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Food, cooking and potteries in the Neolithic Mijiaya site, Guanzhong area, North China, revealed by multidisciplinary approach

Yating Qu[1], Junxiao Zhu[2*], Han Yang[1] and Longlong Zhou[1]

Abstract

Investigating the coevolutions in human food resources, cooking technologies and pottery functions will provide a vital perspective for understanding the driving force of social development in Neolithic China. Here, we preliminarily present a multianalytical study on the plant microfossils of pottery residues, the stable isotopic compositions and radiocarbon dating of animal bones, and the characteristics of pottery vessels (including their types, textures and smoked traces) from the Mijiaya site. The results indicate that the Mijiaya people (ca. 3093–1961 cal. BC) probably relied on the various food resources consisting of the diversified crops, livestock and some foraging food; Mijiaya people had refined the pottery functions by changing their types, textures and assemblages, and they also used some auxiliary tools for increasing the cooking efficiency and obtaining the complex foodstuff. Integrated with agricultural development and technological innovation during Neolithic China, the foodways at the Mijiaya site also shed light on its inherited social tradition and social organization in the Late Neolithic period.

Keywords Mijiaya site, Neolithic foodways, Pottery function, Plant microfossils, Stable isotopes

Introduction

Food consumption is essential for human nutrition intake, and the adoption of cooking, which has made food nutrition more available for humans, has played a significant role in human biological evolution [1–3]. Cooking also complicated the human behaviour of obtaining foodstuffs by causing the mixture of various food resources and multistep processing from preparation to consumption [4, 5]. The successive appearance of diverse assemblages of stone and pottery vessels represents an important step forward in cereal processing during the Neolithic period; meanwhile, pottery functionality was improved through a suite of changes in their types and textures for more applicative cooking contents and structures [6–10]. All of these factors had a profound influence on human subsistence, residential strategies and social organization [11–14].

The exploration of Neolithic foodways has received much attention in the interpretation of Neolithic society, economy and culture [12, 15–17]. Supporting evidence from ethnoarchaeological studies and further cooking experiments indicates that the residues of foodstuffs can be preserved in processing vessels, and food processing can be taken as a vital indicator of human subsistence and society [6, 18–21]. By applying many different approaches, including through plant microfossils, lipid biomarkers, proteomics, stable isotopes, microbiology, use-wear and phosphorus, a multianalytical study on the charred residues surviving in archaeological ceramic and stone vessels was conducted to reveal ancient food practices [5, 11, 21–25].

*Correspondence:
Junxiao Zhu
zhujunxiao@snnu.edu.cn
[1] Northwest Institute of Historical Environment and Socio-Economic Development, Shaanxi Normal University, Xi'an 710119, China
[2] School of History and Civilization, Shaanxi Normal University, Xi'an 710119, China

It is well known that humans engaged in a broad-spectrum subsistence strategy for climate adaptation in the Late Pleistocene, which laid the foundation for agricultural emergence in early Neolithic China [26–28]. The hunter-gatherers already practised food processing by grinding stones, and they also created the early pottery used for cooking animal or plant foods [29–33]. Subsequently, the development of multiple agricultures and pottery production contributed to the transition of human food resources from foraging to producing, and this also promoted technological innovation of food cooking in Neolithic China [12, 34–38]. To date, the diversity of food processing (including steaming, boiling, baking and brewing), as well as the storage, presentation and serving of food, has been partly linked to the diverse textures and types of pottery vessels and their assemblages (e.g., pointed-based amphora, polished black pottery goblet and basin with carved grooves); moreover, the various food resources (e.g., all kinds of crops, gathering plants, raising and hunting animals and fishing food) were processed and made into many foodstuffs (e.g., husking granule and porridge, grinding powder and shaping noodles, brewing recipes and wine) in Neolithic China [12, 35–49].

However, it is unclear how humans refined pottery functions for complex food processing in the face of changing food resources. The Mijiaya site is an important Neolithic site in the Guanzhong area of North China. In this area, much evidence has indicated that humans engaged in diversified subsistence strategies during the Neolithic period [50–53]. Meanwhile, a centre of pottery production and utilized pottery assemblage could have been established based on the excavation of a large quantity of pottery vessels with various forms [12, 54, 55]. Research on food fermentation techniques was carried out to explore agricultural subsistence, feasting activities and social complexity during the Neolithic period [37, 56, 57]. Combined with the related study in the surrounding area, the Mijiaya site will be taken as an example to explore the coevolutions in human food resources, cooking technologies and pottery functions. This study will provide a new perspective for understanding the potential driving force of social development in Neolithic China.

Materials and methods

Archaeological background

The Mijiaya site (109.03° E, 34.30° N) is situated east of the Chan River and 2.7 km from the Neolithic Banpo site in Baqiao district, Xi'an city, Shaanxi Province, North China (Fig. 1). This site was systematically excavated by the Shaanxi Academy of Archaeology in 2004–2006 and

