npj | heritage science

Article

https://doi.org/10.1038/s40494-026-02376-z

Comparative analysis of lacquer application techniques for heritage museum-quality lacquered furniture imitations and establishment of a standardized evaluation system

Qirong Li[1], Fan Zhang[1] ✉, Wei Jia[2] & Yanqiu Xie[3]

This study addresses the lack of unified technical specifications and evaluation standards for museum-quality imitations of lacquered furniture, which has resulted in inconsistencies in appearance and material performance. To improve visual presentation and support cultural interpretation, four commonly used lacquer techniques were examined: black lacquer, vermilion lacquer, golden lacquer, and hardwood rubbed lacquer. Five sets of comparative experiments were conducted across traditional techniques, modified traditional methods, and modern alternatives, producing 95 samples. The samples were tested for gloss, surface roughness, color difference (ΔE), film adhesion, and thermal cycling performance. A comprehensive evaluation framework was developed covering process stability, visual characteristics, and physicochemical properties. Traditional techniques showed the highest stability and color fidelity, followed by modified traditional methods. Cashew lacquer exhibited low stability and limited depth. Industrial lacquer maintained stable gloss and ΔE but produced overly bright colors. In physicochemical properties, traditional lacquer achieved the best adhesion, while water-based industrial lacquer performed the worst. All samples met acceptable thermal cycling performance. Based on the integrated results, grading criteria and parameter thresholds were established, providing a practical reference for museum applications and a systematic evaluation method for related research.

Lacquered furniture, as an important bearer of world cultural heritage, embodies remarkable artistic value and profound cultural significance through its sophisticated surface finishing techniques[1]. The integration of intricate craftsmanship with diverse composite materials not only demonstrates ancient artisans' refined understanding of material properties and techniques but also reflects the distinctive aesthetic sensibilities of their respective eras[2]. Today, numerous well-preserved lacquered furniture artifacts are exhibited in major museums worldwide, serving both as tangible material for academic research and as irreplaceable carriers for cultural dissemination and cultural transmission and recognition of their value[3].

Because of their long histories, the lacquer layers of museum collections often suffer deterioration caused by human handling, environmental fluctuations, and storage conditions. Common problems include warping, cracking, and detachment of lacquer layers[4]. Severely damaged objects can no longer be exhibited, while those with minor deterioration may be restored and returned to display[5]. In museum practice, the period between restoration cycles is often described as the dormant period of an artifact[6]. To fill the display gaps created during such dormant periods, museums frequently employ high fidelity imitations of lacquered furniture that reproduce the original form, style, and craftsmanship[7]. Imitations have become widespread in museums internationally, serving to protect original objects and to provide audiences with a more complete presentation of ancient technologies[8]. They also address the challenges associated with the transportation of original artifacts and can be flexibly used in traveling or temporary exhibitions[9].

[1]College of Materials Science and Technology, Beijing Forestry University, Beijing, China. [2]Department of Palace History, The Palace Museum, Beijing, China. [3]College of Materials and Energy, Central South University of Forestry and Technology, Changsha, China. ✉e-mail: Zhangfan_23@bjfu.edu.cn

In China, practical cases of large lacquered furniture imitations are especially common. Representative institutions include the Palace Museum in Beijing, the Shenyang Palace Museum, and museums affiliated with the Eastern and Western Qing Tombs. Replicated pieces are often used in restored historical settings as spatial elements to recreate historical interiors. Examples include the zitan carved and enamelled chair in the Jingshen Palace of the Palace Museum, the golden lacquer throne fragments in the Hall of Ancestral Worship, and numerous other replicated furnishings, such as yellow silk umbrella stands.

Existing research on ancient lacquered furniture has primarily concentrated on analyzing the composition and identifying the materials of lacquer coatings. After decades of development, the field has established a mature analytical framework that typically relies on the combined use of multiple techniques to ensure accuracy and reproducibility[10–12]. Common methods include Fourier transform infrared spectroscopy, Raman spectroscopy, scanning electron microscopy with energy dispersive spectroscopy, and X-ray diffraction, all of which are used to identify inorganic pigments, fillers, and microstructures within lacquer films. In recent years, pyrolysis gas chromatography mass spectrometry has become increasingly prominent because of its high sensitivity to urushiol-based components and its characteristic pyrolysis patterns, making it a crucial method for distinguishing raw lacquer, cashew lacquer, and other plant-based lacquers[13,14]. Supported by these analytical approaches, scholarly consensus now identifies ancient lacquer films as composite structures consisting of organic binders together with inorganic fillers and pigments. These films contain polymerized urushiol matrices blended with ground layers, inorganic colorants, or metal powders, forming multilayered systems that provide mechanical strength along with chromatic and optical properties[15,16].

While analytical techniques have advanced and consensus on material composition has gradually formed, materials science research has simultaneously deepened our understanding of the intrinsic properties of natural lacquer. Recent studies on the chemical composition of urushiol molecules, the enzyme-catalyzed polymerization mechanism, the formation of gloss, weathering behavior, and color stability have provided important theoretical foundations for understanding the formation and aging of traditional lacquer films[17]. At the same time, in response to evolving conservation needs, modern substitute materials such as cashew lacquer, industrial acrylic coatings, and water-based industrial paints have been increasingly adopted in conservation and replication practices[18–21]. However, current research focuses predominantly on their physicochemical properties[22,23] and lacks systematic investigation of their visual performance within the context of museum replication, as well as their behavior when combined with other materials. As a result, the selection of lacquer materials in current replication practices remains insufficiently supported by scientific evidence.

From a practical standpoint, the traditional production process of large lacquered furniture is highly complex. It involves substrate preparation, the application and polishing of lacquer ash ground layers, and the repeated coating of raw lacquer. Each step depends heavily on artisan experience and requires precise control of timing, environmental conditions, and material behavior[24]. In real museum settings, however, replication projects are constrained by exhibition schedules, funding conditions, and local climate requirements. Consequently, it is often difficult to fully adhere to traditional procedures. More importantly, the absence of unified technical standards and evaluation criteria leads to substantial differences among institutions in material selection, process execution, and quality assessment. As a result, replicas displayed within the same exhibition may vary significantly in appearance and craftsmanship. Such inconsistencies can weaken the authenticity of the historical information conveyed by the exhibits and may hinder visitors' understanding of traditional lacquer aesthetics.

In light of these challenges, this study selects four historically representative lacquer decoration techniques, namely black lacquer, cinnabar lacquer, gilded lacquer, and hardwood wiped lacquer. By systematically comparing the visual performance and physicochemical properties of traditional techniques, improved techniques, and modern substitute processes, the study aims to clarify their respective characteristics and limitations. The objective is to establish a scientific and operational technical framework and evaluation system specifically designed for museum replication of lacquered furniture. This framework seeks to achieve controllable production procedures, quantifiable quality indicators, and standardized technical methodologies. By establishing verifiable correlations among visual appearance, material stability, and exhibition requirements, the study aims to provide reliable guidance for museum replication practices and to support the sustainable transmission of traditional lacquer craftsmanship in contemporary contexts.

Methods

Materials and sample preparation

This study conducted a comprehensive review and analysis of historical records and traditional craft manuals related to lacquerware. These sources provided the basis for reconstructing traditional techniques and determining four representative lacquer processes: black lacquer, vermilion lacquer, golden lacquer, and hardwood wiping lacquer. The sources of these techniques, the selection criteria, and the methodological procedures used to define them are summarized in Table 1.

Traditional lacquer materials investigated in this study include natural black lacquer, vermilion lacquer, and golden lacquer. Natural black lacquer is produced by reacting ferrous sulfate with sodium hydroxide to generate an iron hydroxide precipitate, which then chemically combines with raw lacquer (also known as clear lacquer)[25(pp. 68–70)]. The reaction for forming iron hydroxide is as follows:

$$FeSO_4 + 3NaOH \rightarrow Fe(OH)_3 \downarrow + Na_2SO_4$$

In fact, soot was also commonly used for preparing black lacquer in ancient times. In this study, however, iron hydroxide was selected as the primary black pigment mainly due to its clear documentation in historical sources and its superior controllability in experimental conditions—iron-based blacks exhibit more stable chromatic behavior and better dispersion in raw lacquer[25(pp.69)].

Traditional vermilion lacquer is prepared from natural cinnabar (HgS) mixed with raw lacquer[26], while traditional golden lacquer is made by blending imitation gold foil with raw lacquer[25(pp.76–79)]. The semi-cooked lacquer used for the hardwood wiping lacquer technique was sourced from Tashui Town, Anzhou District, Mianyang City, Sichuan Province, China.

In addition to lacquer preparation, traditional lacquer ash consists of three layers—coarse ash, medium ash, and fine ash—and final surface gloss is achieved by wiping semi-cooked lacquer combined with pearl-powder polishing.

To compare the effects of traditional, modified, and modern lacquer techniques on visual appearance and physicochemical performance, a series of controlled comparative experiments was designed. In addition to the four traditional techniques, commonly employed simplified or alternative procedures used in museum practice and contemporary production were incorporated, including:

- Replacing traditionally prepared colored lacquer with modern lacquer, which is made by mixing natural raw lacquer with synthetic pigments[20];
- Reducing the number of lacquer-ash layers;
- Adjusting lacquer-ash formulations, such as substituting modern tile ash for loess and glutinous rice powder;
- Using cashew lacquer—a lower-cost synthetic lacquer—in combination with tile ash to prepare modified lacquer ash[27];
- Applying industrial putty as the base layer, followed by industrial color lacquer as the finishing coat.

Each technique was treated as an independent system, and cross-application or hybridization was strictly avoided. For example, mixing cashew lacquer with raw lacquer significantly delays drying time and was therefore prohibited[23].

