acetic acid	41
Job's tears wine	Lactic acid, Malic acid, Citric acid, Tartaric acid, Acetic acid, Oxalic acid	43
Grape wine	Lactic acid, Succinic acid, Malic acid, Citric acid, Tartaric acid	38
Apple wine	Lactic acid, Fumaric acid, Succinic acid, Malic acid, Citric acid, Tartaric acid	38
Jujube wine	Lactic acid, Succinic acid, Malic acid, Citric acid	42
Honey wine	Lactic acid, Succinic acid, Pyruvic acid, Citric acid, Tartaric acid, Oxalic acid	39

[a]Huangjiu: 黄酒, literally translated as "yellow wine", is a traditional Chinese alcoholic beverage fermented from cereals such as millets and rice.

Results

Starch grains

A total of 244 starch grains were extracted from 13 of the 28 samples, and no starch grains were discovered in the other 15 samples or any of the control samples, suggesting that the analysis was not contaminated and that the 244 grains could be interpreted as valid data. Of the 244 starch grains analyzed, 77 grains were unidentified (UNID) due to damage or lack of typical characteristics. The remaining 167 starch grains, identified through comparison with modern reference materials (Fig. 5), were derived from five plant types and underground storage organs (USOs) (Fig. 6, Table 4). These include Panicoideae (include foxtail millet, common millet, and Job's tears *Coix lacryma-jobi* L.), rice, Triticeae, legume (include *Vigna* and other legumes), snake gourd root (*Trichosanthes kirilowii*), and other USOs. See details of identification in the Supplementary Material.

Among the 244 starch grains observed, 123 exhibited distinctive brewing-related damage and were all recovered from five pottery cups (S5, S9, S11, S13, and S15), while no brewing-related starch grains were identified in the six *jiandiping*, six jars, or one bottle analyzed (Table 4). Specifically, a total of 80 grains displayed damage related to enzymatic hydrolysis, as evidenced by small pits on the surface, partial edge loss, blurred extinction crosses, weakened birefringence, and concave inward hilum (Fig. 7). A total of 43 grains displayed damage consistent with fermentation and gelatinization, characterized by swelling, melting, and the expansion of the central depression from the hilum, resulting in a ring-shaped structure with some grains displaying only the edge and the central area almost completely disappearing (Fig. 7). As the starch grains continue to decompose, the extinction cross arm gradually disappears until the crystal structure was lost. Thereby, these five cups were selected for analyses of husk phytoliths, fungi, and organic acids. However, no fungal remains and husk phytoliths were extracted from these five cups.

Organic acid remains

According to the starch results, five pottery cups (S5, S9, S11, S13, and S15) were selected for the organic acid analysis. To account for the possibility of liquid coming into contact with the outer surface during use, ultrasonic sampling was conducted on the outer surfaces of two randomly selected cups (Table 5: S11-1 and S13-1), in addition to the inner surfaces of all cups. Control samples included a soil sample taken from the surfaces of one pottery cup (Table 5: *S5-1) and a blank sample.