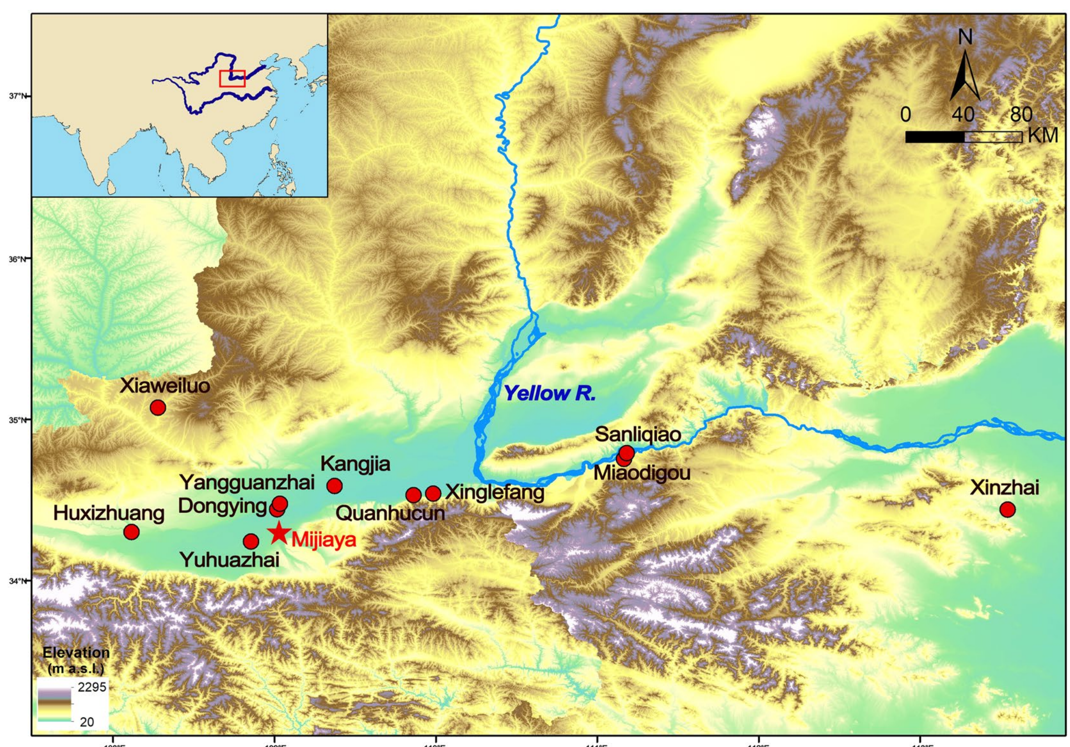

Fig. 1 Geographical locations of the Mijiaya site and some mentioned sites

the Xi'an Municipal Institute of Cultural Heritage Preservation and Archaeology in 2010–2011 [58, 59]. Abundant remains (e.g., house, ash pit, tomb, stoneware, animal bones, pottery, stove, etc.) were unearthed. A large quantity of pottery vessels were identified as *jian-diping*-pointed-based amphora (尖底瓶), *jia* -tripod vessel (斝), *li*-tripod vessel (鬲), *dou*-pedestal dish (豆), *pen*-basin (盆), *guan*-high-necked jar with globular belly and jar with handles (罐), *qigai*-tower-shaped lid (器盖), and so on. They were mainly characterized as sandy or clay potteries, and some of them (e.g., *li*, *jia*, *guan*, etc.) obviously had smoked traces. Based on the pottery typology, the cultural strata of Mijiaya site was divided into three archaeological phases, belonging to the late Yangshao Culture, Miaodigou II Culture and Keshengzhuang Culture. The Keshengzhuang Culture was believed to be a typical 'Longshan Culture' in the Guanzhong area [58, 59].

Sample collection

Six animal bones from the three archaeological phases of the Mijiaya site were selected for AMS ^{14}C dating and stable isotopes analyses. Many *li* potteries appeared in the Keshengzhuang phase, and the interior surface of tripod legs of some *li* potteries was observed to be adhered by the carbonized residues (Fig. 2a). *Guan* pottery was the most common pottery form at this site, and the imprints of carbonized seeds were found on the base of one *guan* pottery (Fig. 2b). Hence, the two potteries were sampled to extract the starches and phytoliths from these residues. These samples were excavated from the Mijiaya site in 2010 to 2011 (details in Table 1 and Fig. 2). In addition, the statistical analyses on the pottery forms, stove and other observed objects (e.g., smoked traces) are mainly based on the excavation report of the Mijiaya site in 2004–2006, supplemented with those in 2010–2011 [58, 59].

Experimental methods and statistical analysis

Bone collagen was extracted by using the modified procedure outlined by Longin [60] in the Beta Analytic Radiocarbon Dating Laboratory. The main processes are the initial cleaning stage, the dissolution of the mineral fraction with 0.2 N hydrochloric acid solutions

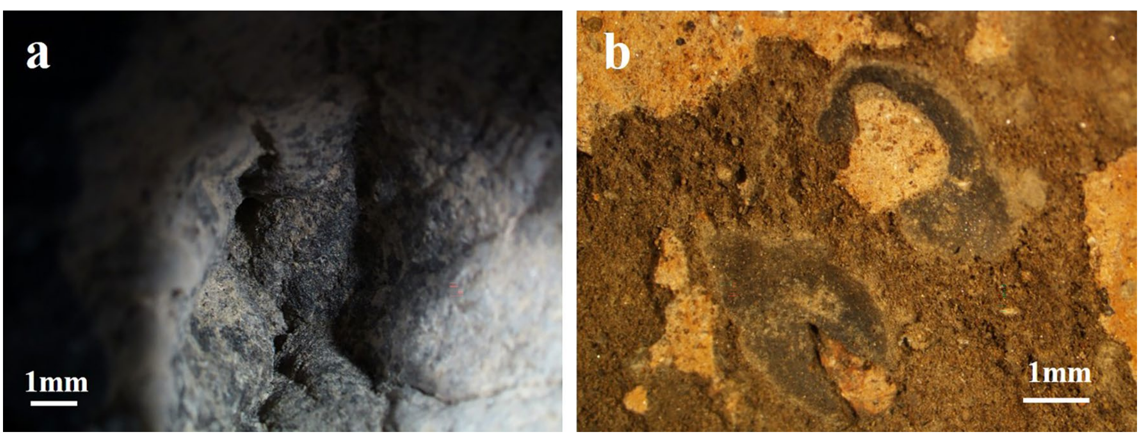

Fig. 2 The observation of pottery residues from the Mijiaya site under the stereoscopic microscope. a: the charred residues preserved in the tripod leg of *li* pottery (2011XBM19#T0308③:55, Keshengzhuang Culture); b: the imprints of charred seeds on base of *guan* pottery (2010XBM10#T0401②a, Yangshao Culture), (scale bar 1 mm)

Table 1 The information, ^{14}C-data, C and N contents and stable isotopic data of animal samples from the Mijiaya site