The experiments included four technique groups—black lacquer, vermilion lacquer, golden lacquer, and hardwood wiping lacquer. Based on differences in materials and lacquer-ash configurations, each group

Table 1 | Scope, selection criteria, and methodological procedures for determining traditional lacquer techniques used in the experimental design

Review dimension	Description	Description	Specific guidance for material selection and technique reconstruction
1. Scope of technique selection	Historical documents detailing lacquer materials and procedures, including *The Records of Lacquerwork (Xiushi Lu)*, *Rules for Craftsmen* (Vol. IV), *Huojidang*, and *Couxiangdang of Qing dynasty*; Archival records and reproduction documentation from the Palace Museum, Shenyang Palace Museum, and the Eastern/Western Qing Tombs; Contemporary technical summaries related to black lacquer, cinnabar lacquer, gold lacquer, and hardwood wiping lacquer.	Historical documents detailing lacquer materials and procedures, including *The Records of Lacquerwork (Xiushi Lu)*, *Rules for Craftsmen* (Vol. IV), *Huojidang*, and *Couxiangdang of Qing dynasty*; Archival records and reproduction documentation from the Palace Museum, Shenyang Palace Museum, and the Eastern/Western Qing Tombs; Contemporary technical summaries related to black lacquer, cinnabar lacquer, gold lacquer, and hardwood wiping lacquer.	Provides the foundational theoretical and historical basis for determining the structural framework, workflow, and key procedural stages of the four lacquer techniques.
2. Selection criteria	Clarity of technique: priority given to records containing explicit information on materials, sequential steps, ratios, or operational details; Cross-source consistency: a technique is considered "verifiable" only when its description appears consistently in at least two independent sources.	Clarity of technique: priority given to records containing explicit information on materials, sequential steps, ratios, or operational details; Cross-source consistency: a technique is considered "verifiable" only when its description appears consistently in at least two independent sources.	Ensures that only verifiable, traceable, and reconstructible procedures are incorporated, forming a reliable basis for defining experimental parameters.
3. Method of extraction and cross-comparison	Procedural chain decomposition: Organization of steps into comparable nodes (ground preparation → ash layer construction → pigment application → polishing/finishing); Material–procedure–effect analysis: identification of key operations influencing visual and physicochemical properties; Comparison with modern materials: Evaluation of performance deviations between contemporary substitutes and traditional material requirements.	Procedural chain decomposition: Organization of steps into comparable nodes (ground preparation → ash layer construction → pigment application → polishing/finishing); Material–procedure–effect analysis: identification of key operations influencing visual and physicochemical properties; Comparison with modern materials: evaluation of performance deviations between contemporary substitutes and traditional material requirements.	Identifies the core procedural elements of each technique, such as: For Black, Vermilion, and Golden lacquer: selection and preparation of coarse and fine lacquer layers, pigment preparation, and ash-layer composition; For hardwood wiping lacquer: choice of oil–lacquer mixtures and polishing powders; These findings define controllable experimental variables such as ash layer fineness and thickness, types of coarse/final lacquer, drying/curing conditions, etc.

Table 2 | Experimental design for comparative analysis of lacquer finishing processes

Group	Process type	Lacquer type	Ash layers	Drying conditions	Net time (days)
Black-1	Traditional lacquer ash + natural black	Natural raw lacquer + $Fe(OH)_3$	7	40 °C, 95% RH (CTHC)	45.5
Black-2	Traditional lacquer ash + modern black	Raw lacquer + modern pigment	7	40 °C, 95% RH (CTHC)	17.5
Black-3	Simplified lacquer ash + modern black	Raw lacquer + modern pigment	3	40 °C, 95% RH (CTHC)	15.5
Black-4	Cashew lacquer ash + cashew black	Cashew lacquer	3	Air-drying, 30 °C, 25% RH	~15.5
Black-5	Water-based putty + water-based black	Industrial water-based paint	–	Air-drying, 30 °C, 25% RH	0.5
Vermilion-1	Traditional lacquer ash + natural vermilion	Raw lacquer + cinnabar	7	40 °C, 95% RH (CTHC)	18.5
Vermilion-2	Traditional lacquer ash + modern vermilion	Raw lacquer + modern vermilion pigment	7	40 °C, 95% RH (CTHC)	17.5
Vermilion-3	Simplified lacquer ash + modern vermilion	Raw lacquer + modern vermilion pigment	3	40 °C, 95% RH (CTHC)	15.5
Vermilion-4	Cashew lacquer ash + cashew vermilion	Cashew lacquer + vermilion pigment	3	Air-drying, 30 °C	~15.5
Vermilion-5	Water-based putty + water-based vermilion	Industrial water-based paint	–	Air-drying, 30 °C	0.5
Golden-1	Traditional lacquer ash + natural gold	Raw lacquer + gold powder	7	40 °C, 95% RH (CTHC)	19
Golden-2	Traditional lacquer ash + modern gold	Raw lacquer + modern gold pigment	7	40 °C, 95% RH (CTHC)	17
Golden-3	Simplified lacquer ash + modern gold	Raw lacquer + modern gold pigment	3	40 °C, 95% RH (CTHC)	15
Golden-4	Cashew lacquer ash + cashew gold	Cashew lacquer + gold pigment	3	Air-drying, 30 °C	~15
Golden-5	Water-based putty + water-based gold	Industrial water-based paint	–	Air-drying, 30 °C	0.5
Hardwood-1	Tizhuang wiping + pearl powder polishing	Semi-mature lacquer	–	40 °C, 95% RH (CTHC)	15
Hardwood-2	Tizhuang wiping + modern polishing	Semi-mature lacquer	–	40 °C, 95% RH (CTHC)	15
Hardwood-3	Cashew transparent wiping + modern polishing	Cashew transparent lacquer	–	Air-drying, 30 °C	15
Hardwood-4	Water-based lacquer (primer + topcoat)	Industrial water-based lacquer	–	Air-drying, 30 °C	1

CTHC Constant Temperature and Humidity Chambe, "Net time (days)" refers to the actual processing time required for each step, excluding non-operational waiting periods. Detailed formulations, sanding and polishing procedures, and full preparation conditions are provided in Supplementary information (Supplementary Tables S1–S5), along with complete information on all commercial materials, including manufacturers and product names.

contained five baseline groups for black lacquer, five for vermilion lacquer, five for golden lacquer, and four for hardwood wiping lacquer, resulting in a total of 19 comparative process groups. Five samples were prepared for each group, yielding a total of 95 experimental samples. All samples were fabricated in a standardized size of 10 × 10 × 1 cm to ensure consistency in substrate dimensions for coating application and comparative testing. All samples were produced within the same fabrication batch to minimize variability arising from material or environmental differences during preparation. The detailed experimental design and sample preparation procedures are presented in Table 2.

Table 3 | Classification and description of the 19 coating techniques

Label	Technique group	Process description
A	Black lacquer	Traditional lacquer ash + natural black lacquer
B	Black lacquer	Traditional lacquer ash + modern black lacquer
C	Black lacquer	Modern simplified lacquer ash + modern black lacquer
D	Black lacquer	Cashew lacquer ash + cashew black lacquer
E	Black lacquer	Water-based putty sealer + water-based industrial black lacquer
F	Vermilion lacquer	Traditional lacquer ash + natural vermilion lacquer
G	Vermilion lacquer	Traditional lacquer ash + modern vermilion lacquer
H	Vermilion lacquer	Modern simplified lacquer ash + modern vermilion lacquer
I	Vermilion lacquer	Cashew lacquer ash + cashew vermilion lacquer
J	Vermilion lacquer	Water-based putty sealer + water-based industrial vermilion lacquer
K	Golden lacquer	Traditional lacquer ash + natural golden lacquer
L	Golden lacquer	Traditional lacquer ash + modern golden lacquer
M	Golden lacquer	Modern simplified lacquer ash + modern golden lacquer
N	Golden lacquer	Cashew lacquer ash + cashew golden lacquer
O	Golden lacquer	Water-based putty primer + water-based gold lacquer
P	Hardwood wiping lacquer	Tizhuang lacquer wiped clear + pearl powder polishing
Q	Hardwood wiping lacquer	Tizhuang lacquer wiped clear + modern polishing powder
R	Hardwood wiping lacquer	Cashew transparent lacquer wiped clear + modern polishing powder
S	Hardwood wiping lacquer	Water-based lacquer primer + water-based topcoat

Table 4 | Test item and reference standard

Test item	Reference standard
Gloss measurement	GB/T 4893.4—2013 "Test for physicochemical properties of furniture surface paint films—Part 4: Determination of gloss"
Surface roughness measurement	ISO 21920-2:2021 "Geometrical Product Specifications (GPS)—Surface texture: Profile method—Part 2: Terms, definitions and surface texture parameters"
CIE lab color parameter determination	ISO/CIE 11664-4:2023 "Colorimetry—Part 4: CIE 1976 L*a*b* colour space"
Film adhesion test	GB/T 4893.7—2013 "Test for physicochemical properties of furniture surface paint films—Part 7: Determination of adhesion by cross-cut test"
Thermal cycling resistance test	GB/T 4893.6—2013 "Test for physicochemical properties of furniture surface paint films—Part 6: Determination of resistance to cold-hot temperature difference"

For clarity and ease of comparison, the 19 coating techniques used in this study (labeled A–S) are summarized in Table 3. Detailed step-by-step fabrication images and final surface presentations of all 95 samples are provided in Supplementary information (Supplementary Figs. S1–8).

