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A study on the manufacturing process of a coiled wood core lacquerware unearthed in Xuzhou

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Zichen Zhao[1], Qingguang Wang[2], Zongmin Li[3,4], Yihua Sun[1], Haoran Lv[4], Yutong Chen[1] & Xing Zhao[1] ✉

The Xuzhou coiled wood core lacquerware is a rare northern Chinese example with no recorded manufacturing method. To reconstruct its techniques, we analyzed detached core and lacquer films using multiple advanced analytical tools. Results show that the lacquerware employs a coiled wood core: a base of joined narrow slats and walls of successively stacked Cunninghamia lanceolata strips, collectively known as the Quandie (圈叠) in Chinese. Brick or tile powder was used as part of the foundation layer, with a fabric layer applied above the wooden core. The lacquerware adopts the Suxiu (素髹) craft, with a black exterior and a red interior. The raw lacquer used in this lacquerware contains a mixture of urushiol and laccol, tung oil was also detected in the film. These findings clarify the manufacture of coiled wood core lacquerware and inform its scientific conservation and restoration.

Lacquer culture originated in China[1], and later spread to East Asia and the rest of the world[2,3]. Although extensive literature has documented the techniques and processes involved in lacquerware production[4–6], there are no records of coiled wood core lacquerware. In recent years, coiled wood core lacquerware has gradually attracted widespread attention, with research mainly focused on lacquerware unearthed from southern China[7–10]. The coiled wood core lacquerware unearthed in Xuzhou has, however, become the only example discovered so far in northern China.

From December 2020 to April 2021, an archaeological excavation was conducted in coordination with the Xuzhou Wenmiao Block construction project, covering an area of 900 square meters. The excavation unearthed over 1600 ceramic and metal artifacts, including a lacquered wooden object found in the Ming dynasty stratum of the northern partition beam in area TN1E1[11], which confirms its burial during or after that period but does not allow for a precise determination of its manufacturing date. When it was unearthed, the entire lacquerware was inverted on the ground and severely damaged, with only the base, parts of the walls, and dried lacquer film remaining (Fig. 1a). The base is circular, with a diameter of 132.8 mm and a thickness of ~1.7 mm, made from long, narrow wooden strips. It shows clear marks of ringed feet, marks of the a fabric layer's previous existence, and slight deformation (Fig. 1b). The surrounding area is decayed, with three cracks visible. Only eight wooden strips remain on the walls, none intact. Both the inner and outer surfaces of the lacquerware are coated with lacquer, with the inner side being red and the outer side black. There is an unclear seal inscription (Fig. 2).

This study uses modern analytical techniques to investigate the materials and manufacturing processes of this lacquerware, aiming to provide a scientific basis for the restoration and conservation of ancient lacquerware, while also offering important physical data for the study of China's lacquerware manufacturing history.

Methods

Samples

This study selects samples from the core base, strip-shaped core used to form the wall of the lacquerware, lacquer ash, and lacquer film for analysis. For convenience in documentation, the sample codes consist of an English part and a numerical part (Table 1).

Digital X-ray imaging analysis

The base of the lacquerware was supported by an acrylic plate, and digital radiographic images were acquired using a digital X-ray imaging system (Selenia™, Hologic Inc., Danbury, Connecticut, USA). The imaging was performed under the following conditions: tube voltage of 39 kVp, tube current-time product of 11.6 mAs, compression thickness of 13.6 cm, with the X-ray tube positioned at 0°, and no compression paddle used. A silver (Ag) filter was applied during imaging.

Optical microscopy (OM) analysis

For microscopic analysis, the sample C02 was first dehydrated in a graded series of polyethylene glycol aqueous solutions (PEG 1500, analytical grade), ranging from 10% to 90% (w/w), with each concentration applied for 24 h.

[1]China-Central Asia "the Belt and Road" Joint Laboratory on Human and Environment Research, Key Laboratory of Cultural Heritage Research and Conservation, School of Culture Heritage, Northwest University, Xi'an, China. [2]Xuzhou Institute of Cultural Relics Protection and Archaeological Research, Xuzhou, China. [3]Department of Cultural Heritage and Museology, Fudan University, Shanghai, China. [4]Xuzhou Museum, Xuzhou, China. ✉e-mail: zhaoxing@nwu.edu.cn

Fig. 1 | Current condition of the lacquerware sample upon excavation. a Side view. **b** Top view.

Fig. 2 | Red seal inscription on the lacquerware base.

Table 1 | Sample names and codes

Sample code	Sample description	Sampling location	Remarks
C01	Core	Fallen around the lacquerware	all samples were taken from the fallen areas
C02	Core	Fallen around the lacquerware	
A01	Lacquer ash	Foundation layer	
RF01	Red lacquer film	Inner side of the base	
BF01	Black lacquer Film	Outer side of the base	

After dehydration, the specimen was embedded in molten PEG 1500. Thin sections were prepared using a fully automated rotary microtome (RM2255, Leica Microsystems, Wetzlar, Germany) along the cross, radial, and tangential planes. Section thickness was 15 µm for cross sections and 10 µm for radial and tangential sections. The prepared slides were examined using a biological microscope (BX51, Olympus Corp., Tokyo, Japan). Microscopic images were captured for documentation. Wood anatomical features were compared with references including Timbers of China, Wood Identification Atlas, and the InsideWood database for species identification.

Extended depth-of-field microscopy analysis

The cleaned core and lacquer film samples were observed using an extended depth-of-field digital microscope (VHX-6000, KEYENCE, Osaka, Japan) at magnifications of 50×, 100×, 200×, and 300×, with illumination provided by a ring-shaped LED light source. For cross-sectional observation of the stratigraphy of the lacquer film, the samples were embedded in a fast-curing epoxy resin system (Buehler, Lake Bluff, Illinois, USA) prior to imaging.

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) analysis

The microstructure of the lacquer foundation layer was examined using a field-emission scanning electron microscope (Apreo S, Thermo Fisher Scientific, USA). The sample was sputter-coated with gold and observed at an accelerating voltage of 8 kV, using secondary electron detection, a working distance of 10 mm, and a horizontal field width of 104 µm. Elemental composition analysis was performed using an energy-dispersive X-ray spectrometer (X-Max 20, Oxford Instruments, Oxford, UK), equipped with a SuperATW window, a 20 mm^2 active area, and an energy resolution better than 127 eV, enabling detection of elements from Be (Z = 4) to U (Z = 92). Comparative analysis was conducted using modern brick powder and tile powder samples. Particle size measurements of the filler materials were conducted using Nano Measurer software (Version 1.2), and the statistical distribution of particle sizes was plotted using OriginPro 2023 (Version 10.0, OriginLab Corporation, Northampton, Massachusetts, USA).

X-ray diffraction (XRD) analysis

X-ray diffraction (XRD) analysis was performed to determine the mineralogical composition of the lacquer foundation layer using a Smart-LAB diffractometer (Rigaku, Tokyo, Japan). The specific testing conditions were as follows: tube current of 150 mA, tube voltage of 40 kV, scanning range from 5° to 90° (2θ), scanning speed of 10°/min, and step size of 0.01°. The instrument operated at a maximum power of 9 kW, utilizing a copper (Cu) target and a standard Z sample stage for measurements. Data processing was carried out using OriginPro 2023 (Version 10.0, OriginLab Corporation, Northampton, Massachusetts, USA) to analyze and interpret the spectral results.