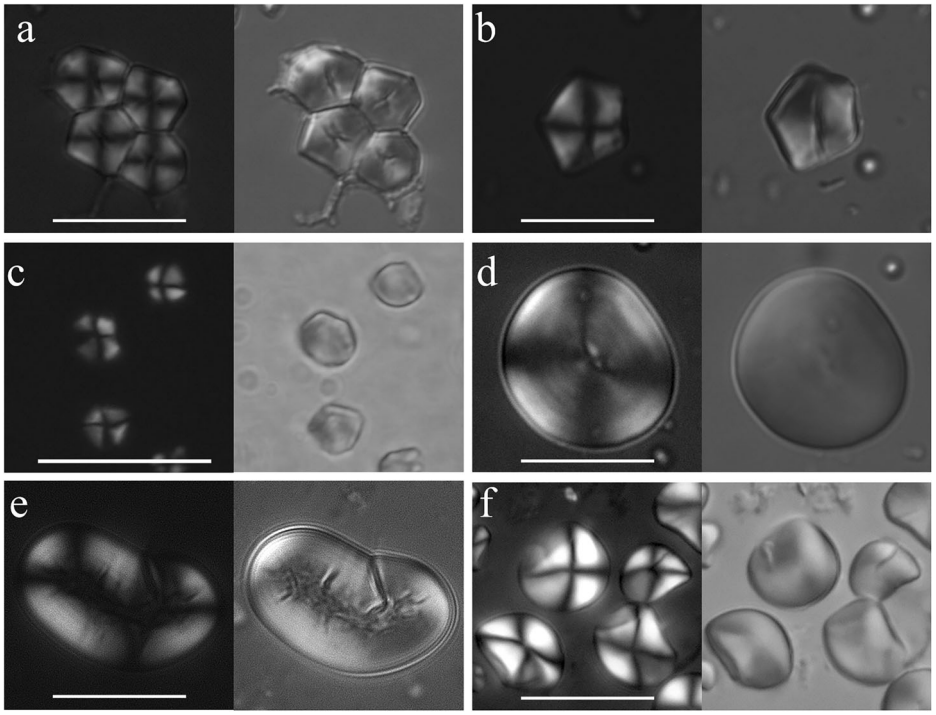

Fig. 5 | Modern reference starch grains used for comparison in this study (scale bar: 20 μm). **a** Foxtail millet; **b** Job's tears; **c** Rice; **d** Triticeae; **e** Mung bean; **f** Snake gourd root.

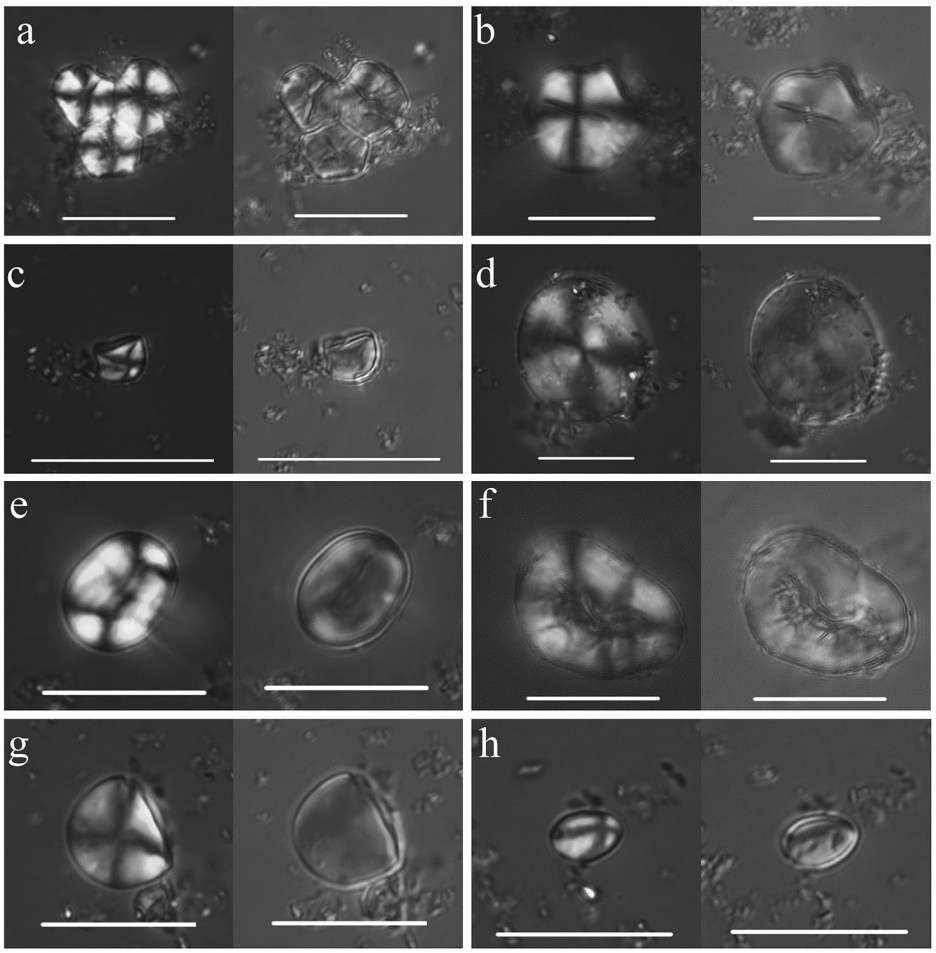

Fig. 6 | Types of starch grains at the Shuanghuaishu site (scale bar: 20 μm). **a** Foxtail millet; **b** Job's tears; **c**: Rice; **d** Triticeae; **e** Legume; **f** *Vigna* (possibly mung bean, *Vigna radiata*); **g** Snake gourd root; **h** Underground storage organ.