Testing procedures and equipment

Following the completion of sample fabrication, a series of systematic tests was conducted to objectively evaluate differences in appearance and performance across various processes and color groups. These measurements were selected to address the central questions of the study—namely, whether modern and modified processes can visually approximate traditional lacquer finishes, whether they possess sufficient mechanical and environmental stability for museum display, and which specific process parameters most strongly influence these differences.

The study employed gloss, surface roughness, CIE Lab color parameters, reflectance, film adhesion, and thermal cycling resistance to comprehensively assess the visual qualities and physicochemical stability of different lacquer techniques. Gloss, roughness, and CIE Lab values reflect how well each technique reproduces surface optical characteristics and tactile texture[28–30], while reflectance measurements enable the construction of spectral reflectance curves that further elucidate color differences among process groups[31–33]. At each measurement position, gloss, surface roughness, and CIE Lab values were recorded once to ensure consistency across all samples. Film adhesion addresses the risk of abrasion or impact that replicas may encounter during exhibition and handling[34,35], and thermal cycling tests simulate sudden fluctuations in temperature and humidity to evaluate the stability of lacquer coatings during transport or display in non-climate-controlled environments[36].

The standards referenced for testing each indicator in this study are shown in Table 4 below.

Measurements of gloss, surface roughness, and Lab values were taken at three positions (top, middle, and bottom) on each experimental sample[37]. Tests for paint film adhesion and thermal cycling resistance were performed on one randomly selected sample from each process group.

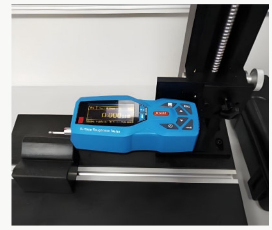
The testing equipment and corresponding parameters are presented in Table 5.

Data processing and analysis

Data processing and analysis in this study comprised three dimensions—process stability, visual appearance, and physicochemical properties:

- Process stability was assessed by examining the intra-group dispersion of key quantitative indicators. Box plots were used to visualize the distribution range and consistency of gloss, roughness, and CIE Lab values (Section "Distribution characteristics and outlier treatment"). Additionally, one-way ANOVA with 95% confidence-interval error bars (Section "Variance analysis and confidence intervals") was used to quantify the error range of each process group, providing a

Table 5 | Sample test equipment and related information

No.	Equipment (Model)	Manufacturer	Parameters	Main application	Picture
1	Jitai instrument TR210 surface roughness tester	Beijing Jitai Instrument Testing Equipment Co., Ltd. (TIME® series)	Sampling length: 2.5 mm; Evaluation length: 5; Measuring range: ±80 μm; Main display: Ra	Measurement of surface roughness (Ra value) of specimens	
2	LS195 gloss meter	Shenzhen Linshang Technology Co., Ltd.	Measuring angle: 60°; Measuring spot: 9 × 15 mm; Measuring range: 0–200 GU	Measurement of surface gloss (GU value) of specimens	
3	Dataflash 110 spectrophotometer (for structural color reflectance spectra and chromatic values)	Datacolor Inc., USA	Light source: pulsed xenon flash lamp (including D65 spectrum and UV component); Spectral range: 400–700 nm, step 10 nm; Bandwidth: 10 nm; Reading time: approx. 3 s	Measurement of Lab values and color reflectance of specimens; color simulation	
4	BYK 5116 cross-cut adhesion tester	BYK-Gardner GmbH, Germany	Cross-cut mode: 9 × 9	Qualitative evaluation of coating adhesion	
5	HWS-350 constant temperature and humidity chamber	Shaoxing Siyang Instrument Manufacturing Co., Ltd.	Temperature control range: 5–60 °C; Cooling power: 330 W; Heating power: 1200 W. During testing: 40 °C ± 2 °C, 95% ± 3% RH; sample placement time: 1 h; cycle repeated 3 times. After testing: reset to 20 °C ± 2 °C, 60–70% RH; specimens stored for 18 h[54]	Testing thermal cycling resistance of specimens	
6	BCD-589118 refrigerator	Anhui Wan'ai Electric Technology Co., Ltd.	Low-temperature setting: −20 °C; sample placement time: 1 h; cycle repeated 3 times	Testing thermal cycling resistance of specimens	

statistical basis for defining technical tolerances, while also determining whether differences among process groups were statistically significant.

- Visual appearance analysis focused on comparing color differences (ΔE) and spectral reflectance curves between modified modern processes and traditional techniques (Section "Color differences and reflectance features").
- Physicochemical properties were evaluated primarily through paint film adhesion and resistance to thermal cycling (Section "Adhesion and thermal cycling performance").

Results

Distribution characteristics and outlier treatment

Box plots, as a widely used statistical visualization method, provide an intuitive representation of data distribution and dispersion[38]. In this study, box plots were employed to compare the variability of test indicators across different process groups, serving as a key reference for assessing process stability. The results of the box plot analysis for each indicator are presented below (Fig. 1).

Since the CIE L, a, and b parameters mainly function as fundamental variables for calculating color difference (ΔE), their absolute values have

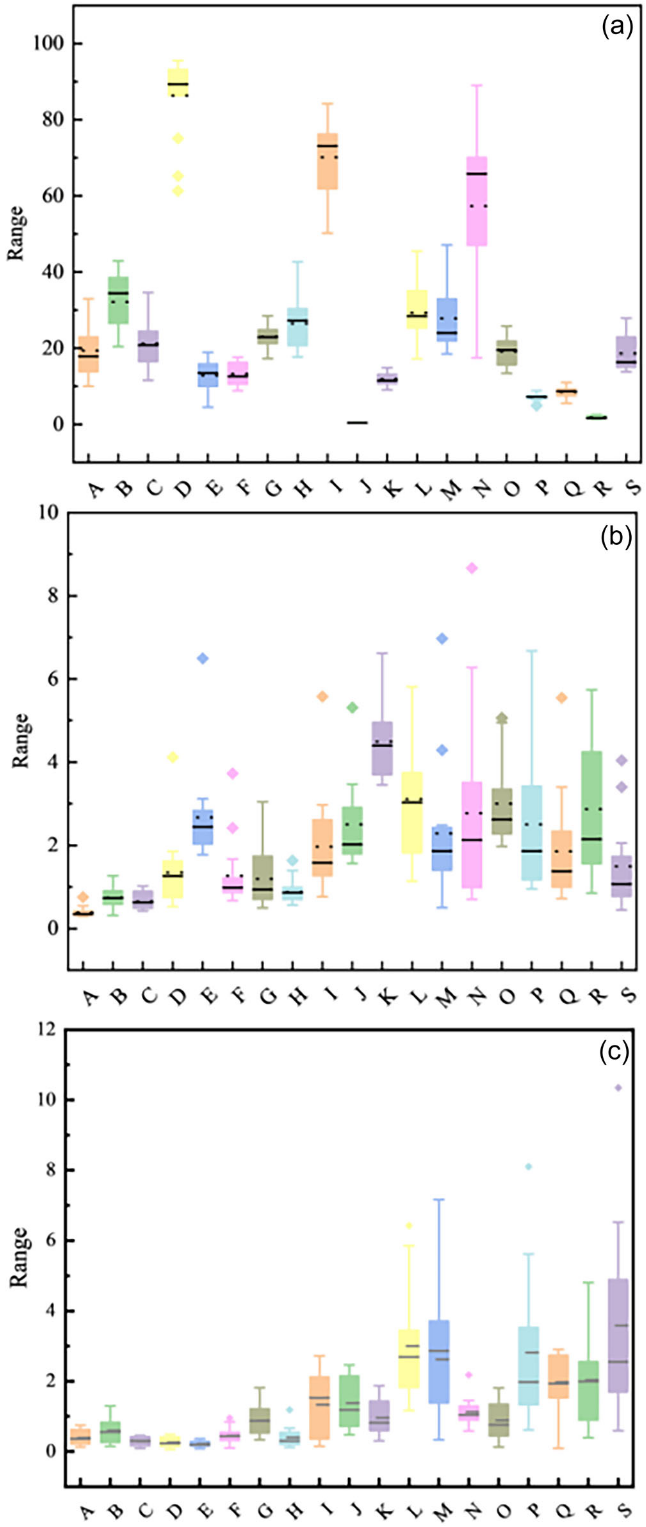


Fig. 1 | Box plots of gloss, surface roughness, and Δ*E* values for each process group. **a** Boxplots of Gu-values for the nineteen lacquer coating processes, showing the distribution and variation of surface gloss among different lacquering techniques. **b** Boxplots of Ra-values for the nineteen coating processes, illustrating differences in surface roughness produced by each technique. **c** Boxplots of Δ*E* values for the nineteen coating processes, demonstrating the overall color difference after coating formation.

limited comparative significance. Accordingly, this study does not present sequential rankings of *L*, *a*, and *b* values, but instead focuses on evaluating the stability and variability of the composite color difference (Δ*E*)[39]. The calculation of Δ*E* for each process follows the formula:

$$\Delta E_{\mathrm{i}} = \sqrt{(L_{\mathrm{i}} - L_{\mathrm{mean}})^2 + (a_{\mathrm{i}} - a_{\mathrm{mean}})^2 + (b_{\mathrm{i}} - b_{\mathrm{mean}})^2}$$

L_{mean}, a_{mean}, and b_{mean} represent the mean values of all measurement points for each process sample, and ΔE_{i} denotes the color difference between each individual measurement point and its corresponding mean value.