Fourier transform infrared spectroscopy (FT-IR) analysis

Fourier transform infrared (FT-IR) spectroscopy was conducted using an FT-IR spectrometer (LUMOS, Bruker, Bremen, Germany). The potassium bromide pellet method (KBr, AR, Sinopharm Chemical, China) was employed. Both the extracted fabric and lacquer film samples were analyzed. The scanning range was 4000–600 cm^{-1}, with a resolution of 4 cm^{-1} and 24 scans per sample. Modern reference samples of cotton, hemp, wool, and silk were also tested for comparison. All spectra were processed using the smoothing function in OriginPro 2023 (Version 10.0, OriginLab Corporation, Northampton, Massachusetts, USA) with a span of 60 points.

Laser micro-confocal Raman spectroscopy (RS) analysis

Raman analysis was conducted at room temperature under darkroom conditions using a confocal Raman spectrometer (inVia, Renishaw, UK) with a 785 nm excitation laser. The test sites were examined under magnifications of 50× using the microscope. The laser power was set to 0.05% of the maximum output (300 mW), and the actual laser power reaching the sample surface was ~45 µW. The tested samples included lacquer film from the lacquerware (RF01 and BF01), as well as black lacquer film added carbon (archaeological sample). Data processing was carried out using OriginPro 2023 (Version 10.0, OriginLab Corporation, Northampton, Massachusetts, USA) to analyze and interpret the spectral results.

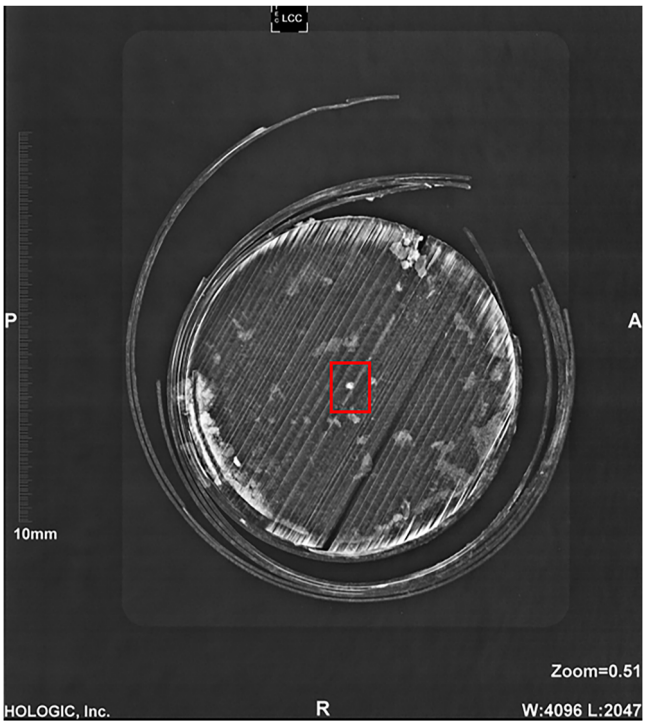


Fig. 3 | Digital X-ray radiograph of the lacquerware base. The image shows a small point at the center of the base plate, highlighted by a red square.

Fig. 4 | Cross-sectional view of sample C01 under extended depth-of-field microscopy.

Pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS) analysis

Pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS) analysis was performed using a multifunctional pyrolyzer (EGA/PY-3030D, Frontier Lab, Japan) coupled with a GC/MS system (7890B-7000C, Agilent Technologies, USA). Separation of analytes was achieved on an HP-5 capillary column (5% diphenyl/95% dimethylpolysiloxane, 30 m × 0.25 mm × 0.25 μm). Less than 1 mg of sample was mixed with 5 μL of a 10% tetramethylammonium hydroxide (TMAH) methanol solution (analytical grade, Aladdin Reagent Co., Shanghai, China) in a stainless-steel sample boat, and introduced into the pyrolysis chamber. Online methylation derivatization was performed simultaneously with pyrolysis at 500 °C for 12 s. The interface temperature between the pyrolyzer and the GC inlet

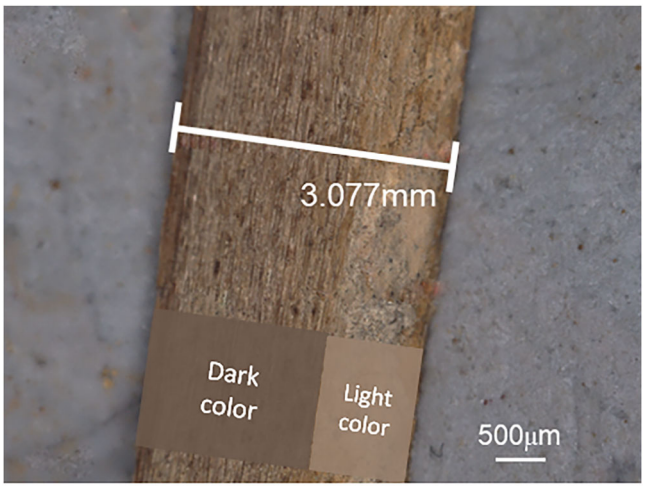


Fig. 5 | Side view of sample C01 under extended depth-of-field microscopy. **scale bar:** as indicated; **ruler tick:** marks denote distance (mm); **color contrast:** marks the boundary between lighter overlapping zones.

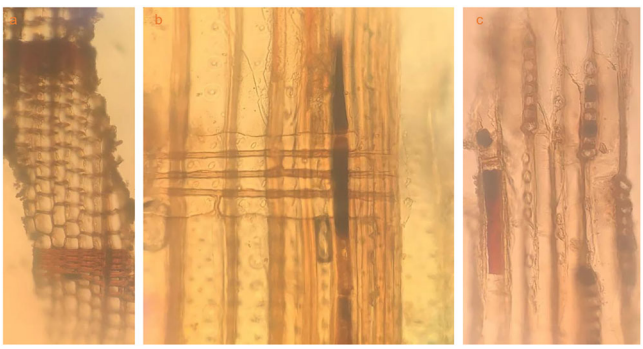


Fig. 6 | Microstructural three-cut views of core sample. a Cross-sectional view. **b** Radial view. **c** Tangential view.

was set to 300 °C. The GC injector temperature was maintained at 300°C with a split ratio of 50:1. Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min.

The GC oven temperature was initially held at 50 °C for 2 min, then ramped at 4 °C/min to 300 °C, and held for 5 min. The mass spectrometer operated in electron ionization (EI) mode at 70 eV, with an ion source temperature of 230°C and a quadrupole temperature of 150 °C. Full-scan acquisition was performed over a mass range of 10–600 m/z. Pyrolysis products were identified by interpreting mass spectra and comparing them with the NIST library, and further supported by the ESCAPE (Expert System for Characterization using AMDISPlus Excel) method introduced by the Getty Conservation Institute (GCI) in the Recent Advances in Characterizing Asian Lacquer (RAdICAL) workshop.

Results

Wooden core

Based on digital X-ray radiography, it is revealed that the base of the lacquerware is constructed from wooden slats of varying widths, and with a small point in the center of the base plate that does not pass through the base[12]. This point may have been left by a drawing compass used to cut out the circular wooden panel[13]. The outermost layer of the base is wrapped with fine wooden strips to secure the entire structure (Fig. 3).