Table 4 | Identification of starch grains recovered at the Shuanghuaishu site

Lab No.	Pottery	Type A Panicoideae	Type B Rice	Type C Triticeae	Type D Legume	Type E Snake gourd root	USOs	UNID	Total	Brewing damage
S1	Cup								0	0
S2	Cup								0	0
S3	Cup								0	0
S4	Cup								0	0
S5	Cup	4		10		4	3	5	26	14
S6	Cup								0	0
S7	Cup	6				1			7	0
S8	Cup							1	1	0
S9	Cup	2				3		3	8	5
S10	Cup								0	0
S11	Cup	15	12	23	5	15	15	53	138	71
S12	Cup								0	0
S13	Cup	4		8	1	4	3	13	33	29
S14	Cup								0	0
S15	Cup	2		1	3				6	4
S16	*Jiandiping*								0	0
S17	*Jiandiping*			2				2	4	0
S18	*Jiandiping*								0	0
S19	*Jiandiping*	2			2	1			5	0
S20	*Jiandiping*								0	0
S21	*Jiandiping*								0	0
S22	Jar	5							5	0
S23	Jar								0	0
S24	Jar	1							1	0
S25	Jar								0	0
S26	Jar	8							8	0
S27	Jar	2							2	0
S28	Bottle								0	0
	Total	51	12	44	11	28	21	77	244	123

Table 5 | Organic acids at the Shuanghuaishu site

Organic acids	RT (min)								
	*S5-1	S5	S9	S11-1	S11	S13-1	S13	S15	Black
Lactic acid	-	0.82	-	-	1.41	-	15.88	-	-
Succinic acid	-	22.75	-	-	-	-	20.30	-	-
Fumaric acid	-	20.69	12.58	-	0.70	-	-	-	-
Malic acid	-	-	3.66	-	-	-	-	-	-
Tartaric acid	-	-	-	-	-	3.60	-	-	-
Citric acid	-	-	-	-	-	-	-	-	-
Pyruvic acid	-	13.92	9.56	-	15.01	17.60	19.09	3.71	-
Acetic acid	-	15.30	6.94	11.80	14.80	20.58	11.59	8.61	-
Oxalic acid	-	-	14.50	12.93	16.47	-	-	-	-

"*" means the control sample. "-" means that the organic acid is not detected.

Except for citric acid, the remaining eight common organic acids in fermented beverages were detected in the five pottery cups (see LC-MS data for details in the Supplementary Material). No organic acids were detected in the control samples, and it can be assumed that the extracted organic acids were not contaminated. Lactic acid, succinic acid, fumaric acid, pyruvic acid, and acetic acid were detected in S5. Fumaric acid, malic acid, pyruvic acid, acetic acid, and oxalic acid were detected in S9. Lactic acid, fumaric acid, pyruvic acid, acetic acid, and oxalic acid were detected in S11. Lactic acid, succinic acid, tartaric acid, pyruvic acid, and acetic acid were detected in S13. Pyruvic acid and acetic acid were detected in S15.