The box plot results indicate the following:

- Gloss: All techniques in the black lacquer group (A–E) displayed highly concentrated distributions. Within the vermilion (F–J), golden lacquer (K–O), and hardwood rubbed lacquer groups (P–S), the traditional techniques (A, F, K, P) exhibited markedly superior data concentration compared with other techniques in their respective groups. Modified lacquer techniques (G, H, L, M, O, Q, R) generally ranked second. In contrast, cashew lacquer techniques in the vermilion and golden lacquer groups (I, N) and the water-based lacquer technique in the hardwood rubbed lacquer group (S) showed greater dispersion and weaker stability. Although industrial lacquer techniques in the vermilion and golden groups (J, O) displayed relatively stable distributions, their absolute gloss values were excessively low.
- Surface Roughness (Ra): The black lacquer group (A–E) showed the highest concentration, with traditional processes (A) and modified processes (B, C) performing best. Cashew black lacquer (D) and industrial black lacquer (E) exhibited scattered distributions, reflecting poor stability. In the vermilion group (F–J), processes F and H achieved concentrated distributions, while G, I, and J were more dispersed. The golden lacquer group (K–O) displayed significantly higher dispersion than both the black and vermilion groups, with all samples scattered. The hardwood rubbed lacquer group (P–S) showed a similar trend of broad dispersion.
- Color Difference (Δ*E*): In the black lacquer group (A–E), all techniques demonstrated high stability. Within the vermilion group (F–J), traditional technique F and modified technique H achieved the best performance, whereas cashew lacquer (I) and industrial lacquer (J) showed unstable distributions. In the golden lacquer group (K–O), traditional technique K maintained high stability, cashew lacquer (N) and industrial lacquer (O) performed well, while modified techniques L and M showed poor performance. The hardwood rubbed lacquer group (P–S) generally exhibited wide dispersion of Δ*E* values.

After completing box plot analysis, a total of 25 outliers were removed. The finalized dataset is provided in the Supplementary information (Supplementary Table S6).

Variance analysis and confidence intervals

Analysis of variance (ANOVA) is employed to examine differences between categorical and quantitative variables[40]. In this study, it is applied to analyze variations in indicators among different process groups within major categories. Significant differences ($P < 0.05$) were identified in gloss and roughness indicators across all process groups within the four major categories—black lacquer, vermilion, gold, and hardwood. In contrast, no significant differences ($P > 0.05$) were observed in the Δ*E* values among the hardwood lacquer rubbing groups, see Table 6 for details.

While ANOVA effectively identifies whether differences between techniques are statistically significant, it does not fully capture the uncertainty associated with mean estimates[41]. To address this limitation, this study further employs 95% confidence interval (CI) error bar charts to visually assess the mean differences and corresponding confidence ranges for each technique. These plots intuitively illustrate both the reliable intervals of sample means and the variability of the data, thereby enabling a more comprehensive evaluation of the stability and applicability of different finishing techniques[42]. Moreover, they provide empirical support for the formulation of scientifically sound process standards.

The 95% CI error bar plots for the mean values of each process across different groups at various indicator levels are presented below (Fig. 2).

Based on these plots, the means and upper/lower bounds of their confidence intervals were statistically compiled and summarized. The results, presented in Table 7, provide a clear overview of the average ranges for various indicators across different processes, serving as an essential reference for defining technical requirements in process standardization.

Color differences and reflectance features

To further investigate the differences in color expression between traditional and modern modified techniques, and to provide a reference basis for museums in formulating color requirements for different finishing processes, the ΔE values between modern craft samples and traditional techniques were calculated and analyzed.

The calculation of ΔE values was conducted using the following formula:

$$\Delta E_i = \sqrt{(L_i - L_{\text{trad\_mean}})^2 + (a_i - a_{\text{trad\_mean}})^2 + (b_i - b_{\text{trad\_mean}})^2}$$

L_i, a_i, b_i represent the Lab values at each measurement point of the modern process sample, and $L_{\text{trad\_mean}}$, $a_{\text{trad\_mean}}$, $b_{\text{trad\_mean}}$ denote the

Table 6 | ANOVA results for all lacquer types (Gloss, Ra, ΔE)

Group (mean ± standard deviation)							
Group	**A(*n* = 15)**	**B(*n* = 15)**	**C(*n* = 15)**	**D(*n* = 15)**	**E(*n* = 15)**	***F***	***p***
Gloss (GU)	19.37 ± 7.06	32.10 ± 7.79	21.25 ± 6.50	91.09 ± 3.34	12.84 ± 4.36	340.75	<0.001**
Roughness (Ra,μm)	0.36 ± 0.07	0.74 ± 0.28	0.65 ± 0.20	1.15 ± 0.43	2.40 ± 0.41	94.89	<0.001**
Δ*E*	0.40 ± 0.22	0.60 ± 0.35	0.30 ± 0.12	0.26 ± 0.14	0.21 ± 0.09	7.426	<0.001**
Group	F(*n* = 15)	G(*n* = 15)	H(*n* = 15)	I(*n* = 15)	J(*n* = 15)	*F*	*p*
Gloss (GU)	13.28 ± 3.13	23.04 ± 2.80	26.48 ± 6.67	70.15 ± 9.36	0.43 ± 0.05	347.065	<0.001**
Roughness (Ra,μm)	0.99 ± 0.25	1.19 ± 0.71	0.83 ± 0.21	1.71 ± 0.73	2.30 ± 0.64	15.818	<0.001**
Δ*E*	0.41 ± 0.21	0.88 ± 0.42	0.34 ± 0.18	1.33 ± 0.94	1.39 ± 0.74	9.774	<0.001**
Group	K(*n* = 15)	L(*n* = 15)	M(*n* = 15)	N(*n* = 15)	O(*n* = 15)	*F*	*p*
Gloss (GU)	11.92 ± 1.70	29.33 ± 7.17	27.81 ± 8.23	57.31 ± 22.17	19.13 ± 3.74	35.612	<0.001**
Roughness (Ra,μm)	4.49 ± 0.90	3.11 ± 1.33	1.77 ± 0.53	2.35 ± 1.57	2.85 ± 0.99	11.647	<0.001**
Δ*E*	0.96 ± 0.47	2.75 ± 1.31	2.62 ± 1.77	1.04 ± 0.26	0.89 ± 0.52	11.999	<0.001**
Group	P(*n* = 15)	Q(*n* = 15)	R(*n* = 15)	S(*n* = 15)	NA	*F*	*p*
Gloss (GU)	7.33 ± 0.73	8.51 ± 1.60	1.83 ± 0.45	18.62 ± 4.61	NA	117.642	<0.001**
Roughness (Ra,μm)	2.50 ± 1.71	1.59 ± 0.83	2.87 ± 1.68	1.15 ± 0.49	NA	5.091	0.004**
Δ*E*	2.44 ± 1.59	1.98 ± 0.84	2.03 ± 1.24	3.06 ± 1.91	NA	1.667	0.185

** Indicates statistical significance at $p < 0.001$.

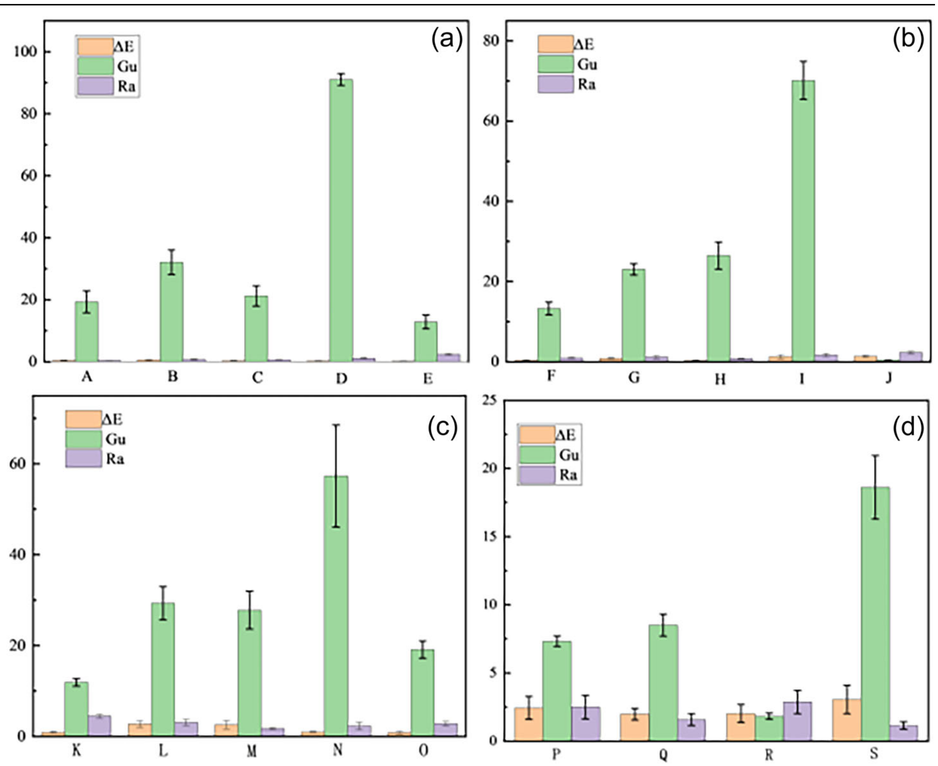


Fig. 2 | 95% confidence interval (CI) error bar plots of mean values for the black, vermilion, gold, and hardwood rubbed lacquer groups. **a** Error plots of Δ*E*, Gu, and Ra for the Black lacquer group (processes A–E), showing the mean values and 95% confidence intervals of color difference, gloss, and surface roughness. **b** Error plots of ΔE, Gu, and Ra for the Vermilion lacquer group (processes F–J). **c** Error plots of ΔE, Gu, and Ra for the Gold lacquer group (processes K–O). **d** Error plots of Δ*E*, Gu, and Ra for the Hardwood rubbed lacquer group (processes P–S), illustrating indicator variability across wiping–lacquer techniques.