Each strip-shaped core used to form the wall of the lacquerware was individually observed under the extended depth-of-field microscope (Fig. 4). The edges of the strip-shaped core samples are straight, with no signs of bonding, suggesting that each strip underwent processing such as

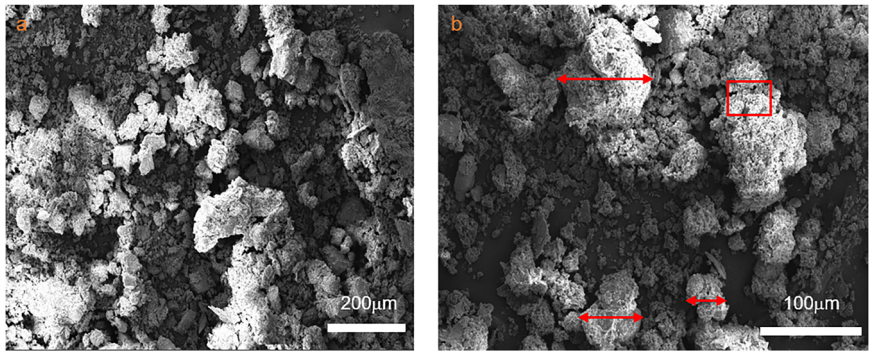


Fig. 7 | SEM image of lacquer ash (the red square indicates the EDS detection area). a 200×. **b** 500×.

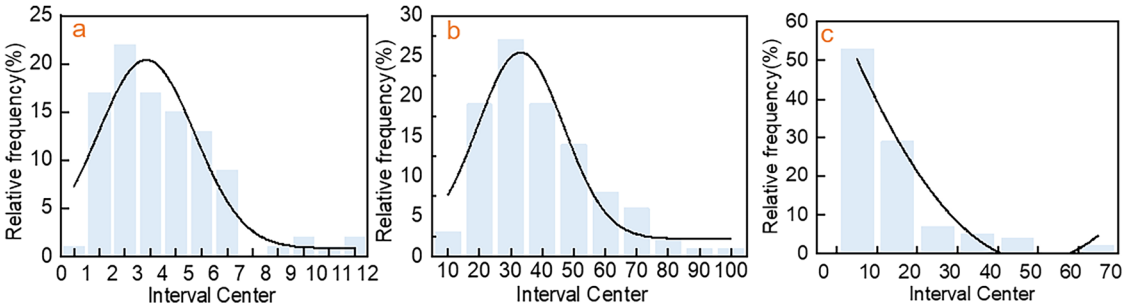


Fig. 8 | Particle size distribution. a Particle size distribution of modern tile powder. **b** Particle size distribution of modern lacquer ash. **c** Particle size distribution of archaeological lacquer ash samples).

Table 2 | EDS results of lacquer ash (Wt%)

Element	O	Si	Ca	Al	K	Mg
Content	54.18 ±0.50	18.40 ±0.53	16.08 ±0.58	6.95 ±0.50	2.71 ±0.33	1.68 ±0.16

cutting and shaving. The cross-section of the core samples is rectangular, with varying sizes between the different pieces, ranging from 0.724 cm × 2.170 cm to 1.432 cm × 2.474 cm.

Each strip-shaped core exhibits varying shades of color on the same lateral surface (Fig. 5), possibly caused by extended overlap with adjacent cores underground. The overlapping areas likely retained more of the wood's original color, while the regions in direct contact with the burial soil darkened due to prolonged environmental exposure. This observation supports the inference that the wooden strips were originally overlapped during the construction of the lacquerware core.

Microscopic observation of wood anatomical structures (Fig. 6), in combination with comparisons to standard wood identification charts and relevant literature[13], it can be determined that the core is Cunninghamia lanceolata (cedar) from the Cupressaceae family[14].

Foundation Layer

Based on SEM observations, the lacquer ash particles were found to exhibit irregular morphologies, yet discernible projections allowed for further particle size analysis (Fig. 7). Therefore, the Feret diameter was adopted to estimate particle sizes from the projected outlines[15]. As shown in Fig. 8, the particle sizes vary widely, with a maximum of 67.97 μm, a minimum of 2.28 μm, and an average of 14.04 μm, indicating a highly uneven distribution. This suggests that raw lacquer might have been used as a binding agent during preparation, leading to cohesion among the particles after curing[16].

According to Xiushilu (髹饰录), the Wanqi (垸漆)technique involves the application of lacquer ash, prioritizing horn and porcelain powders, followed by bone ash and clam powder, with brick and tile powders as alternate choices[17]. The results of EDS (Table 2) showed that the foundation layer mainly contains O, Si, Ca, Al, K and Mg, which are common elements from clay minerals and calcite[18]. The analysis results from XRD (Fig. 9) confirm that the main components of the lacquer ash from this coiled wood core lacquerware are SiO_2 and $CaCO_3$, indicating that brick powder or tile powder were predominantly used, with no evidence of animal bone ash[19,20] or other additives[21]. These findings are also consistent with the location where the lacquerware was unearthed. The coiled wood core lacquerware was discovered at the underground city site in the Wenmiao Street area of Xuzhou, which was a civilian artifact, not part of a high-status tomb's burial goods.

On the two opposite sides of a single strip-shaped core used to form the wall of the lacquerware (i.e., the sides extending from the shorter edges of the cross-section), lacquer ash was adhered, with noticeable mark visible on the lacquer ash. The width of the impressions was measured to be between 0.293 mm and 0.322 mm (Fig. 10), which directly corresponds to the fabric extracted from the base of the lacquerware. The extracted spinning yarn, composed of a single thread made of multiple fibers twisted in a "Z-twist"[22] fashion and measuring approximately 0.35 mm in diameter, was observed under an extended depth-of-field microscope. (Fig. 11). This indicates that the marks on the lacquer ash were caused by fiber layer, thus confirming that the "Biaobu (裱布)"[23].

The organization structure of the fiber is plain weave, In traditional lacquerware manufacturing, fabric was often applied over the wooden core to enhance structural stability, with silk, cotton, and ramie being the most common materials[24]. However, due to the limited quantity and poor preservation of the fabric sample, precise fiber identification could not be achieved(Fig. 12). The diameters of the yarn are around 0.200–0.300 mm, which is consistent with ramie[25] The density of the fabric was measured, and it was found to be ~5-6 threads per centimeter (Fig. 13). Considering the low thread count and the direction of the yarn, it is inferred that the fabric used to enhance structural stability was

likely made of coarse bast fiber fabric. Bast fibers (e.g., hemp, ramie,)is native to most parts of China[26], and was officially recorded in lacquerware production guidelines during the Qianlong period as a suitable material for cloth layers[27].

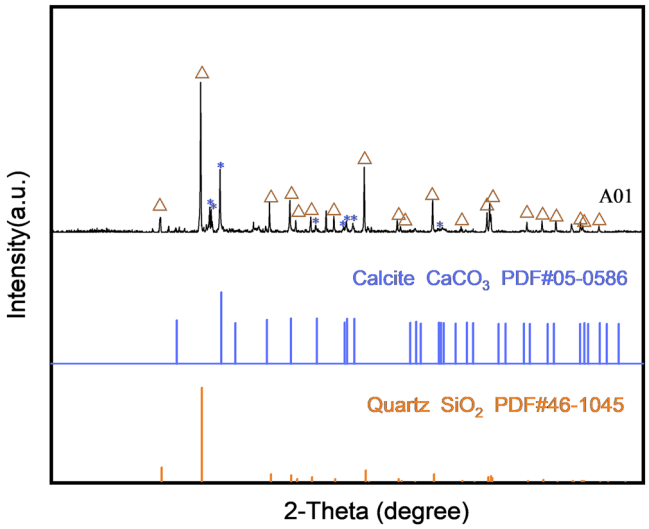


Fig. 9 | XRD pattern of A01.The diffractogram shows characteristic reflections assigned to silica (SiO_2) and calcium carbonate ($CaCO_3$).**orange**: SiO_2; **blue**:$CaCO_3$; **x-axis:** 2θ (°); **y-axis:** intensity (a.u.).