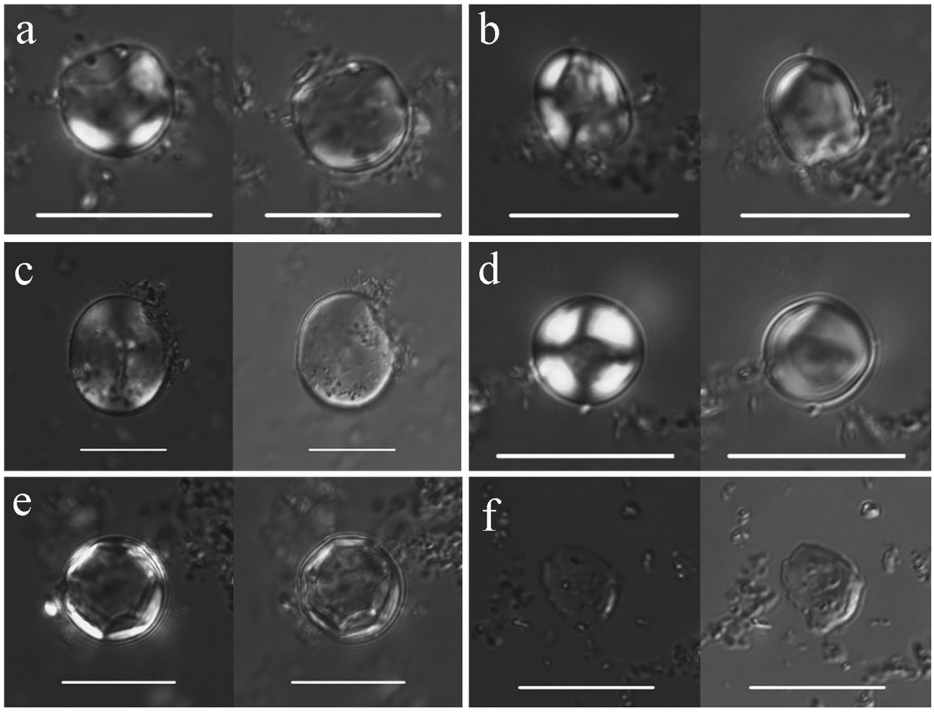

Fig. 7 | Brewing damaged starch grains in the five cups from Shuanghuaishu (scale bar: 20 μm). **a**, **b** Showing blurred extinction crosses and weakened birefringence; **c** Showing small pits and disappearing extinction cross; **d**, **e** Showing central depression; **f** Showing swelling and melting.

Discussion

This study aims to determine which types of pottery vessels were associated with the brewing and consumption of alcoholic beverages at the Shuanghuaishu site, and to explore the drinking practices within the site during the late Yangshao to early Longshan periods.

Among the analyzed vessels, starch grain analysis suggests that six *jiandiping*, six jars, and one bottle were likely not used for the production or consumption of alcoholic beverages. The starch results for the *jiandiping* align with our previous research at the Qingtai site[17]. The Qingtai site (Fig. 1), located in central Henan and dating to the late Yangshao period (*ca.* 5500-4750 cal BP), is spatially and temporally close to the Shuanghuaishu site (~40 km apart). By contrast, residue analyses from the early to middle Yangshao Culture period in the Central Plains indicate that *jiandiping* was closely associated with alcoholic beverages[8]. Therefore, the data from the Shuanghuaishu and Qingtai sites collectively suggest that during the late Yangshao to early Longshan periods, *jiandiping* in the Central Plains, particularly in the central Henan region, may no longer have been a typical pottery type associated with brewing or consuming alcoholic beverages. Although the combined dataset of *jiandiping* from the Shuanghuaishu and Qingtai sites is limited and insufficient to represent the entire Central Plains, it provides preliminary evidence supporting this hypothesis. The specific functions of the *jiandiping* and jars analyzed remain unclear, primarily due to the sparse recovery of starch grains from their surfaces, which limits functional interpretation. Moreover, as this study focuses specifically on vessels related to alcohol production and consumption, a more detailed analysis of these forms lies beyond its scope. As for the single bottle specimen, the absence of starch grains is likely due to the small sample size, and its function also requires further investigation.

A total of 205 starch grains were recovered from the five pottery cups (S5, S9, S11, S13, and S15), with 60% ($n = 123$) exhibiting brewing damage characteristics. Additionally, organic acids commonly found in fermented beverages made from cereals, fruits, and honey were detected on these five pottery cups. Combined evidence from starch grain and organic acid analyses strongly suggests that these five pottery cups were used to contain alcoholic beverages. The starch grains recovered in the five cups include cereals, USOs, and legumes. These findings suggest that the alcoholic beverages consumed by the Shuanghuaishu residents were compositionally diverse. This diversity of ingredients in the beverages may have been produced through two possible modes: one involving the co-fermentation of multiple ingredients into a single mixed beverage, and another where different ingredients were fermented separately to produce various single-component beverages. Regardless of the mode, these fermented ingredients are basically consistent with the types of plant food consumed by the residents of Shuanghuaishu[20,37].