Cultural strata	Burial context	Common name	Lab No	Conventional Age (BP)	Calendar calibration (cal. BC, 2σ)	C %	N %	C/N	$\delta^{13}C$‰	$\delta^{15}N$‰
Yangshao	2011XBM19# T0203 H3	deer (humerus)	Beta-571644	4090 ± 30	2859–2497	40.8	14.6	3.3	−19.7	6.0
	2011XBM19# T0203 H1	pig (humerus)	Beta-571645	4380 ± 30	3093–2911	40.6	14.8	3.2	−9.4	8.7
Miaodigou II	2011XBM19# T0408H18	deer (femur)	Beta-571646	3680 ± 30	2192–1961	40.6	14.4	3.3	−19.2	5.1
	2011XBM19# T0308H87	cattle (limb)	Beta-571647	3730 ± 30	2272–2032	40.3	14.5	3.2	−13.0	6.6
Keshengzhuang	2011XBM19# T0308H70:1	cattle (rib)	Beta-571648	3700 ± 30	2199–1980	41.5	15.2	3.2	−12.3	9.4
	2011XBM19# T0301H13	cattle? (limb)	Beta-571649	3800 ± 30	2343–2138	41.2	14.9	3.2	−14.7	7.2

(HCl) at ~ 21 °C, and the removal of secondary organics with 1–2% alkali solutions (50/50 wt/wt % NaOH) at room temperature. The extracted collagen was then analysed by IRMS (Thermo Fisher Delta V Advantage (50–40,000 mV), wrapped within a standard IRMS tin boat and placed into an autodispenser on a Costech 4010 Elemental Analyzer (EA)) for the $\delta^{13}C$ and $\delta^{15}N$ values and C and N contents. The standards are traceable to NIST RM 8539, 8540, 8541 and 8542. The $\delta^{13}C$ and $\delta^{15}N$ values were relative to VPDB-1, and the analytical precision was 0.3‰. The isotopic results are shown in Table 1.

Then, the well-preserved bone collagen was dated by accelerator mass spectroscopy (AMS) ^{14}C in the Beta Analytic Radiocarbon Dating Laboratory. The dates were calibrated using OxCal v4.4.4 (https://c14.arch.ox.ac.uk/oxcal.html) and IntCal 20 [61]. The results are shown in Table 1.

The residue samples were prepared by using the modified procedure outlined by Piperno (1988) [62] and Lentfer and Boyd (1998) [63] in the Key Laboratory of Vertebrate Evolution and Human Origins of Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences. The interior surface of the tripod leg (*li* pottery) was gently cleaned with a dental brush and distilled water to eliminate the possibly adhering sediment; then, it was filled with 15 ml distilled water and shaken in an ultrasonic bath for 15 min at room temperature to completely dislodge the adhering residues. Then, the solution was transferred to a 15 ml centrifuge tube and centrifuged (3000 rpm for 3 min), and the supernatant was pipetted off. A 10 ml 5% solution of EDTA ($Na_2EDTA \cdot 2H_2O$) was added to the tube, and it was shaken for 2 h to facilitate dispersal. After that, the residue was washed for three times and centrifuged. The surface of the carbonized seed imprints on the base of the *guan* pottery was gently scraped off by using a clean blade, and the residue was collected within a 1.5 ml centrifuge tube. Then, the surrounding sediments were also sampled and dispersed with EDTA solution, and the starches and phytoliths were extracted from the sediments by using the heavy liquid $ZnBr_2$ at a specific gravity of 2.4. Then, all samples were mounted in 1:1 (vol/vol) glycerin/distilled water solution on a microscope slide and examined under a light microscope (Nikon ECLIPSE LV100 POL) at 500X magnification. The shape and distinctive features of each starch/phytolith were recorded and photographed under nonpolarized light and/or polarized light.

Finally, based on the reports on the excavation of the Mijiaya site in 2004–2006 and Zone I of the Mijiaya site in 2010–2011 [58, 59], the pottery forms and their assemblages from the late Yangshao Culture, Miaodigou II Culture and Keshengzhuang Culture were statistically analysed, especially noting the appearance of some new pottery forms. *Guan* jars, as the most common pottery form at the Mijiaya site, were statistically analysed in terms of their textures and colours. Then, the forms and textures of potteries adhered to the smoked traces and the types of auxiliary stoves for food processing were also detected systematically.

Results

Identification of contaminations and the $\delta^{13}C$ and $\delta^{15}N$ values of animal bones from the Mijiaya site

The contents of C and N in the collagen extracted from the animal bones at the Mijiaya site range from 40.3–41.5% and 14.4–15.2%, respectively, with atomic C/N ratios of 3.2–3.3 (Table 1), which are in the ranges of collagen with C (15.3–47.0%) and N (5.5–17.3%) contents and C/N ratios (2.9–3.6) generally considered well preserved for the stable isotopic analysis [64, 65]. The $\delta^{13}C$ values of the deer are –19.7‰ and –19.2‰, with an average of – 19.5 ± 0.4‰ (n = 2); the $\delta^{15}N$ values are 6.0‰ and 5.1‰, with an average of 5.6 ± 0.6‰ (n = 2). One pig displays a $\delta^{13}C$ value of – 9.4‰ and a $\delta^{15}N$ value of 8.7‰. All the cattle had $\delta^{13}C$ and $\delta^{15}N$ values ranging from – 14.7‰ to – 12.3‰ (mean of – 13.3 ± 1.2‰, n = 3) and from 6.6‰ to 9.4‰ (mean of 7.7 ± 1.5‰, n = 3), respectively. Based on the general isotopic fractionation between diet and bone collagen (+ 5‰) [66, 67], the lowest $\delta^{13}C$ and $\delta^{15}N$ values of deer from the Mijiaya site indicate that they mainly consumed C_3 plants; in contrast, this pig diet was dominated by C_4-based food, and the cattle were reliant on mixed C_3 and C_4 plants.

AMS ^{14}C- dating of animal bones from the Mijiaya site

The radiocarbon dating of animal collagen shows that the ages of the late Yangshao phase, Miaodigou II phase and Keshengzhuang phase at the Mijiaya site can be dated to ca. 3093–2497 cal. BC, ca. 2272–1961 cal. BC and ca. 2343–1980 cal. BC, respectively (Table 1). The results are consistent with the judgment based on the archaeological remains (pottery typology) at this site [58, 59]. This provides new evidence for establishing the cultural chronology in the Guanzhong area, especially for discussing the chronological relationship between the Miaodigou II Culture and Keshengzhuang Culture.