Table 7 | Results of mean with 95% confidence interval (CI)

Indicator type	Group	Process Type	Mean	Lower limit	Upper limit
Gloss (GU)	Black group	A	19.37	15.79	22.94
		B	32.10	28.16	36.04
		C	21.25	17.96	24.54
		D	91.09	89.20	92.98
		E	12.84	10.63	15.05
	Vermilion group	F	13.28	11.69	14.87
		G	23.04	21.62	24.46
		H	26.48	23.10	29.86
		I	70.15	65.41	74.88
		J	0.43	0.41	0.46
	Golden group	K	11.92	11.06	12.78
		L	29.33	25.70	32.96
		M	27.81	23.64	31.97
		N	57.31	46.09	68.53
		O	19.13	17.24	21.02
	Hardwood wiping group	P	7.33	6.95	7.71
		Q	8.51	7.70	9.33
		R	1.83	1.61	2.06
		S	18.62	16.29	20.95
Roughness (Ra,μm)	Black group	A	0.36	0.33	0.40
		B	0.74	0.60	0.88
		C	0.65	0.55	0.76
		D	1.15	0.93	1.37
		E	2.40	2.18	2.61
	Vermilion group	F	0.99	0.85	1.13
		G	1.19	0.83	1.56
		H	0.83	0.71	0.94
		I	1.71	1.33	2.09
		J	2.30	1.97	2.64
	Golden group	K	4.49	4.04	4.95
		L	3.11	2.44	3.78
		M	1.77	1.48	2.06
		N	2.35	1.52	3.17
		O	2.85	2.34	3.37
	Hardwood wiping group	P	2.50	1.64	3.37
		Q	1.59	1.16	2.02
		R	2.87	2.02	3.72
		S	1.15	0.89	1.42
Color Difference (ΔE)	Black group	A	0.40	0.29	0.51
		B	0.60	0.42	0.77
		C	0.30	0.23	0.36
		D	0.26	0.19	0.33
		E	0.21	0.16	0.26
	Vermilion group	F	0.41	0.29	0.53
		G	0.88	0.67	1.09
		H	0.34	0.25	0.44
		I	1.33	0.85	1.80
		J	1.39	1.01	1.76
	Golden group	K	0.96	0.72	1.20
		L	2.75	2.07	3.44
		M	2.62	1.72	3.51
		N	1.04	0.91	1.18
		O	0.89	0.62	1.15
	Hardwood wiping group	P	2.44	1.61	3.27
		Q	1.98	1.55	2.40
		R	2.03	1.38	2.68
		S	3.06	2.03	4.10

mean values of all test points in the corresponding traditional process sample.

The results of the variance analysis of ΔE values between major groups and traditional techniques are presented in Table 8. These results not only quantify the degree of deviation in color perception but also provide a comparative framework to evaluate whether modern modified processes can visually approximate traditional finishing. Furthermore, spectral reflectance curves were analyzed to complement the ΔE data, offering additional insight into the consistency of color rendering across different wavelength ranges[43].

Analysis of variance results for each group indicate that modern process samples exhibit significant differences in ΔE values compared to traditional samples ($p < 0.05$). According to the internationally recognized CIE 1976 color-difference perception standard, combined with the mean values of each technique shown in Table 4, it can be observed that—except for the black group—all other groups exhibit perceptible color deviations ($\Delta E > 3$) between modern and traditional samples[44]. Within the hardwood rubbed lacquer group, the ΔE value between the modern polishing powder process and the traditional sample was relatively small. However, since the color performance of this technique is easily affected by substrate location and tonal variation, its results lack a universal reference value. Consequently, if imitation requirements are established from the perspective of "color performance similarity," only the black group is suitable for further 95% CI error bar analysis, the results of which are presented in the figure below (Fig. 3). The upper and lower limits of ΔE color differences between each process in the black group and traditional black lacquer are summarized in Table 9.

To further investigate the differences in color rendering among various processes, reflectance curves for each group were plotted as shown in the figure below (Figs. 4–7).

The reflectance curves of the black lacquer group indicate consistently low levels, consistent with the optical characteristics of low reflectance in black[45]. Among them, Group A exhibits the lowest reflectance, with the strongest absorption in the 400–450 nm band, resulting in a deep and stable visual impression. Groups B and C show an overall upward shift in reflectance, particularly in the 500–650 nm range, producing a visual appearance that tends toward a lighter, grayish black. Group D exhibits lower overall reflectance than traditional black and simple black, with a steadily rising curve indicative of a warmer tone. Group E demonstrates the highest reflectance, with a marked increase above 600 nm, leading to a brighter and lighter black appearance.

In the vermilion group, Group F shows reduced reflectance in the 400–500 nm range (blue-violet region) with strong absorption, followed by a sharp increase beyond 550 nm, reaching about 15% near 600 nm. This spectral profile corresponds to a stable and saturated vermilion hue with a deep chromatic quality. Groups G and H display curves largely consistent with traditional vermilion but with slightly higher reflectance in the 550–650 nm band, resulting in brighter hues with lighter tones and diminished heaviness. Group I demonstrates elevated reflectance across the entire spectrum, particularly exceeding 30% in the 600–650 nm band, yielding a more vivid red hue that leans toward bright red or orange-red, but

Table 8 | Results of ANOVA for ΔE values between different process groups and traditional samples

Color group	Subgroup (Mean ± SD)	*F*	*p*
Black group	B:(*n* = 15): 2.01 ± 0.65; C: (*n* = 15): 1.19 ± 0.25 D: (*n* = 15): 3.97 ± 0.17; E: (*n* = 15): 2.95 ± 0.21	142.418	0.000**
Vermilion group	G: (*n* = 15): 6.98 ± 0.70; H: (*n* = 15): 7.92 ± 0.41 I: (*n* = 15): 23.10 ± 1.58; J: (*n* = 15): 47.85 ± 1.52	4005.037	0.000**
Golden group	L: (*n* = 15): 7.70 ± 1.21; M: (*n* = 15): 8.98 ± 0.86 N: (*n* = 15): 24.33 ± 0.85; O:(*n* = 15): 32.54 ± 0.93	2323.974	0.000**
Hardwood wiping group	Q:(*n* = 15): 2.38 ± 1.53; R: (*n* = 15): 5.93 ± 6.74 S: (*n* = 15): 32.54 ± 0.93 ;	251.404	0.000**

** indicates statistical significance at *p*

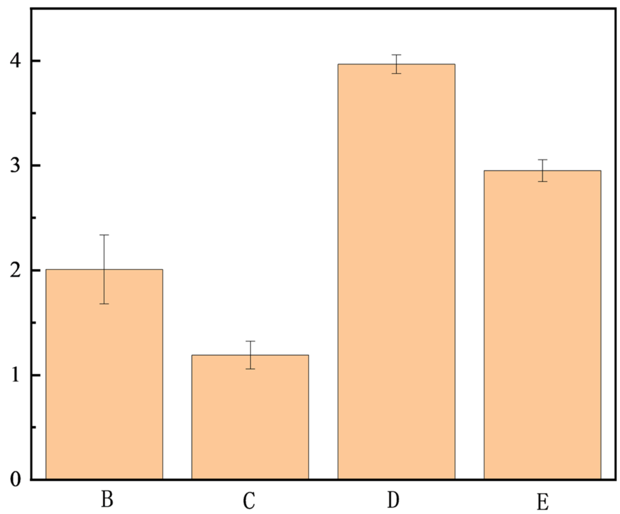


Fig. 3 | 95% CI error bar plots of ΔE values between modern and traditional processes in the black lacquer group. This figure presents the 95% confidence interval (CI) error bar plots of ΔE values within the Black lacquer group, comparing modern lacquering processes with traditional lacquer techniques. The plot illustrates the range and variability of color difference (ΔE) among the corresponding processes in this group.

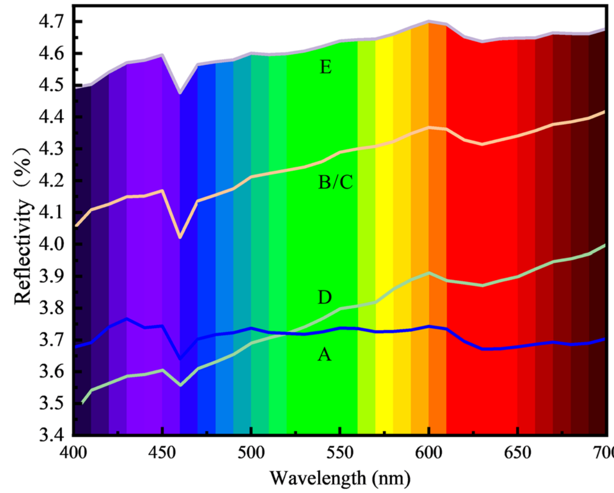


Fig. 4 | Reflectance curves of the black lacquer group. This figure shows the spectral reflectance curves of the Black lacquer group (processes A–E). The reflectance profiles across the visible spectrum reveal differences in optical and chromatic characteristics among the five black-lacquer coating processes.