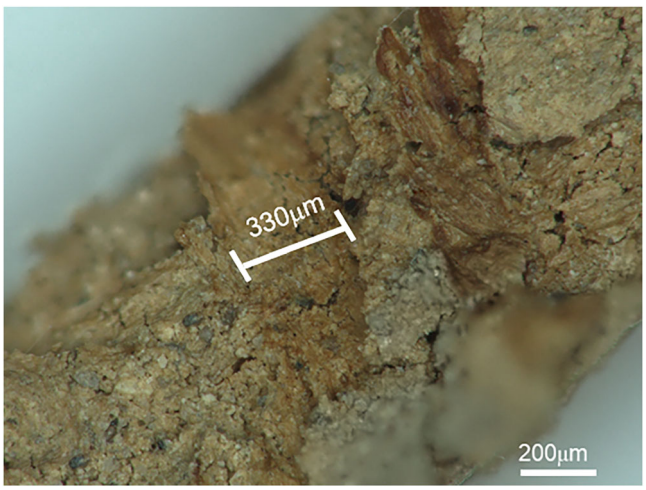


Fig. 10 | Image of the side of a single strip-shaped core with marks caused by the fabric layer under extended depth-of-field microscopy. **scale bar:** as indicated; **ruler tick:** marks denote distance (μm).

Lacquer film

In this lacquerware, red lacquer was applied to the interior and black lacquer to the exterior. Based on extended depth-of-field and SEM imaging of the red and black lacquer film samples (Fig. 14), the red lacquer film comprises two distinct layers: a dark brown primer layer (70.82 μm) and a red pigmented lacquer layer (55.96 μm). A smooth and straight interface between the two indicates that polishing was performed.

The FT-IR results (Fig. 15) show that both the red and black lacquer film samples exhibit a series of absorption peaks corresponding to raw lacquer at wavenumbers of 3400 cm^{-1}, 2920 cm^{-1}, 2620 cm^{-1}, and 1453 cm^{-1}. Among them, the absorption peak around 3400 cm^{-1} corresponds to the hydroxyl group on the phenolic ring of the lacquer phenol; the range 2800–2900 cm^{-1} shows the asymmetric and symmetric stretching vibration peaks of methyl and methylene groups; 1500–1620 cm^{-1} corresponds to the aromatic ring skeleton vibration; and 1453 cm^{-1} corresponds to the bending vibration peak of the methylene group. Absorption peaks around 778–779 cm^{-1} are caused by in-plane bending vibrations of 1,2,3-trisubstituted groups in lacquer phenol, indicating that the lacquer phenol mainly consists of a 1,2,3-trisubstituted structure. The main infrared absorption peaks of the lacquer film samples match well with the infrared characteristic absorption peaks of lacquer phenol (one of the main components of raw lacquer). Therefore, it can be concluded that the film-forming material for all the lacquer films is raw lacquer[28].

The Raman analysis results show that the red lacquer film sample has clear and concise characteristic peaks (Fig. 16a), with a peak at 254 cm^{-1}

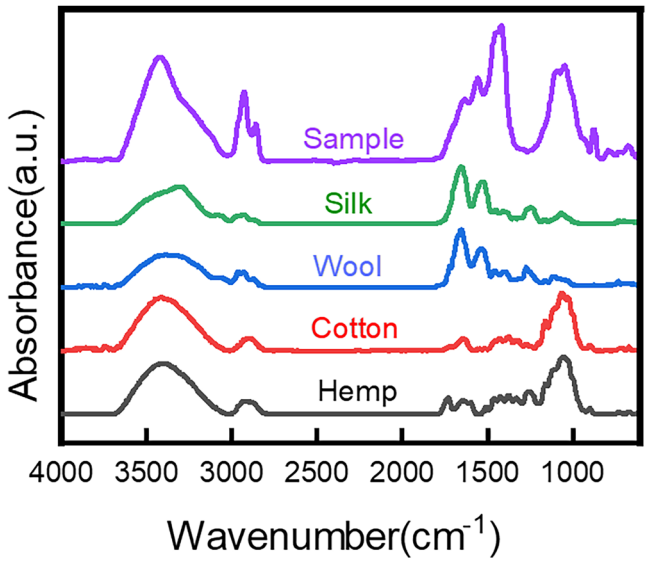
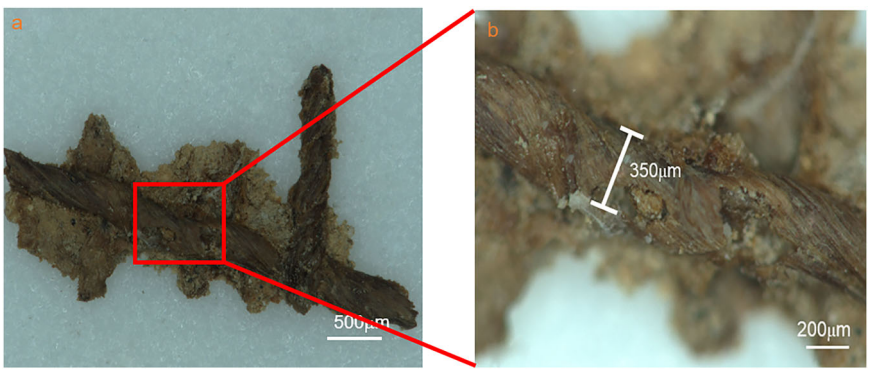


Fig. 12 | FTIR spectra comparison: extracted fabric sample versus modern reference standards for cotton, hemp, wool, silk.

Fig. 11 | Image of ancient spining yarn extracted from the lacquerware base under extended depth-of-field microscopy. a 50×. **b** 200×.



corresponding to the cinnabar characteristic peak[29], indicating that the colorant used in the red lacquer layer is cinnabar. The Raman spectrum of the black lacquer film sample (Fig. 16b) does not exhibit the distinct characteristic absorption peaks of carbon black commonly seen in ancient black lacquer films[30], suggesting that no chromogenic substances were likely added. The black coloration is presumed to originate primarily from the raw lacquer itself.