Starch grains and phytoliths extracted from the pottery residues

The pottery residues yielded 40 starch grains. Most of them are from the carbonized residues of *li* pottery (35 grains), and only five grains are from the *guan* pottery. According to the morphological observation and measurement of these starch grains under the microscope, they are classified into five types (Fig. 3). Type A, type

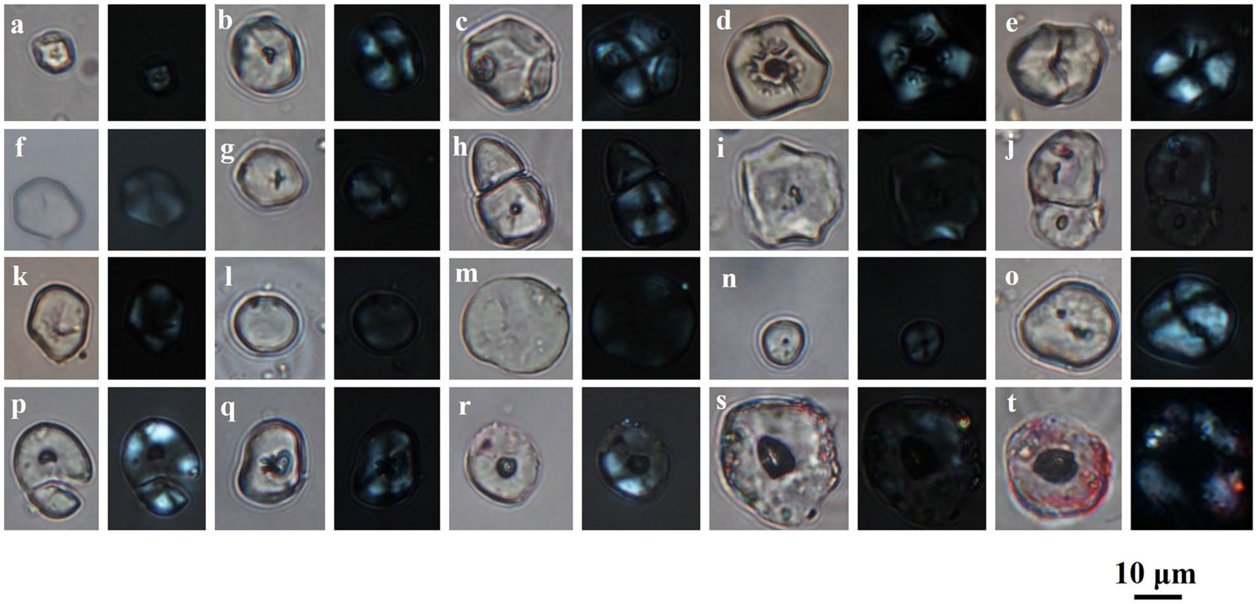

Fig. 3 Starch grains extracted from the pottery residues (*li* and *guan*) at the Mijiaya site. Type A: *Panicum miliaceum/ Setaria italica* (a-e), type B: *C. lacryma-jobi* (f-k), type C: Triticeae (l, m), type D: unidentified (n-p), type E: unidentified (q-t); the grains (a-s) are from the *li* pottery, and the grain (t) is from the *guan* pottery

B and type C are identified from millets (*Panicum miliaceum* and/or *Setaria italica*), Job's tears (*C. lacryma-jobi*) and Triticeae, respectively, based on some reference data (Additional file 1: Table S1). Moreover, some grains show the breakage of hilum, deformation and partial loss of shape, loss of extinction cross and appearance of centric hollows (Fig. 3i, k, m, p, r). These damaged grains are probably consistent with food processing [56, 68].

In addition, a total of 42 phytoliths were extracted from *li* pottery and *guan* pottery. Based on the classification and characteristics of phytoliths in some published literatures [62, 69], more than eight phytolith types have been identified, including double-peaked glume cells, bulliform, η-shaped phytoliths, rectangular, bilobate, rondel, elongate echinate, acicular and smooth-elongate (Fig. 4, Additional file 1: Table S1). Twelve parallel bilobates phytoliths forming in the rice leaves and the η-shaped phytoliths being present in the millet glume (*P. miliaceum*) are recovered from the *guan* pottery. In contrast, the more diversified phytoliths, including six parallel bilobate phytoliths and three rice bulliform phytoliths forming in the rice leaves and four double-peaked glume cells from the rice husk, are extracted from the *li* pottery. Most of the recovered phytoliths (61.9%) are associated with crops, especially the enrichment of parallel bilobate phytoliths in *guan* pottery, suggesting human agricultural activity and pottery utilization.

Statistical analysis of the primary forms and textures of potteries from the different cultural strata at the Mijiaya site

As the Fig. 5 shows, diverse types of pottery vessels were discovered in the different cultural strata at the Mijiaya site. Successive changes in the pottery assemblages are also present at this site. Particularly, certain types of Yangshao vessels (*jiandiping* and *loudou*) were replaced by some new pottery types (e.g., *li* and *jia*) in the Keshengzhuang phase.

The most common pottery type at the Mijiaya site is *guan* jar at all times. 89.2% of the *guan* potteries from the late Yangshao phase are red-sandy potteries, and 25.8% of these potteries have smoked traces. In contrast, the *guan* potteries from the Keshengzhuang phase are mainly grey-sandy (50.9%) and grey-clay (31.6%) potteries, and only six potteries (10.5%) were observed to have smoked traces. This indicates that the percentage of *guan* potteries with clay matrix had obviously increased in the Keshengzhuang phase (up to 33.4%). Meanwhile, the new pottery types (*li* and *jia*) are up to 16.1% and 8.5% in the pottery assemblage in the Keshengzhuang phase, respectively. Most *li* and *jia* potteries are grey-sandy potteries, and 20.6% of the *li* potteries have smoked traces (Fig. 6).