Table 9 | 95% CI results of the mean ΔE values between the black group processes and the traditional process

Indicator type	Group	Process type	Mean	Lower limit	Upper limit
ΔE Value vs. traditional sample	Black	B	2.01	1.68	2.34
		C	1.19	1.06	1.32
		D	3.97	3.88	4.06
		E	2.95	2.85	3.06

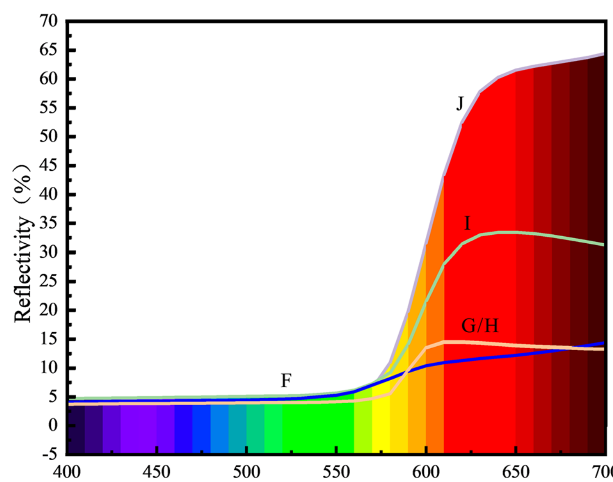


Fig. 5 | Reflectance curves of the vermilion lacquer group. This figure displays the spectral reflectance curves for the Vermilion lacquer group (processes F–J). The curves illustrate variations in color response and optical behavior across vermilion-colored lacquer coatings.

lacking the grounded quality of traditional vermilion. Group J exhibits the highest reflectance, exceeding 60% in the 600–700 nm range, producing a high-saturation, bright red that contrasts sharply with the deep, textured impression of traditional vermilion[46].

The gold lacquer group, particularly the traditional technique Group K, displays low reflectance at shorter wavelengths (<10%), with a sharp increase beyond 550 nm, peaking at 35–40% near 700 nm. This spectral profile corresponds to a deep, stable golden hue, representative of traditional lacquer's visual weight. Groups L and M exhibit similar profiles but with more gradual increases and slightly lower peak reflectance (30–35%), yielding darker, more subdued tones with reduced metallic luster. Group N shows a sharp increase beyond 550–600 nm, peaking at 50–55%, producing a brighter and more translucent golden hue[47]. Group O demonstrates the highest reflectance, with a steep rise beyond 550 nm and a peak approaching 75–80%, corresponding to an extremely bright yellow-gold, akin to industrial metallic finishes such as "gold powder paint."

The hardwood rubbed lacquer group exhibits highly similar reflectance profiles. The traditional Group P maintains the lowest reflectance in the

400–500 nm range (3–5%), with a rapid rise beyond 600 nm, reaching approximately 27–28% near 700 nm. This results in a restrained reddish-brown appearance with an understated, steady effect[48]. Group Q shows slightly higher overall reflectance than Group P, producing a marginally brighter hue while remaining within the traditional deep-red spectrum. Group R exhibits low reflectance in the short-wavelength range but shows a pronounced increase in the red region (approaching 30%), yielding a vivid, bright red that conveys more modern transparency compared to traditional techniques. Group S presents the highest reflectance in the red region (>35%), producing an overall brighter and more vivid red hue. However, its appearance tends toward superficiality, lacking the integrated depth achieved through the layered fusion of wood and lacquer in traditional craftsmanship[49].

Adhesion and thermal cycling performance

Following the assessment of process stability and color performance, further tests were conducted on coating adhesion and thermal resistance, as these indicators are critical for evaluating the practical applicability and durability of different finishing processes[50].

Magnified observations of samples subjected to cross-cut adhesion testing were used to determine adhesion grades, with the results summarized in Table 10. Grading criteria followed the standard GB/T 4893.4—2013.

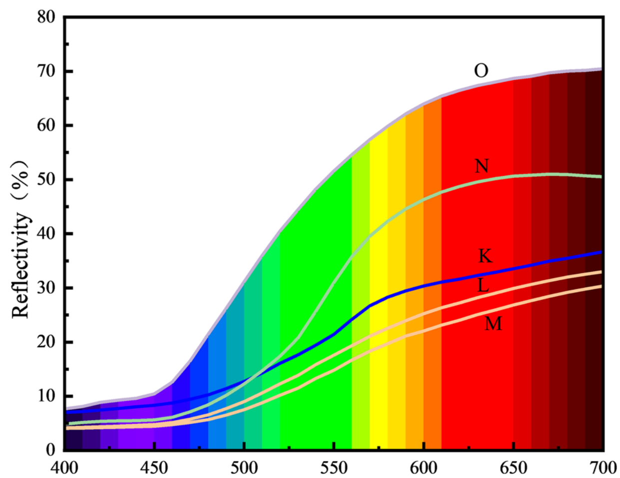


Fig. 6 | Reflectance curves of the gold lacquer group. This figure presents the spectral reflectance curves of the Gold lacquer group (processes K–O). The reflectance transitions reflect the influence of gold-powder lacquer layers and the differences in surface optical properties among the gold-lacquer coating techniques.

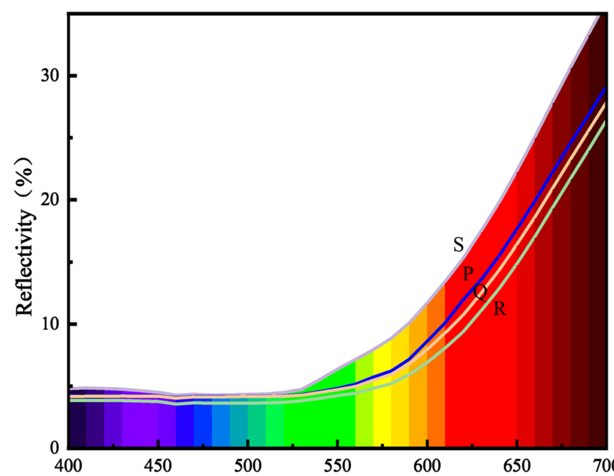


Fig. 7 | Reflectance curves of the hardwood rubbed lacquer group. This figure shows the spectral reflectance curves of the Hardwood rubbed lacquer group (processes P–S). The reflectance patterns demonstrate the optical characteristics of lacquer surfaces produced through traditional hardwood rubbing techniques and variation across different rubbing–lacquering processes.

Table 10 | Performance grades of coating adhesion for different processes

Group	Subgroup	Adhesion grade	Performance description
Black	A	0	Cutting edges are completely smooth, with no grid area detached.
	B	1	Slight coating detachment at the intersections of cuts, covering no more than 5% of the cross-cut area.
	C	1	Same as grade 1.
	D	1	Same as grade 1.
	E	2	Slight coating detachment at the intersections of cuts, covering more than 5% but less than 15% of the cross-cut area.
Vermilion red	F	0	Same as grade 0.
	G	1	Same as grade 1.
	H	1	Same as grade 1.
	I	2	Same as grade 2.
	J	4	Large-scale coating detachment along the cutting edges, covering more than 35% but less than 65% of the cross-cut area.
Golden group	K	1	Same as grade 1.
	L	1	Same as grade 1.
	M	1	Same as grade 1.
	N	2	Same as grade 2.
	O	4	Same as grade 4.
Hardwood wiping lacquer	P	0	Same as grade 0.
	Q	0	Same as grade 0.
	R	1	Same as grade 1.
	S	1	Same as grade 1.

Note: High-resolution detail images are provided in Supplementary information (Supplementary Fig. S9).

Table 11 | Performance of Different Lacquering Techniques under Thermal Cycling

Group	Subgroup	Performance description
Black	A	No occurrence of cracks, blistering, significant loss of gloss, or discoloration
	B	Same as above
	C	Same as above
	D	Same as above
	E	Same as above
Vermilion Red	F	No occurrence of cracks, blistering, significant loss of gloss, or discoloration
	G	Same as above
	H	Same as above
	I	Slight blistering
	J	Slight blistering and discoloration
Golden Group	K	No occurrence of cracks, blistering, significant loss of gloss, or discoloration
	L	Same as above
	M	Same as above
	N	Same as above
	O	Slight blistering and discoloration
Hardwood Wiping Lacquer	P	No occurrence of cracks, blistering, significant loss of gloss, or discoloration
	Q	Same as above
	R	Same as above
	S	Same as above

High-resolution detail images are provided in Supplementary information (Supplementary Fig. S10).

Thermal cycling resistance was evaluated by comparing the condition of test specimens before and after exposure to alternating hot and cold environments. The results are summarized in Table 11, with evaluation conducted in accordance with GB/T 4893.7—2013.

Discussion

Based on a systematic comparison of process stability, visual presentation, and physicochemical properties, this study integrates and comprehensively analyzes the experimental results to provide a well-rounded evaluation of the advantages and limitations of each finishing technique. The discussion aims to inform grading practices and technical implementation strategies in the imitation of lacquered furniture.

The core objective of lacquer furniture imitation lies in achieving high-fidelity visual reproduction[51]. Final visual outcomes require a holistic assessment of color expression, gloss levels, and surface roughness[52]. Drawing on the mean 95% CI error bar charts generated in this study, a systematic analysis was conducted across these indicators to identify the visual presentation characteristics of each technique. The results are summarized in Table 12.

While the mean values of each indicator directly determine the overall effectiveness of a process, stability and physicochemical performance also play a decisive role. Gloss, roughness, and ΔE stability influence surface uniformity and consistency, whereas adhesion and thermal cycling resistance determine durability under varying environmental and practical conditions[53]. By combining the results of box-plot stability analysis and physicochemical property testing, the comprehensive performance of different processes was synthesized, with the outcomes summarized in Table 13.

Overall, the ranking of finishing quality across the black, vermilion, and golden lacquer groups is as follows:

Traditional lacquer ash with traditional lacquer > Two modified traditional processes > Cashew lacquer > Industrial lacquer.

Within the hardwood rubbed lacquer group, the order is: P group > Q group > R group > S group.

It should be noted, however, that industrial lacquer techniques outperformed cashew lacquer in specific indicators within certain groups—for example, the relatively stable gloss of the industrial vermilion lacquer group, or the finer surface roughness achieved using modern polishing powders compared with traditional pearl powder in the hardwood rubbed lacquer group. These advantages, however, derive largely from the intrinsic material properties rather than the craftsmanship itself. Industrial color lacquers, for instance, demonstrate higher numerical consistency primarily due to their inherently lower gloss levels. Similarly, modern polishing powders can reach mesh sizes above 10,000, whereas traditional pearl powders typically remain in the 5000–6000 mesh range. While adopting such modern materials may enhance performance, doing so risks producing a finish that appears excessively uniform and modern, thereby undermining the rustic authenticity valued in traditional techniques.