Lacquer identification was achieved by Py-GC/MS. The discrimination between the three types is based in the detection of marker compounds for each lacquer[31]: 1.2-dimethoxy-3-pentadecenylbenzene for Toxicodendron vernicifluum; 1,2-dimethoxy-3-heptadecenylbenzene and1,2-dimethoxy-3-heptadecenylbenzene for Toxicodendron succedaneum; 1,2-dimethoxy-3-(10-phenyldecyl)benzene and 1,2-dimethoxy-3-(12-phenyldodecyl)benzene for Melanorrhoea usitate[32]. The compound class distribution of the lacquer film from the coiled wood core sample is visualized using the ESCAPE protocol, as shown in Fig. 17. The Py-GC/MS analysis identified a range of characteristic degradation products of raw lacquer, including substituted phenolic derivatives and their oxidation products, saturated and unsaturated hydrocarbons, alkylbenzenes, simple phenols, and aliphatic carboxylic acids. These pyrolysates are consistent with the thermal decomposition profile of urushiol-type lacquers. The analysis revealed the simultaneous presence of both 3-pentadecylcatechol and 3-heptadecylcatechol, with the former occurring at a significantly higher concentration than the latter. Notably, the lacquer used in this lacquerware contains a mixture of urushiol and laccol, suggesting that urushi and laccol raw lacquer may have been mixed. While T. succedaneum has traditionally been associated with lacquers from Vietnam and Taiwan, this species has also been recorded in southern China[33], particularly in Guangxi Province where

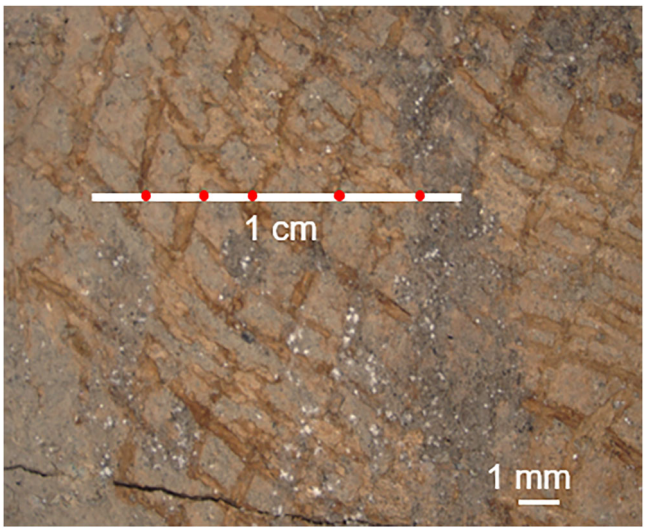


Fig. 13 | Image of the side of a base core with marks caused by the fabric layer under extended depth-of-field microscopy.white line segment: 1 cm (scale); red dots: stitches (needle holes).

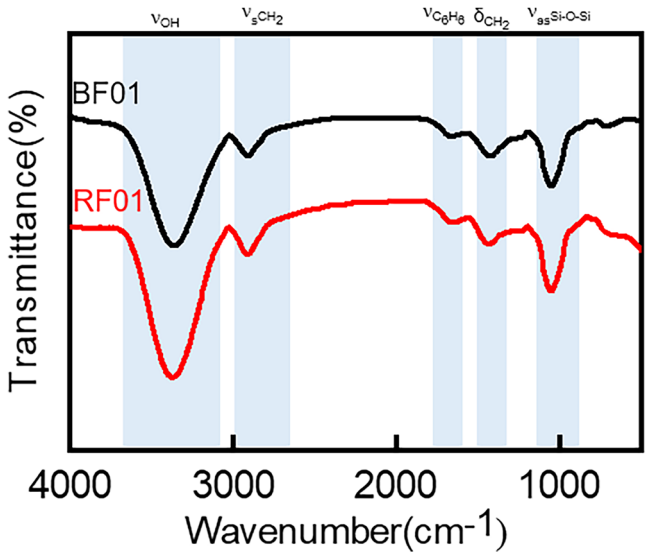
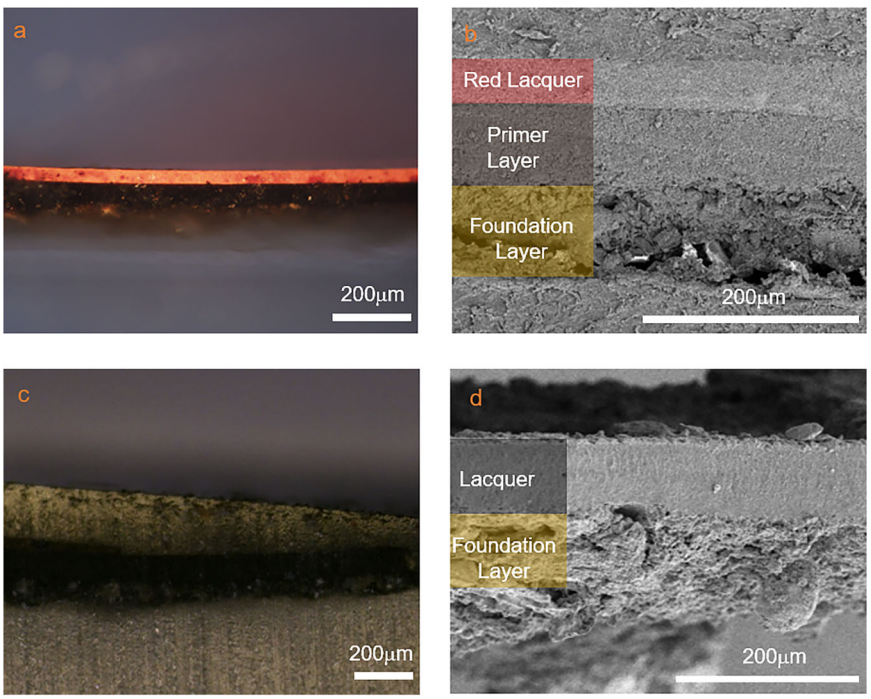


Fig. 15 | Infrared spectrum of lacquer film sample. **black curve:** black lacquer film; **red curve:** red lacquer film; **x-axis:** wavenumber (cm^{-1}); **y-axis :** intensity (a.u.).

Fig. 14 | Cross-sectional microscopic images of lacquer film samples. a OM image of RF01 sample, **b** SEM image of RF01 sample, **c** OM image of BF01 sample, **d** SEM image of BF01 sample).



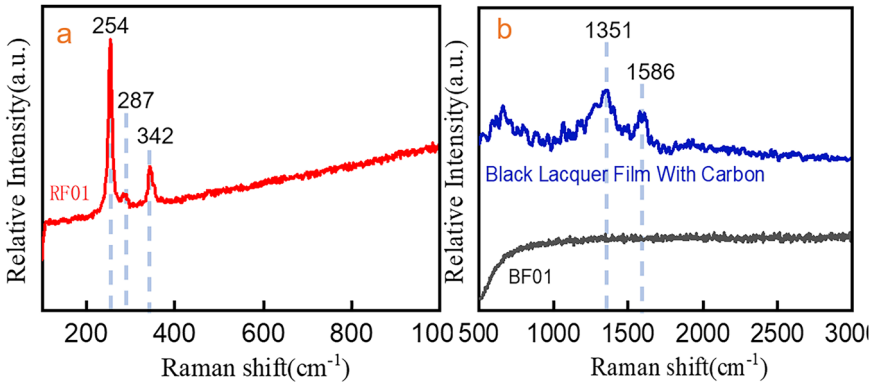


Fig. 16 | Raman spectrum of lacquer film sample. **a** RF01 sample. **b** BF01 sample and black lacquer samples from other excavated site.