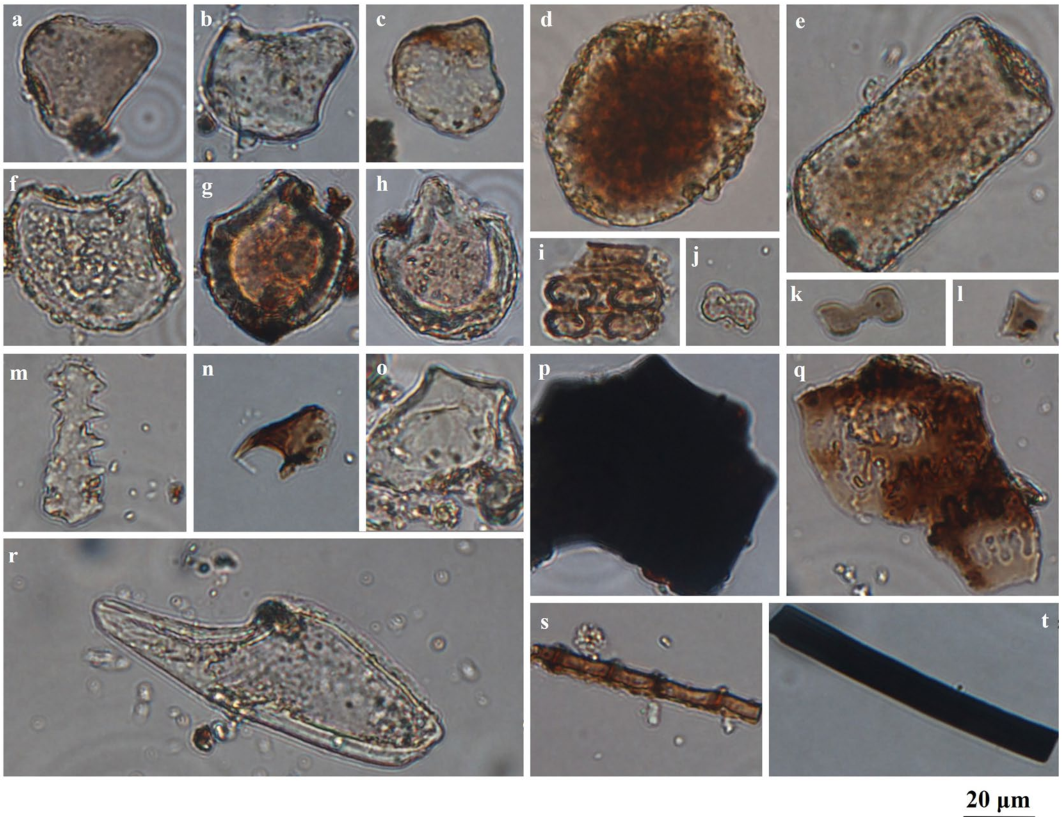

Fig. 4 Phytoliths extracted from the pottery residues (*li* and *guan*) at the Mijiaya site. Bulliform (a-d), rectangular (e), rice bulliform (f–h), parallel bilobates from the rice (i, j), bilobate (k), rondel (l), elongate echinate (m), double-peaked glume cells from the rice husk (o, p), acicular (n, r), η-shaped phytoliths from the broomcorn millet husk (q), multicellular phytolith with long saddle?(s), smooth-elongate (t); the phytoliths (i, q, s) are from the *guan* pottery, and others are from the *li* pottery

Additionally, six pottery stoves (*Taozao*, 陶灶) and one stove site (excavated in Zone I in 2010–2011) were unearthed from the Yangshao cultural stratum, and five stove sites were recovered from the Keshengzhuang cultural stratum at the Mijiaya site. These stoves, generally with burnt earth, were characterized by their rounded belly with small mouth and wide base, pocket-shape belly with flat base, and oval belly with rounded bottom or cylindrical belly. Some stoves were confirmed to be located in the houses.

Discussion

Subsistence strategies and the various food resources at the Mijiaya site

The increased evidence from the archaeobotanical and zooarchaeological studies documented that millet cultivation and animal husbandry (generally with high proportions, as shown in Fig. 7 and Additional file 1: Table S2, S3) were dominant in the human subsistence strategies in the Guanzhong area of northern China during the Late Neolithic period. The stable isotopic evidence further reflected that the millets and livestock had been taken as the staple foods for humans, and the millets also played a key role in animal husbandry at many Neolithic sites, based on their higher $\delta^{13}C$ and $\delta^{15}N$ values (Fig. 8 and Additional file 1: Table S4), such as the Yuhuazhai site [53, 70], Quanhucun site [71–73], Xinglefang site [74–76], Dongying site [52, 77] and Yangguanzhai site [78, 79]. Meanwhile, the cultivated rice had spread to this area as early as the early Yangshao period [51, 53], and rice agriculture had relatively increased in importance in the Longshan period (Fig. 7) [71, 74, 80]. Moreover, the eastwards dispersal of crops and livestock (e.g., wheat, sheep, cattle, etc.) first emerged at the western end of the Eurasiac continent before 3000 BC and contributed to the more diversified food resources [81, 82].

This study provides new evidence for the Mijiaya people engaging in rice agriculture in the Late Neolithic period, since various rice phytoliths (including parallel bilobates, rice bulliform and double-peaked glume cells from the rice leaves and husk) were extracted from the pottery residues (Fig. 4). Combining previous studies