Moreover, certain box-and-whisker plots of process stability showed elongated whiskers, reflecting the statistical influence of outliers. This suggests the need for cautious interpretation when evaluating stability solely through such visualizations.

In summary, the process rankings proposed in this study—based on comprehensive analyses of both visual effects and overall properties—offer a reliable reference framework for classifying finishing techniques in lacquer furniture imitation.

In practice, the selection of appropriate techniques must account for multiple factors, including the type of museum exhibition, display duration, exhibit preparation cycles, and available funding. For example, while black, vermilion, and golden lacquer imitations can be produced strictly in accordance with historical documentation, the substantial time and financial costs necessitate context-specific evaluations. To address this, the classification levels, technical parameter requirements, and applicable scenarios for each technique are summarized in Table 14.

As a novel type of museum exhibit, the standardization of finishing techniques for imitated lacquered furniture is crucial for promoting the scientific development of exhibitions, enhancing visitors' aesthetic experience, and ensuring consistency between exhibits and their display contexts. To address this need, this study designed comparative experiments encompassing traditional techniques, modified traditional methods, and modern alternative processes across four representative lacquer types: black lacquer, vermilion lacquer, golden lacquer, and hardwood rubbed lacquer. The experimental results were systematically analyzed in three dimensions: process stability, visual appearance, and physicochemical properties.

Based on these findings, a grading system for lacquer furniture imitations and specific technical parameter thresholds for each process were established. These results provide practical guidelines for the production and exhibition of imitated lacquered furniture in museum settings. Furthermore, the comprehensive analytical framework developed herein offers a valuable reference for related research in cultural heritage imitation and finishing techniques.

It should be noted that this study examines five representative lacquer techniques, whereas traditional lacquer craftsmanship encompasses a far broader range of colored lacquer types. Significant variations in raw materials, layer structures, and production methods across different historical periods make comprehensive comparisons difficult under current experimental conditions and resource limitations. Moreover, although the reconstruction procedures were based on historical texts and archival records, certain forms of tacit artisanal knowledge cannot be fully reproduced under laboratory conditions, and the natural variability of lacquer as a biological material inevitably introduces uncertainty.

Future research will extend to a wider spectrum of colored lacquer techniques, classified according to historical periods and regional characteristics. In addition, long-term assessments of physicochemical performance, including aging resistance, lightfastness, and environmental durability, will be incorporated to establish a more comprehensive and quantitative evaluation framework for lacquered surfaces.

Table 12 | Performance of different lacquering techniques in terms of indicators and final visual effects

Group	Subgroup	Gloss (Gu)	Roughness (Ra)	Reflectance/spectral characteristics (summary)	Final visual effect (conclusion)
Black	A	Low	Low	Low across full band; slight rise in red region	Deep, restrained black; high blackness, low brightness; matte, delicate, and steady.
	B	Medium	Low	Clear upward shift at 500–650 nm	Dark but brighter and slightly gray; more transparent, less heavy.
	C	Low	Low	Similar to traditional black, overall slightly higher	Close to traditional black; brighter and grayer, matte yet less thick.
	D	Very high	Slightly lower	High, fluctuating reflectance in long-wave region	Bright, warm-toned black with strong mirror effect; insufficient blackness, prone to color drift.
	E	Low	Slightly high	Highest in red region; overall elevated	Shallow, bright/grayish black; dry texture, lacking depth and thickness.
Vermilion red	F	Low	Low	Moderate in red region (~15%)	Pure, deep, saturated vermilion; heavy and steady.
	G	Low	Slightly high	Red region slightly higher than traditional	Brighter and lighter; reduced blackness and heaviness, still steady.
	H	Slightly higher	Low	Stronger peak in red region	More vivid vermilion; slightly higher brightness, still relatively steady.
	I	Very high	Slightly higher	Red region significantly elevated (>30%)	Bright, orange-red tendency; gorgeous and transparent, less traditional steadiness.
	J	Very low	Slightly high	Red region peaks above 60%	Shallow/bright red with commercial tone; weakest heaviness, more superficial.
Golden group	K	Low	Slightly high	Rises to ~35–40% after 550 nm	Dark gold, steady; granular metallic sense, antique and subdued.
	L	Medium	Slightly lower	Overall darker and smoother	More restrained gray-gold; weaker metallic effect than traditional.
	M	Medium (slightly lower)	Slightly low	Close to traditional	Similar to traditional dark gold/bronze; slightly insufficient brightness.
	N	High	Medium	Peaks at 50–55%	Bright, transparent gold; high magnificence, reduced heaviness.
	O	Higher than traditional	Medium (between cashew and traditional)	Peaks up to 75–80%	High-brightness industrial gold; strong glittering effect, weakest traditional character.
Hardwood wiping lacquer	P	Low	Slightly low	Red region rises to ~27–28%	Restrained, steady reddish-brown wood tone; warm and heavy.
	Q	Slightly high	Slightly low	Overall slightly higher than previous	Brighter, fuller; still warm and steady.
	R	Low (significantly lower)	Slightly higher	Stronger rise in red region	Brighter but hazy; higher vividness, less transparency and heaviness.
	S	Medium	Similar to cashew	Overall higher	High brightness, light color; thinner texture, slightly superficial.

Table 13 | Comprehensive performance of different lacquering techniques

Group	Subgroup	Gloss concentration	Roughness concentration	ΔE	Adhesion grade	Thermal cycling resistance	Overall performance
Black	A	High	Very high	<1	0 (highest)	Good	Best overall performance; extremely stable and reliable.
	B	High	Moderate	<1	1	Good	Excellent performance, slightly inferior to traditional black.
	C	High	Moderate	<1	1	Good	Excellent performance, close to traditional black.
	D	Average	Average	<1	1	Good	Moderate performance; slightly weaker stability.
	E	High	Average	<1	1	Good	Poor durability; relatively weak performance.
Vermilion red	F	High	High	<1	0 (highest)	Good	Best overall performance; highly reliable.
	G	High	Average	<1	1	Good	Relatively strong performance; slightly inferior to traditional vermilion.
	H	High	Average	<1	1	Good	Relatively strong performance; stable results.
	I	Average	Average	>1	2	Good	Moderate performance; larger color difference.
	J	Very high but low value	Average	>1	4	Fair, with defects	Poor adhesion; weakest overall performance.
Golden group	K	High	Slightly high	<1	1	Good	Excellent performance; strong stability.
	L	High but lower	Slightly low	2–3	1	Good	Moderate performance; large color difference.
	M	High	Slightly high	2–3	1	Good	Moderate performance; close to traditional gilding.
	N	Poor	Average	>1	2	Good	Average performance; insufficient adhesion.
	O	High	Average	<1	4	Fair, with defects	Poor adhesion; weakest overall performance.
Hardwood wiping lacquer	P	High	Poor	–	0 (highest)	Good	Best overall performance; outstanding adhesion.
	Q	High	Average	–	0 (highest)	Good	Excellent performance; stable and reliable.
	R	High	Poor	–	1	Good	Relatively strong performance; slightly weaker adhesion.
	S	Slightly lower	Average	–	1	Good	Moderate performance; average overall behavior.

Table 14 | Classification of different lacquer techniques and their applicable exhibition scenarios

Group	Subgroup	Grade	Cost level (see Table 1)	Technical requirements	Applicable scenario	Rationale
Black	A	First-class	Extremely high	See Tables 3, 8, and 9	Special exhibitions of cultural relics; original-state displays	Deep and stable color, high restoration fidelity, excellent performance; traditional lacquer allows audience to experience authentic historical aesthetics
	B	Second-class	High	Same as above	Special exhibitions; original-state displays	Lower cost than traditional black; color and performance close to traditional effect; suitable for mid-to-high-end imitations
	C	Second-class	Medium	Same as above	Auxiliary items in high-level exhibitions	Simplified technique with acceptable performance; cost-effective; suitable to complement main exhibits
	D	Third-class	Low	Same as above	Exhibition props; educational exhibitions	Bright color but slightly lower stability; suitable for cost-limited, non-core displays
	E	Fourth-class	Very low	Same as above	Temporary exhibitions; cultural & creative exhibitions	Lowest cost; simple technique; unstable; suitable only for short-term or low-budget displays
Vermilion red	F	First-class	High	Same as above	Same as black group	Same as black group
	G	Second-class	High	Same as above	Same as black group	Same as black group
	H	Second-class	Medium	Same as above	Same as black group	Same as black group
	I	Third-class	Low	Same as above	Same as black group	Same as black group
	J	Fourth-class	Very low	Same as above	Same as black group	Same as black group
Golden group	K	First-class	Extremely high	Same as above	Same as black group	Same as black group
	L	Second-class	High	Same as above	Same as black group	Same as black group
	M	Second-class	Medium	Same as above	Same as black group	Same as black group
	N	Third-class	Low	Same as above	Same as black group	Same as black group
	O	Fourth-class	Very low	Same as above	Same as black group	Same as black group
Hardwood wiping lacquer	P	First-class	High	Same as above	Same as black group first-class	Same as black group first-class
	Q	Second-class	High	Same as above	Same as black group second-class	Same as black group second-class
	R	Third-class	Medium	Same as above	Same as black group third-class	Same as black group third-class
	S	Fourth-class	Low	Same as above	Same as black group fourth-class	Same as black group fourth-class

The technical requirements summarized in Table 10 are derived from the performance ranges and evaluation results presented in Tables 3, 8, and 9, Corresponding images and application scenarios for each grade of lacquered furniture replicas are provided in Supplementary information (Supplementary Table S7).