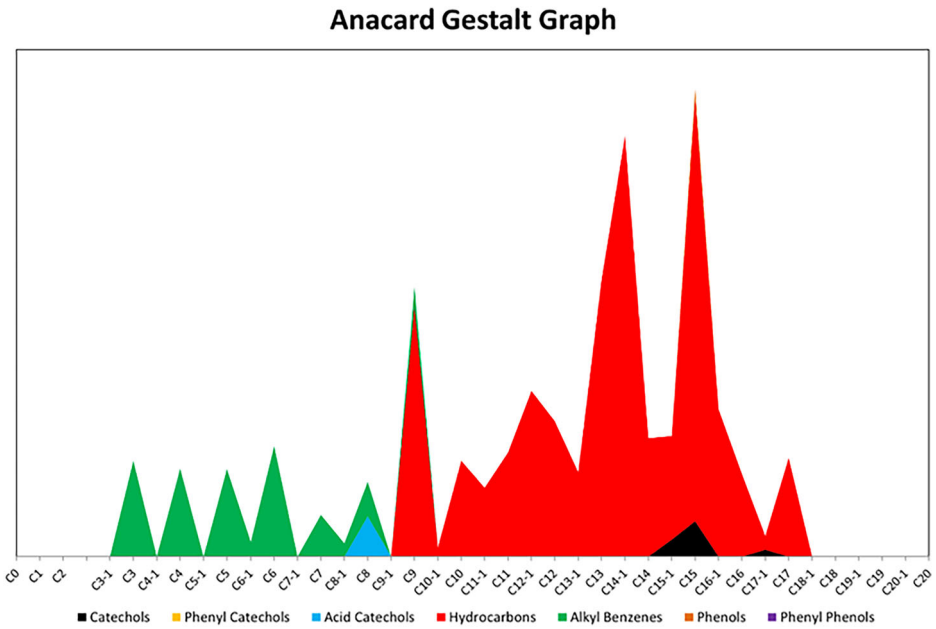


Fig. 17 | Pyrolysis products of the coiled wood core lacquer film.

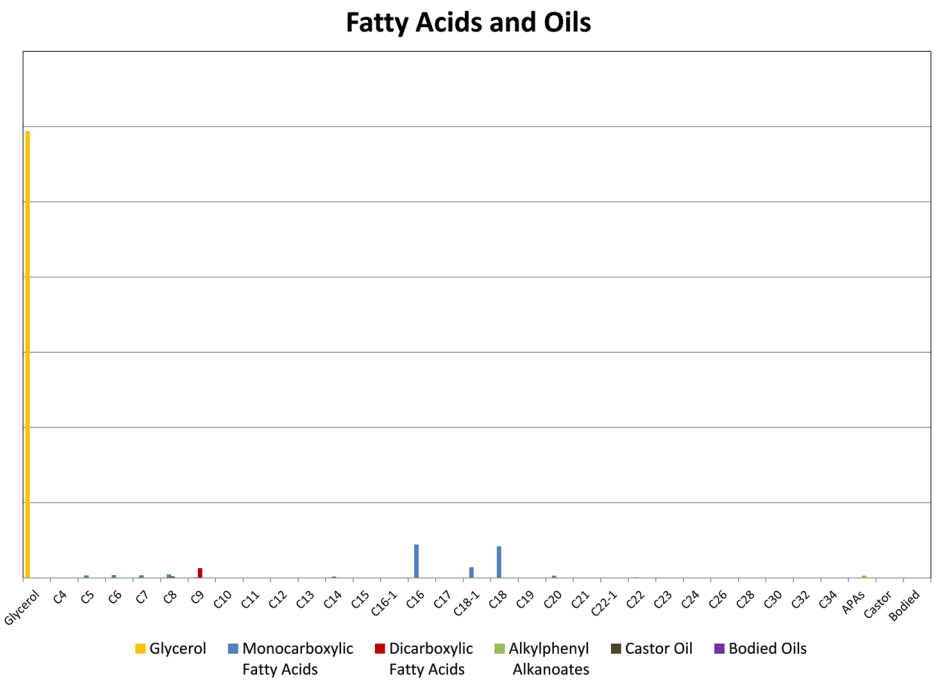


Fig. 18 | Distribution of fatty acids in the coiled wood core lacquer film.

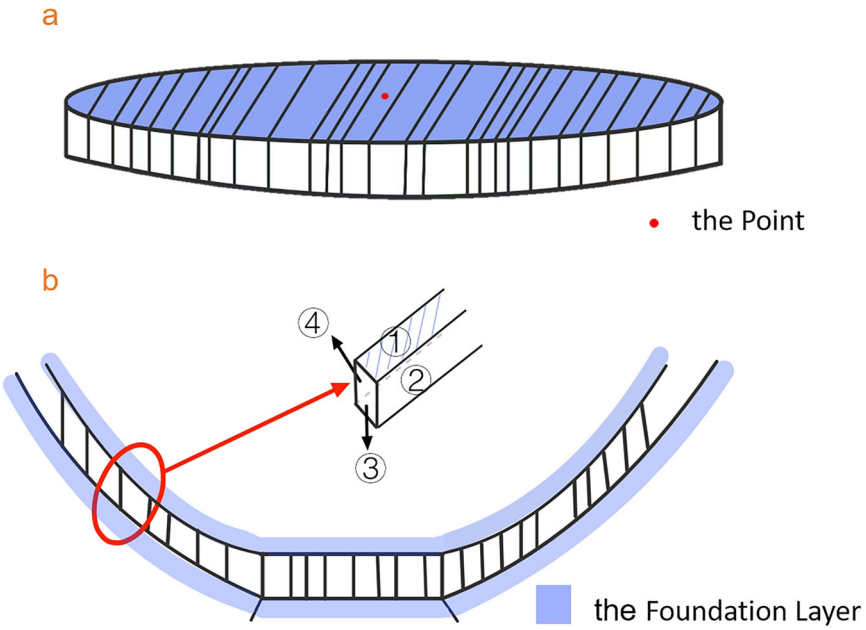


Fig. 19 | Schematic cross-sectional diagram of the restored core of the lacquerware. a The base of the lacquerware. **b** The wall of the lacquerware.

Donglan lacquer trees have been identified as Rhus succedanea[34]. This species has also been identified in several Chinese export lacquerwares[35], supporting its historical use in southern China. Therefore, it is likely that the lacquer used in this lacquerware originated from within China.

A significant amount of glycerol, methyl monocarboxylate and methyl dicarboxylate was detected in the lacquer film (Fig. 18), suggesting that vegetable oil may have been incorporated into the lacquer solution[36]. Previous studies have shown that different drying oils exhibit specific P/S (palmitic/stearic) and A/P (azelaic/palmitic) ratios[37], which can be used to identify the type of vegetable oil present. The ratio of azelaic acid to palmitic acid (A/P) was 0.29, confirming that drying oils were added to the coiled wood core lacquer film. The ratio of palmitic acid to stearic acid (P/S) was 1.06, which is consistent with tung oil (1–1.2), suggesting that tung oil was the drying oil added to the lacquer film[38].

Alkyl phenyl alkenoates (APAs), a well-established marker of heated tung oil, were notably absent in our sample. This absence can likely be attributed to the processing method employed in the preparation of the tung oil. Existing literature indicates that APAs typically form when drying oils are subjected to elevated temperatures during processing[39]. Consequently, the absence of APAs in our sample suggests that the oil was not exposed to high-temperature treatment, and raw tung oil may have been utilized instead.