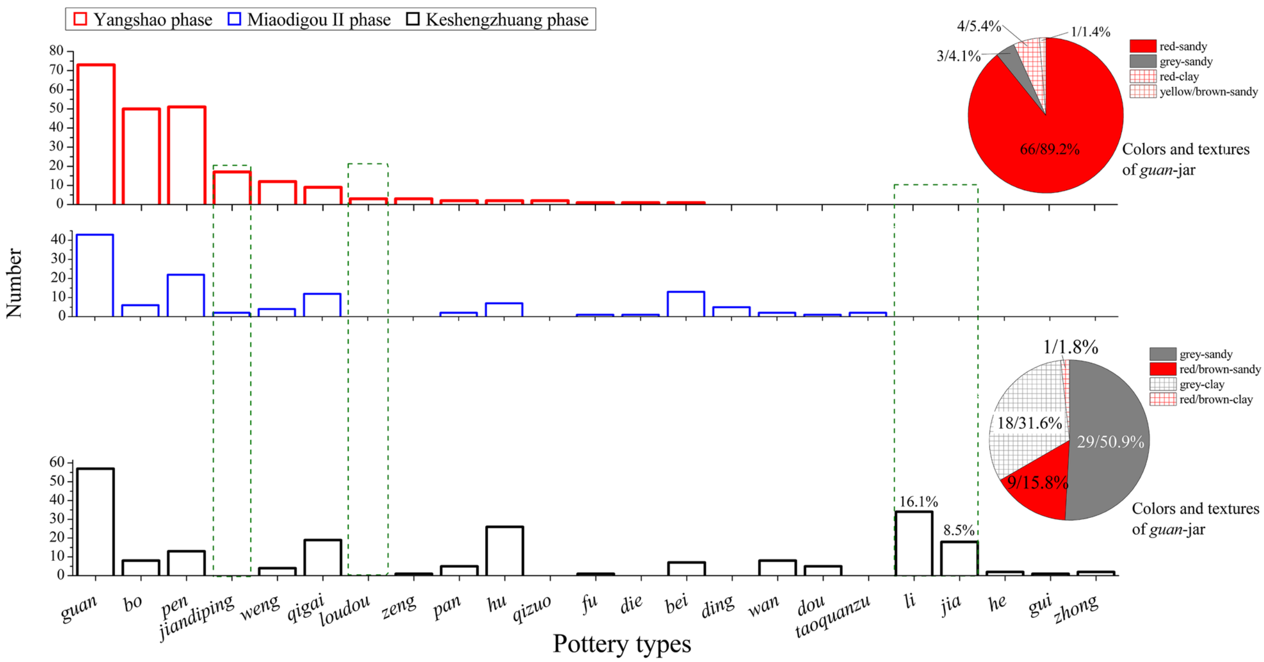

Fig. 5 Number, types, colors and textures of the potteries from the different cultural strata at the Mijiaya site. The initial data are from Ref. [58]. Pottery types include the *guan*-jar (罐), *bo*-bowl (钵), *pen*-basin (盆), *jiandiping* (pointed-based amphora) (尖底瓶), *weng*-urn (瓮), *qigai*-lid (器盖), *loudou*-funnel (漏斗), *zeng*-steamer (甑), *pan*-dish (盘), *hu*-jug (壶), *qizuo*-pedestal stand (器座), *fu*-cauldron (釜), *die*-plate (碟), *bei*-cup (杯), *ding*-tripod cauldron (鼎), *wan*-bowl (碗), *dou*-pedestal dish (豆), *taoquanzu*-pottery ring foot (陶圈足), *li*-tripod cooking vessel (鬲), *jia*-tripod vessel (斝), *he*-spouted ewer (盉), *gui*-tripod pitcher (鬶) and *zhong*-goblet (盅)

Fig. 6 Tripod vessels of *li* (鬲) and *jia* (斝) with the smoked traces (red circle) and sandy matrix (red arrow) from the excavation of the Mijiaya site in 2010–2011. a, c: tripod *jia* (2011XBM9#T0303 H34:2 and 2011XBM19#T0407 H71:59); b, d: tripod *li* (2011XBM19#T0202 H30:3 and 2011XBM19#T0202 H9:3)

(Fig. 7 and Fig. 8), the high $\delta^{13}C$ values of domestic animals and the identified η-shaped phytoliths from the broomcorn millet husk (Fig. 4-q) suggest that the Mijiaya people also engaged in millet agriculture, and the raising animals were heavily reliant on millet-based food. Moreover, the plentiful animal bones and the various bone/horn

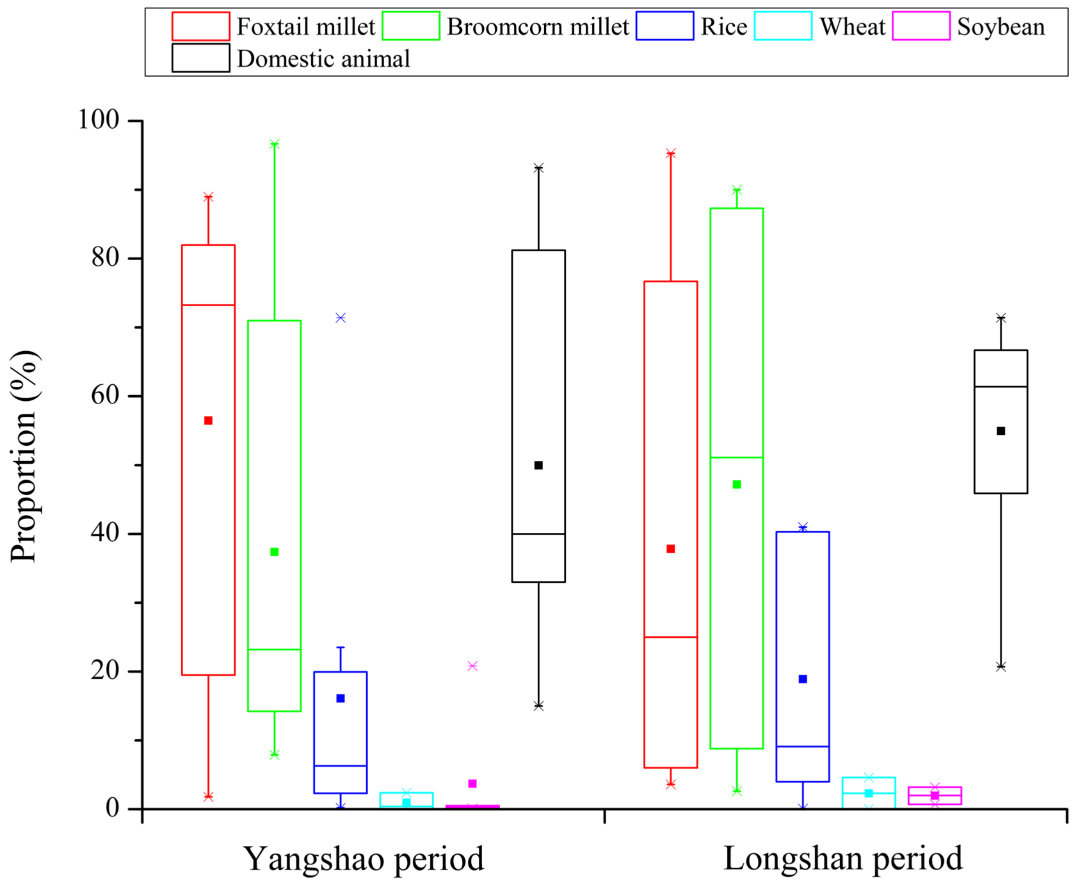

Fig. 7 The boxplot of the proportions of crops and domestic animals from archaeological sites in the Guanzhong area, North China (the initial data are listed in Additional file 1: Table S2, S3)

tools (e.g., arrowhead and awl) at the Mijiaya site [58, 59] document that the Mijiaya people practised animal husbandry and hunting activities (e.g., pig, cattle, deer, etc.). Integrated with previous research on the plant microfossils obtained from the Yangshao potteries at this site [56], it can be concluded that various gathering plants, such as Job's tears (Fig. 3), Triticeae and tubers, were also used by the Mijiaya people. Hence, it can be deduced that the Mijiaya people engaged in diversified subsistence strategies; their food resources mainly included various crops and livestock supplemented with some gathering and hunting foods in the Late Neolithic period.