No husk phytoliths or fungal residues were found in the five pottery cups analyzed. This result does not necessarily imply the absence of related residues in the samples, as it may have been influenced by various factors such as sample collection, preservation conditions, or detection techniques. Firstly, due to the perishable nature of fungi, they are more difficult to preserve in the archeological record compared to other plant or animal remains[44,45]. Therefore, the lack of fungal remains may be related to the specific preservation conditions for microorganisms. Secondly, our previous brewing experiments demonstrated that unfiltered fermented beverages tend to have a turbid appearance, while filtration can reduce the husk phytoliths in the liquid[17]. Therefore, another possible explanation is that the inhabitants of Shuanghuaishu filtered their alcoholic beverages before consumption, thereby removing plant husks in the process. This practice is consistent with findings from the Huizui and Qingtai sites (Fig. 1)[17,46]. These three cases from the heartland of the Central Plains during the late Yangshao to early Longshan periods suggest a trend toward more refined processing of alcoholic beverages, reflecting an increasing emphasis on beverage palatability. Given the low probability of only five cups at the entire site, we hypothesize that there may be additional undiscovered cups in the area that were used for alcoholic consumption.

Pottery cups at Shuanghuaishu primarily appeared during the late Yangshao to early Longshan periods, a time when regional interactions intensified (Fig. 8)[4]. Archeological excavations reveal that burial customs and ritual-related artifacts originating from the Dawenkou Culture appeared in the Central Plains, and some pottery types incorporated cultural elements from Qujialing Culture (5400–4500 BP) and Dawenkou Culture[4]. For instance, pottery such as ring-footed cup and *gu*-shaped cup unearthed at the Shuanghuaishu site were introduced from the Dawenkou Culture[18]. Among the five pottery cups analyzed in this study, the vessel type of S15 cannot be determined due to damage, while the other four are identified as