Discussion

Based on the results obtained from a series of scientific analyses, the regular arrangement of the wooden strip samples suggests a unique core-forming craft, providing insight into the manufacturing process of the lacquerware in Xuzhou. The lacquerware unearthed from Xuzhou is a coiled wood core lacquerware, which can be divided from the outer to the inner layers as follows: black lacquer film layer, foundation layer (composed of lacquer ash and fabric), wooden core, foundation layer (lacquer ash and fabric), and red lacquer film layer.

Figure 19 is a schematic cross-sectional diagram of the restored wooden strip of the lacquerware. The base of the lacquerware(Fig. 19a) is constructed from wooden slats of varying widths, with the outermost layer wrapped in fine wooden strips to reinforce and secure the structure. Each strip-shaped core used to form the wall of the lacquerware that comes into contact with the inner red lacquer film is labeled as surface ①. Following the ordering method in Fig. 19b, the surfaces are named in a clockwise direction as surfaces ②, ③, and ④. According to the extended depth-of-field microscope observations, the coiled wood core manufacturing process can be explained as follows: Surface ① and its opposite (surface ③) show marks caused by the fabric layer; surface ② and its opposite (surface ④) exhibit a distinct color boundary with varying shades. The formation of this phenomenon corresponds closely to the coiled wood core manufacturing process: surfaces ① and ③ constitute the inner and outer surfaces of the lacquerware, adjacent to the foundation layer; surfaces ② and ④, which are stacked with adjacent Cunninghamia lanceolata (cedar) wooden strips, exhibit color variation likely resulting from extended overlap during burial, where areas in direct contact with soil appear darker, while overlapping regions retain the original wood tone, forming a distinct boundary between light and dark areas on the same surface[40].

The coiled wood core, exemplifying the traditional Quandie (圈叠) core-forming technique in lacquerware production in China, is formed by joining narrow wooden slats for the base, with a small point in the center of the base plate, and successively stacking strips of tough and resilient wood for the walls[41]. The coiled wood core technique differs from the rolled wooden core[13]. In coiled wood core, multiple thin wooden strips are layered and stacked, which disperses the internal stress of the wood, helps to overcome the anisotropy of the wood, and makes it less prone to deformation and cracking. The material range is more extensive, as ordinary wood can be used for the strip stacking, avoiding the limitations of using high-quality materials like camphor wood or nanmu wood that were previously required for making the wooden strips. This alleviates the problem of material shortages. Additionally, the appearance of the coiled wood core craft has provided more diverse shapes in lacquerware development. Unlike the bending wood technique, which can only produce cylindrical shapes like boxes, goblets, or cups[42,43], coiled wood core is more suited for creating small, curved forms such as bowls, basins, and plates, as well as detailed molding of flowered edges in lacquerware.

The foundation layer of the lacquerware is composed of lacquer ash and fabric. The lacquer ash primarily consists of brick powder or tile powder, while the fabric—used to enhance structural stability—is inferred to be a coarse bast fiber fabric.

The entire lacquerware adopts the Suxiu (素髹) technique, which is characterized by the application of monochrome lacquer finishes without additional decorative patterns[44]. Red lacquer was applied to the interior surface, while black lacquer was applied to the exterior.

The raw lacquer used in this lacquerware contains a mixture of urushiol and laccol; tung oil was also detected in the film. The red lacquer

film comprises two distinct layers: a dark brown primer layer and a red pigmented surface layer. The smooth and well-defined interface between them suggests that polishing was performed between layers. The primer layer, traditionally referred to as Caoqi (糙漆)[45], serves an essential function in lacquerware production by leveling the underlying lacquer ash layer and providing a stable foundation for the subsequent pigmented lacquer and any decorative applications[46]. In contrast, the black lacquer on the exterior was applied as a single-layer coating, without a visible primer.

Overall, this study provides a solid scientific foundation for understanding the historical evolution of lacquerware manufacturing process. In particular, it offers compelling evidence supporting the coiled wood core craft as a distinctive and sophisticated method of core-forming. The findings contribute significantly to the reconstruction of ancient technological systems and the broader appreciation of traditional Chinese craftsmanship.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