Pottery function and the innovation of cooking technology at the Mijiaya site

A large quantity of pottery vessels with various types were discovered at the Mijiaya site. As the most common pottery form, *guan*-jar potteries possess diversified textures, colours and subtypes (Fig. 5). Previous studies have shown that the *guan* jars had multiple functions (cooking, storage, fermentation, etc.) and were used to process various foods (crops, gathering plants, animal fats, etc.) and/or boil water [37, 39, 43, 45, 83, 84], which is commonly associated with pottery textures and/or subtypes (with the deep belly, decorative border or two handles, respectively). Wide-mouth pots (one kind of *guan* jar) from the Mijiaya site were considered for brewing [56]. In this study, the specific functionality of this *guan*-jar with a fine sand matrix is hard to identify, but it can be confirmed that this pottery is related to the function of the crop container based on the imprints of charred seeds (Fig. 2b) and the concentration of plant microfossils (Additional file 1: Table S1).

The percentage of sandy *guan* potteries obviously had decreased (Fig. 5), and a smaller number of these potteries had smoked traces in the Longshan period at the Mijiaya site. Generally, the cooking potteries were made of sand-inclusion materials to maintain their durability during direct heating over a fire, and these potteries generally had smoked traces; in contrast, the potteries utilized for the presentation and serving of food were mainly clay [85, 86]. This suggests that the pottery *guan*-jar from the Mijiaya site possibly was reduced in cooking functionality in the Longshan period. Meanwhile, *li* and

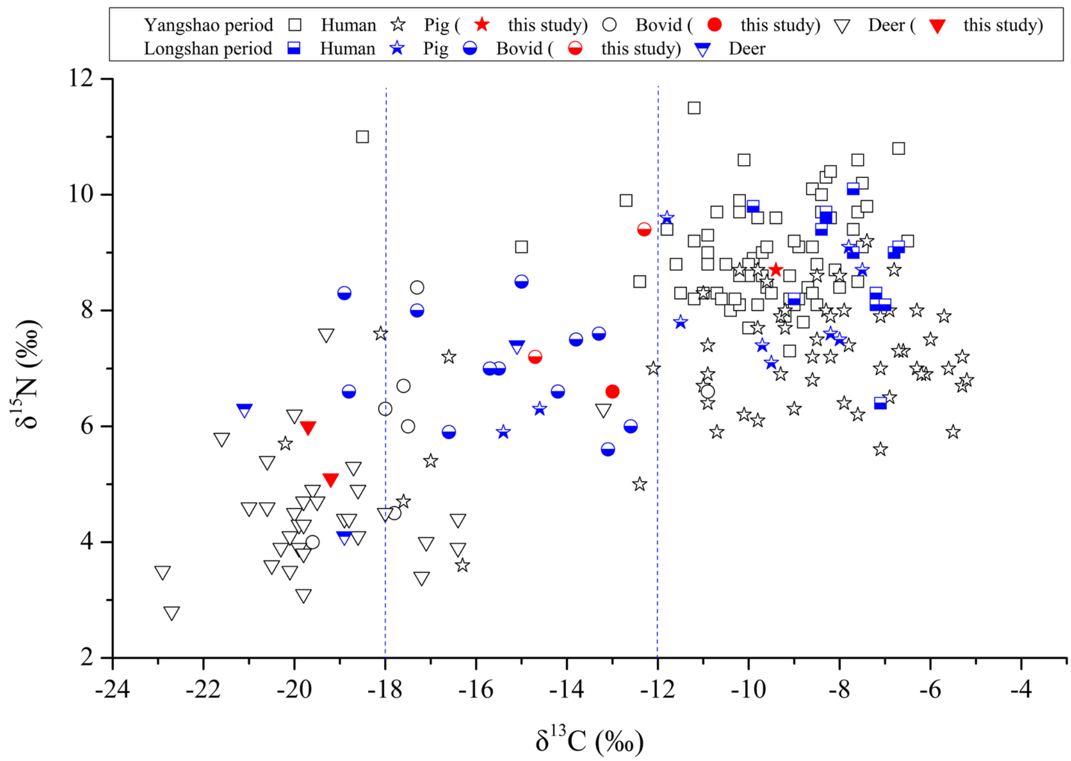

Fig. 8 The scatter plot of the $\delta^{13}C$ and $\delta^{15}N$ values of humans and some animals from the Neolithic sites in the Guanzhong area, North China (the initial data are listed in Additional file 1: Table S4)

jia potteries with relatively high percentages appeared in the pottery assemblage in the Longshan period (Fig. 5), and most of them had grey-sandy bodies commonly with smoked traces (Fig. 6). Integrated with the damaged starch grains extracted from the pottery *li*-tripod vessel (Fig. 3), it can be deduced that the *li* and *jia* potteries from the Mijiaya site were probably used for cooking food instead of pottery *guan*-jars. Moreover, more evidence shows that diversified pottery forms, including *li*, *jia*, *gui*, *pen*, *fu*, *weng*, *ding*, and *yan*, were all used to cook food mainly by boiling and steaming methods, especially in the Longshan period [35, 39, 41, 44, 84, 87, 88].