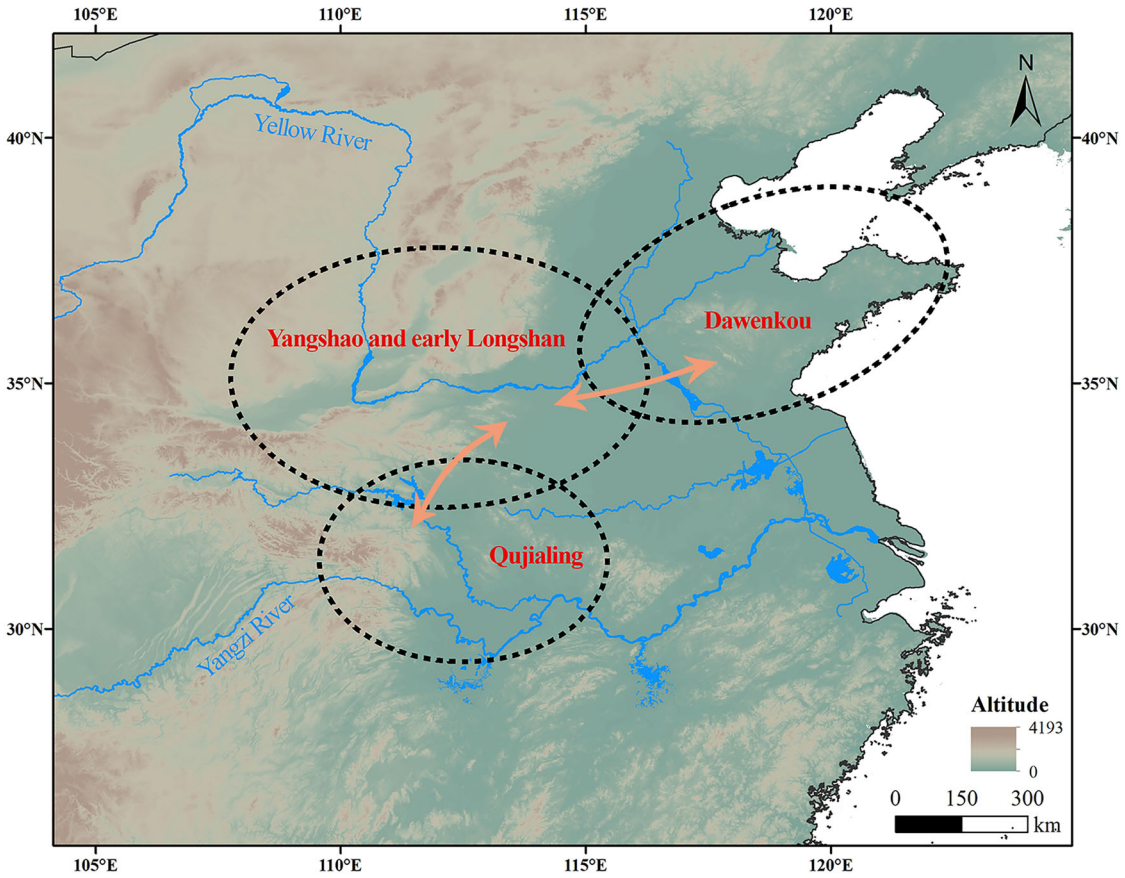

Fig. 8 | Distribution of four archeological cultures and their interactions and influences during the late Neolithic in China.

gu-shaped cups (S5, S9, and S11) and a ring-footed cup (S13). Moreover, pottery cups unearthed in the Central Plains before the late Yangshao period are few, and there is currently no evidence to suggest that they were used as drinking vessels during this time. Instead, *jiandiping* was the traditional and typical vessel for alcoholic beverages[8]. Thus, given the context of regional interactions, the origins of these vessel types, and the absence of a prior tradition of pottery cups for drinking in the region, it is likely that the use of pottery cups for drinking at the Shuanghuaishu site was introduced from the Dawenkou Culture.

Furthermore, this form of drinking practice involving pottery cups is not only an outcome of regional cultural interactions but also reflects the emerging demands for drinking and ritual activities within the Shuanghuaishu site. During the late Yangshao period, signs of social complexity became increasingly evident[2–4]. The Shuanghuaishu site, surrounded by three layers of moats, was a large settlement with a preserved area of ~1,170,000 m^2 (Fig. 2). Within the inner moat, well-planned large architectural complexes and residential areas were uncovered, alongside ritual-related relics such as altars, human sacrificial pits, and animal sacrificial pits (Fig. 2). These findings suggest the presence of ritual concepts and indicate the capability for centralized planning and coordination within the settlement. Besides, a number of small and medium-sized settlements distributed around Shuanghuaishu formed a "pyramid-like" hierarchical structure, with the Shuanghuaishu site serving as the core[18,19]. As the political center of the Central Plains in the late Neolithic, the Shuanghuaishu site likely developed new drinking demands stemming from its central role. These demands may include feasting activities to enhance social connections, ritual occasions to mobilize social resources, and events for elites to display authority and status. In this context, the traditional *jiandiping* in the Central Plains, which symbolized egalitarian values, may have become unsuitable for this emerging complex society. Previous research has demonstrated that *gu*-shaped cups from the Dawenkou Culture were initially used as drinking vessels but later evolved into specialized items for rituals, feasts, and other ceremonial activities[47]. This functional shift indicates that *gu*-shaped cups not only served practical purposes but also became symbols of identity and status. Therefore, the pottery cups at the Shuanghuaishu site, particularly *gu*-shaped cups influenced by the Dawenkou Culture, may have been intended to meet the site's emerging needs for ritual activities.

Data availability

No datasets were generated or analyzed during the current study.

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Author contributions

J.L. analyzed and interpreted the starch grain, phytolith, and fungal data, drafted the original manuscript, and revised and edited the manuscript. Y.Y. supervised the research and reviewed the manuscript. W.G. provided the archaeological samples and funding support. Y.G. analyzed and interpreted the organic acid data. B.S., Q.C., and X.Z. participated in the sampling process. J.Z. reviewed and commented on the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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