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References

1. Zhai, K. et al. The earliest lacquerwares of China were discovered at Jingtoushan site in the Yangtze River Delta. *Archaeometry* **64**, 218–226 (2022).
2. Hidaka, K., Werhahn, S. Y. Lacquerware as a Global Commodity: Distribution and Imitation of Maki-e, in: Japanese Art – Transcultural Perspectives, Brill 279–303 (2024).
3. Sangchel, S. A study on the inflow routes and utilization of East Asian lacquerware in the art market of France during the 17th and 18th centuries, Misuljaryo-Natl. *Mus. Korea Art. J.* **102**, 38–64 (2022).
4. Hong, S. A review of a century of archaeological research on ancient Chinese lacquerware, South. *Cult. Relics* **4**, 48–54 (2021).
5. Romero, R., Illán, A. & Bondía, C. Three studies of luxury Mexican lacquer objects from the 16th to the 19th centuries: analysis of materials and pictorial techniques. *Herit* **6**, 3590–3605 (2023).
6. Wu, F., Zhang, L. & Chen, J. A study on the manufacturing process of Song Dynasty lacquerware with circle-overlapping method. In Collection of Papers on Museum Scientific Research, (ed., Chengyuan M.) 460 (Shanghai Science and Technology Literature Press, 1996).
7. Jiang, C. The protection and restoration of Song Dynasty lacquerware with coiled wood bodies excavated from Changsha, Excavat. *Lit* **3**, 123–129 (2023).
8. Wu, H., Zhao, Y., Lei, Q., Zhao, Y. & Dong, J. A study on the materials and manufacturing processes of Tang and Song Dynasty lacquer bowls unearthed in Jianli, Hubei. *Jianghan Archaeol.* **5**, 122–126 (2023).
9. Li, Y. Appreciation of newly unearthed Song Dynasty lacquerware with elements of Wuxi. *Cult. Relics Identif. Appreciat.* **12**, 4 (2020).
10. Cai, Y. Analysis of the wood-based circle-overlapping production process of Song Dynasty plain lacquerware with flower-shaped rims. *China Raw Lacq.* **42**, 30–33 (2023).
11. Li, Z. A study of the preservation of partial remains in the Xuzhou underground city site, Changzhou Cult. *Relics Rev.* **0**, 122–125 (2021).
12. Koike, T. Study on struction and conservation for East-Asian antique lacquer wares by X-ray CT and scientific analysis. *Int. J. Biol. Macromol.* **41**, 497–503 (2019).
13. Kawabata, K. enko X-ray CT scan analysis of the wood-based structure of Chinese carved lacquerware. *China Raw Lacq.* **34**, 48–52 (2015).
14. Cheng, J. *The Chinese Timber Encyclopedia* (China Forestry Press, 1992).
15. Walton, W. H. Feret's statistical diameter as a measure of particle size. *Nature* **162**, 329–330 (1948).
16. Wu, H., Liu, L., Liu, W., Gong, D. Microscopic analysis of Qing Dynasty painted coffin ornamentation excavated in Yangqu, Shanxi, Jianghan Archaeol., S1 119–127 (2014).
17. Hao, X., Wang, X., Zhao, Y., Tong, T. & Gong, Y. Identification of minerals and mineral pigments in lacquer by the comprehensive comparative analysis of spectroscopy information. *Spectrosc. Lett.* **54**, 446–457 (2021).
18. Hao, X., Wu, H., Zhao, Y., Tong, T., Li, X., Yang, C., Tang, Y., Shen, X. & Tong, H. Analysis on the composition/structure and lacquering techniques of the coffin of Emperor Qianlong excavated from the Eastern Imperial Tombs. *Sci. Rep.* **7**, 8446 (2017).
19. Wang, X., Hao, X., Zhao, Y., Tong, T., Wu, H., Ma, L., Shen, X. & Tong, H. Systematic study of the material, structure and lacquering techniques of lacquered wooden coffins from the Eastern Regius Tombs of the Qing Dynasty, China. *Microchem. J* **168**, 2021 (2021).
20. Li, Z., Li, X., Yu, J., Sun, Y., Geng, J. & Zhao, X. The lacquer craft of the Corridor Coffin (微道棺) from Tomb No. 2 of Tushan in Eastern Han Dynasty. *Xuzhou Coat* **14**, 1222 (2024).
21. Zheng, L., Wang, L., Zhao, X., Xi, Z., Wu, X. & Fan, X. Characterization of the materials and techniques of red lacquer painting of a horizontal plaque inscribed by General Feng Yü-hsiang. *Coatings* **13**, 583 (2023).
22. Wang, Y., Chen, L. & Peng, X. The practice of spinning cotton yarn using S twist. *Fabr. Sci. Technol. Prog.* **4**, 28–30 (2014).
23. Lin, Z. A study on the Gong Chengjun Zhongni-style qin lacquer craftsmanship in the collection of the Hunan Museum. *Cult. Herit. Archaeol. Sci.* **36**, 107–117 (2024).
24. Hao, X., Wu, H., Zhao, Y., Tong, T., Li, X., Yang, C. & Tong, H. Scientific investigation of the lacquered wooden coffin of Xiang Fei excavated from Eastern Royal Tombs of the Qing Dynasty. *N. J. Chem.* **41**, 9806–9814 (2017).
25. Wang, J. *Papermaking Raw Materials of China: An Atlas of Micrographs and the Characteristics of Fibers*, 163–165 (China Light Industry Press, 1999).
26. Han, B., Yang, Y., Wang, B., Jiang, H. & Sablier, M. Rapid identification of bast fibers in ancient handmade papers based on improved characterization of lignin monomers by Py-GCxGC/MS. *Cellulose* **30**, 575–590 (2023).
27. Liu, L., Wu, H., Liu, W., Gong, D. & Zhu, Z. Lacquering craft of Qing Dynasty lacquered wooden coffins excavated from Shanxi, China – A technical study. *J. Cult. Herit.* **20**, 676–681 (2016).
28. Park, J., Choi, J., Lee, U., Kang, M. & Kim, S. Lacquer techniques in the late Joseon dynasty. *J. Korean Wood Sci. Technol.* **51**, 69–80 (2023).
29. Han, B., Fan, X., Chen, Y. & Gao, J. M Sablier The lacquer crafting of Ba state: Insights from a Warring States lacquer scabbard excavated from Lijiaba site (Chongqing, southwest China). *J. Archaeol. Sci. Rep.* **42**, 103416 (2022).
30. Huang, Y., Fu, Y., Shen, D., Lindahl, K. & Wei, S. Characterization and identification of an archaeological 'lacquer' pipe. *Herit. Sci.* **12**, 142 (2024).
31. Veenhoven, J., van Keulen, H., Saverwyns, S., Lynen, F. & van Bommel, M. Optimising the analysis of Anacardiaceae (Asian lacquer) polymers using pyrolysis-gas chromatography-mass spectrometry. *J. Anal. Appl. Pyrolysis* **170**, 105845 (2023).
32. Petisca, M. J., Frade, J. C., Cavaco, M., Ribeiro, I., Candeias, A., Graça, J., & Rodrigues, J. C. Chinese export lacquerware: characterization of a group of Canton lacquer pieces from the 18th and 19th centuries, Unpublished conference proceedings or internal report. (2011).
33. Niimura, N. & Miyakoshi, T. Characterization of natural resin films and identification of ancient coating. *J. Mass Spectrom. Soc. Jpn.* **51**, 439–457 (2003).

34. Wan, Y. Y., Lu, R., Du, Y. M., Honda, T. & Miyakoshi, T. Does Donglan lacquer tree belong to Rhus vernicifera species?. *Int. J. Biol. Macromol.* **41**, 497–503 (2007).
35. Piert-Borgers, B. Untersuchungen zum Fassungsaufbau von Koromandellacken – Vorüberlegungen zu einem Projekt, ICOMOS. *Hefte Dtsch. Natlkom.* **35**, 92–106 (2000).
36. Qin, Y. et al. Exploring thitsi in Qing Dynasty lacquerware: Insights from a preliminary study. *npj Herit. Sci.* **13**, 46 (2025).
37. Heginbotham, A., Chang, J., Khanjian, H. & Schilling, M. R. Some observations on the composition of Chinese lacquer. *Stud. Conserv.* **61**, 28–37 (2016).
38. Schilling, M. R., Heginbotham, A., van Keulen, H. & Szelewski, M. Beyond the basics: a systematic approach for comprehensive analysis of organic materials in Asian lacquers. *Stud. Conserv.* **61**, S3–S27 (2016).
39. Evershed, R. P., Copley, M. S., Dickson, L. & Hansel, F. A. Experimental evidence for the processing of marine animal products and other commodities containing polyunsaturated fatty acids in pottery vessels. *Archaeometry* **50**, 101–113 (2008).
40. Yang, M., Honda, T., Yanagida, A., Okuyama, M. & Wakiya, S. Impact of thermal polymerization and burial environment on the distribution of components within lacquer films. *npj Herit. Sci.* **13**, 236 (2025).
41. Cai, W., Cheng, Y. K., Tseng, H. H., Tai, H. C. & Lo, S. F. Identification and characterization of wood from antique Chinese guqin zithers. *J. Cult. Herit.* **53**, 72–79 (2022).
42. Lei, Q. et al. Scientific analysis of lacquer film from a Warring States Chu coffin unearthed at Tomb No. 1 in Xinzhuang, Pingdingshan, Henan. *Cult. Relics Prot. Archaeol. Sci.* **36**, 66–72 (2024).
43. Song, J., Yao, Z., Xu, J., Yang, J. & Li, H. Study on the lacquering technique of an erbei cup unearthed from Tomb No. 1 at Shuangdun, Lu'an. *Cult. Relics Prot. Archaeol. Sci.* **34**, 38–44 (2022).
44. Wang, S. *The Explanation of Xiushilu: Study on Chinese Traditional Lacquer Technology*, Revised edition. (Cultural Relics Press, 1983).
45. Kim, S. C. & Lee, K. H. Observation by the microscopic analysis of lacquer layer for identification of lacquer-ware function. *J. Korean Wood Sci. Technol.* **36**, 96–104 (2008).
46. Zhu, Z. et al. Shedding new light on lacquering crafts from the Northern Wei Dynasty (386–534 CE) by revisiting the lacquer screen from Sima Jinlong's Tomb. *J. Cult. Herit.* **71**, 309–319 (2025).

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Author contributions

Z. Zhao, H. Lv, Y. Chen, and X. Zhao designed the research; Q. Wang, Z. Li provided archeological samples and background; Z. Zhao, Y. Sun performed analyses; and all authors helped drafting/revising the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Xing Zhao.