Two kinds of stoves, as auxiliary tools for food cooking, were also unearthed and generally embedded within households at the Mijiaya site. The types of stove construction were generally associated with the ceramic vessel forms, food preparation methods and fuel type [89]. Pottery stoves from the Yangshao Culture were considered as heating equipment in brewing activities [56]. Relatively large-scale stove sites and many tripod cooking pots (e.g., *li* and *jia*) were mainly discovered in the Longshan period. The cooking experiments indicated that the pots above burning fuel could achieve a different cooking quality, which is generally characterized by the high heating temperature and soft boiled grains [9]; moreover, the tripods were believed to be more suited for food preparation by simmering or boiling and more flexible for outdoor gathering [13]. Hence, we argue that Mijiaya people probably used tripod cooking pots and stoves to advance fire control technology and increase cooking efficiency for making suitable and digestible food.

Regarding stone tools [44], the phenomena of one pottery form with multiple functions was also observed in the pottery *pen*-basin, *weng*-urn [84, 87] and *jiandiping*-pointed-based amphora [37, 46, 54] in Neolithic China. For example, the functions of the pottery *pen*-basin can be briefly summarized in the sandy flat-based basin used for boiling [35], the perforated basin used for steaming and funneling [37], the spouted basin used for fermenting and filtering [57], and the basin with carved grooves used for grinding/crushing, filtering and boiling [41, 90]. Additionally, the pottery assemblage (consisting of the globular jar and perforated basin) for alcohol fermentation from the pre-Yangshao sites in the Guanzhong area had been innovated to be a special unit (including the pointed-based amphora, flat-based bottle, urn and funnel) in the Yangshao period; meanwhile, the shifts of the beer recipes were also contributed by the local agricultural development, especially the millet and rice cultivations [23, 37, 56, 57, 83, 87]. Hence, changes in the pottery assemblages were also associated with special food processing and advanced technology. However, the pointed-based amphora as the wine vessel [54] disappeared in the Longshan period at the Mijiaya site; meanwhile, some new pottery vessels (e.g., *jia*-tripod vessel, *gui*-tripod pitcher, *zhong*-goblet and *he*-spouted ewer) had been created (Fig. 5). According to the specific functions of bronze vessels with the same types from the Bronze Age sites [91–93], some of these new potteries were possibly used as wine vessels. All of these results indicate that the most basic principle of the changes in the pottery forms was to meet the same functional requirements for food processing during the Neolithic period. Sometime, pottery and stone tools are used together for more complex food processing [35, 44].

Changes in the Neolithic foodways and human subsistence and society

The innovation of technologies (including the microblade, grinding stone, pottery and food cooking) used for human adaptation had been intensified in late Pleistocene China, which greatly facilitated the broad spectrum subsistence strategy and sedentary lifestyle for hunter-gatherers who heavily relied on the more various food resources (e.g., aquatics, small-sized animals and plants) and practised the greater efficiency of food cooking and storage; all of these provided an impetus for the exploitation of agriculture [30, 31, 94–97]. With the development of handicraft industry and the appearance of agriculture in Early Neolithic China, humans gradually engaged in diverse agricultural subsistence and settled in large-scale sedentary villages; meanwhile, Neolithic foodways were mainly characterized by cultivated crops and feeding animals, innovative tools and intensive sustainable agriculture, diverse food cooking methods, elaborate cuisine and feasting traditions, food distribution and labour allocation, and social hierarchy and complexity [12, 32, 33, 38–41, 47–49, 54, 87, 98–102].

The remains of crops and livestock discovered at the Mijiaya site suggest that the Mijiaya people also subsisted on produced food. Integrated with innovative cooking technologies and elaborate foodstuffs [12, 35–49, 57, 83, 87, 90], multiple centres of pottery production and pottery assemblages could have been established in late Neolithic northern China (Additional file 1: Fig. S1) [12, 55]. A variety of ways (changing the pottery texture, form and assemblages and using auxiliary stoves) were taken by the Mijiaya people to further refine the pottery function and manage complex and efficient food processing (especially alcohol fermentation), which reflects an inherited social tradition during the Neolithic period. Furthermore, the stoves combined with cooking utensils and large houses also hint at the Neolithic social organization based on their household cooking practices, labour allocation, sedentary lifestyle and group size in populations [13, 31, 89, 103].

Conclusion

In this study, the late Yangshao Culture, Miaodigou II Culture and Keshengzhuang Culture at the Mijiaya site were dated to ca. 3093–2497 cal. BC, ca. 2272–1961 cal. BC and ca. 2343–1980 cal. BC, providing advanced evidence for establishing the cultural chronology in this area. Integrated with agricultural development and technological innovation during Neolithic China, the multi-analytical study on the food resources, cooking methods and pottery functions at this site suggests that the Mijiaya people were heavily reliant on millet and rice cultivation and animal husbandry; they also refined the pottery functions and managed complex and efficient food processing by changing pottery forms, textures and assemblages and using auxiliary stoves. Furthermore, a set of cooking utensils associated with the various stoves and large houses also indicates household cooking practices, labour allocation, sedentary lifestyle and group size in populations, which hints at the Neolithic social organization in Late Neolithic China.

Several samples were considered as a case study of the subsistence strategies of the Mijiaya people. In future studies, isotopic analyses of human and more animal bones and multianalytical studies on the residues of various pottery vessels from this site will be carried out to further explore economic-social development in Late Neolithic China.

Supplementary Information

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Additional file 1: Table S1. Starch grains and phytoliths extracted from the potteriesin the Mijiaya site. **Table S2.** The proportions of carbonized crop seedsin the crops assemblages extracted from the Neolithic sites in Guanzhong area, North China. **Table S3.** The proportions of domestic animalsin mammal assemblages from the Neolithic sites in Guanzhong area, North China. **Table S4.** The $\delta^{13}C$ and $\delta^{15}N$ values of humans and some animals from the Neolithic sites in Guanzhong area, North China. **Fig. S1.** The pottery assemblages from several Neolithic sites in North China, including Dongying, Quanhucun, Xiaweiluo, Xinzhai, Miaodigou, and Sanliqiao sites. The initial data are from Ref. [28, 53-56].

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Author contributions

YQ and JZ wrote the main manuscript text. HY and LZ collected the plant and animal data from the archaeological sites. All authors reviewed the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The original contributions presented in the study are included in the article and supplementary material, further inquiries can be directed to the corresponding authors.

Declarations

Competing interests
The authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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