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Code availability

No code was used in this study.

Received: 21 September 2025; Accepted: 6 February 2026;
Published online: 20 February 2026

References

1. Y, Y. Research *on Long'en Temple in the mausoleums of the Qing Dynasty (in Chinese)*. Master's thesis. https://doi.org/10.27356/d.cnki.gtjdu.2019.001690 (Tianjin University, 2019).
2. Yuan, X. P. Imitating China: Europe's former Chinese craze (in Chinese). *Zhuangshi* **2010**, 22–29 (2010).
3. Goded, C. O. El mueble de laca española: conexiones con Europa y Asia [El mueble de laca española: conexiones con Europa y Asia] (in Spanish). *Res Mob.* **10**, 69–88 (2021).
4. Luxford, N., Strlič, M. & Thickett, D. Safe display parameters for veneer and marquetry objects: a review of the available information for wooden collections. *Stud. Conserv.* **58**, 1–12 (2013).
5. Bai, Q. & Nam, B. H. Capitalism and reproduction in the new museology: power discourses about Chinese cultural heritage at the Metropolitan Museum of Art. *J. Arts Manag. Law Soc.* **50**, 267–282 (2020).
6. Doni, M. et al. Recent developments in materials science for the conservation and restoration of historic artifacts. *Appl. Sci.* **14**, 11363 (2024).
7. Li, Q. R. et al. Sensory evaluation of cultural relic imitations of Qing dynasty imperial lacquered wooden furniture. *BioResources* **20**, 6853–6876 (2025).
8. Hénin, S. & Casonato, S. Fake but true: model maker Roberto Guatelli, science museums and replicated artifacts of computing history. *IEEE Ann. Hist. Comput.* **42**, 20–32 (2020).
9. Treleani, M. Reproductions, relocations and displacements of cultural heritage. *SCIRES-IT* **11**, 45–52 (2021).
10. Analytical Methods Editorial Board (AMCTB). Scientific investigation of Asian lacquerware. *Anal. Methods*. https://doi.org/10.1039/d5ay90063h (2025).
11. Lozano, I. et al. Characterization of a Qing Dynasty folding fan for exportation. *J. Am. Inst. Conserv.* **64**, 261–284 (2025).
12. Zhao, Z. C. et al. Craftsmanship and techniques of a lacquered ear cup from the ancient Nanyue Kingdom. *Coatings* **15**, 752 (2025).
13. Qin, Y. L. et al. A dual-encoder hierarchical feature fusion network for ancient mural disease detection. *NPJ Herit. Sci.* **13**, 84 (2025).
14. Lu, R. et al. Identification of Ryukyu lacquerware by pyrolysis–gas chromatography/mass spectrometry. *J. Anal. Appl. Pyrolysis* **80**, 101–110 (2007).
15. Zhao, Z. et al. A study on the manufacturing process of a coiled wood core lacquerware unearthed in Xuzhou. *NPJ Herit. Sci.* **13**, 204 (2025).
16. Gong, Z. et al. Analysis of the manufacturing craft of painted gold foils applied on the lacquerware of the Jin Yang Western Han Dynasty tomb in Taiyuan, Shanxi, China. *Herit. Sci.* **12**, 1281 (2024).
17. Lu, R., Yoshida, T. & Miyakoshi, T. Oriental lacquer: a natural polymer. *Polym. Rev.* **53**, 153–191 (2013).
18. Yang, J. L. et al. Preparation of weather-resistant nano-coating materials and its application in the protection of ancient building paintings. *Coatings* **15**, 1161 (2025).
19. Wu, L. J. et al. Urushiol modified epoxy acrylate as UV spray painting oriental lacquer ink. *RSC Adv.* **13**, 1106–1114 (2023).
20. Yu, H. H. et al. HPLC and ToF–SIMS analyses of Toxicodendron vernicifluum tree sap mixed with other natural lacquers. *Molecules* **26**, 434 (2021).
21. Kyei, S. K. et al. A comprehensive review on waste valorization of cashew nutshell liquid: sustainable development and industrial applications. *Clean. Waste Syst.* **6**, 100116 (2023).
22. Otsuka, T. et al. Green polymer chemistry: biomimetic oxidative polymerization of cardanol for a synthetic approach to "artificial urushi. *Polym. J.* **49**, 335–343 (2016).
23. Lee, Y. et al. Quantitative detection of thitsiol and urushiol as markers from the Gluta usitata lacquer tree using HPLC. *Molecules* **29**, 149 (2023).
24. Zhang, T. X. et al. Analyzing the influence of the ground layer on reinforcement strength of lacquer film in the restoration of ancient Chinese lacquer furniture. *BioResources* **14**, 431–439 (2018).
25. Wang, S. X. *Explanation of the Lacquerwork Records* (in Chinese). ISBN 978-7-108-05213-1 (Sanlian Press, 2015).
26. Huang, C., Yang, M. & Tian, K. P. *Ancient Chinese Material Culture Series: Records of Lacquer and Ornamentation (in Chinese)*. (Chongqing Publishing House, 2022).
27. Ebert, B. & Schilling, M. R. A technical analysis of paint media used in twentieth-century Vietnamese lacquer paintings. *Stud. Conserv.* **61**, 52–67 (2016).
28. Papathanasiou, I., Zinelis, S. & Papavasiliou, G. Effect of aging on color, gloss and surface roughness of CAD/CAM composite materials. *J. Dent.* **130**,104423 (2023).
29. Kaynak Öztürk, E. et al. Evaluation of the optical and surface properties of monolithic CAD–CAM ceramics after simulated tooth brushing. *J. Prosthet. Dent.* **132**, 1325.e1–1325.e8 (2024).
30. Öztürk, E. K. et al. Effects of surface finishing procedures, coffee immersion and simulated tooth brushing on the surface roughness, gloss and color stability of a resin matrix ceramic. *Coatings* **15**, 627 (2025).
31. Zhang, W. et al. Preparation and properties of multi-color coatings with ultra-low near-infrared reflectivity. *Surf. Coat. Technol.* **492**, 105122 (2024).
32. Collin, A. et al. Radiative properties of firefighter helmets: effect of color and soot deposition on thermal performance. *Fire Saf. J.* **155**, 104405 (2025).
33. Ooi, K.-L. et al. Body size rather than reflectivity explains thermal constraints on colour variation in an aposematic jewel bug. *Evol. Ecol.* **39**, 307–322 (2025).
34. Yan, X., Peng, W. & Qian, X. Effect of water-based acrylic acid microcapsules on the properties of paint film for furniture surface. *Appl. Sci.* **11**, 7586 (2021).
35. Chen, J. et al. Drying process of waterborne paint film on bamboo laminated lumber for furniture. *Polymers* **15**, 1288 (2023).
36. Krystofiak, T., Lis, B. & Muszyńska, M. The effect of aging tests on gloss and adhesion of lacquer coatings on window elements from pine wood. *Drewno* **59**, 127–137 (2016).
37. Cox, G. M. A survey of types of experimental designs. *Biometrics* **6**, 301 (1950).
38. Williams, J., Hill, R. R. & Pignatiello, J. J. Wavelet analysis of variance box plot. *J. Appl. Stat.* **49**, 3536–3563 (2022).
39. Mielenz, K. D. & Hsia, J. J. Effects of the International Temperature Scale of 1990 (ITS-90) on CIE documentary standards for radiometry, photometry and colorimetry. *J. Res. Natl. Inst. Stand. Technol.* **95**, 545 (1990).
40. de Carvalho, A. M. X., de Souza, M. R. & Marques, T. B. Familywise Type I error of ANOVA and ANOVA on ranks in factorial experiments. *Ciência Rural* **53**, e20220146 (2023).
41. Armstrong, R. A., Eperjesi, F. & Gilmartin, B. The application of analysis of variance (ANOVA) to different experimental designs in optometry. *Ophthalmic Physiol. Opt.* **22**, 248–256 (2002).
42. Nayak, S. S. et al. Diagnostic and prognostic value of triglyceride-glucose index: a comprehensive evaluation of meta-analysis. *Cardiovasc. Diabetol.* **23**, 2392 (2024).

43. Liu, S. H., Liu, Z. J. & Wang, J. Effect of material color on optical properties of thermochromic coatings employed in buildings. *Case Stud. Therm. Eng.* **45**, 102916 (2023).
44. Hopkinson, L., Rutt, K. & Kristova, P. Sourcing limestone masonry for restoration of historic buildings: A spectroscopic pilot study. *J. Cult. Herit.* **16**, 822–830 (2015).
45. Zhang, W. G. et al. Preparation and properties of multi-color coatings with ultra-low near-infrared reflectivity. *Infrared Phys. Technol.* **136**, 105122 (2024).
46. Wang, Y. S. et al. High-color-purity, high-brightness and angle-insensitive red structural color. *Chin. Opt. Lett.* **20**, 021601 (2022).
47. Gutierrez, P. C. et al. Color and golden shine of silver Islamic luster. *J. Am. Ceram. Soc.* **93**, 2320–2328 (2010).
48. Zhu, T. et al. Staining of wood veneers with anti-UV property using the natural dye extracted from Dalbergia cochinchinensis. *J. Clean. Prod.* **284**, 124770 (2020).
49. Huang, X. A. et al. A spectrocolorimetric and chemical study on color modification of heat-treated wood during artificial weathering. *Appl. Surf. Sci.* **258**, 5360–5369 (2012).
50. Wang, Q. Y. et al. Performance of drying oil modified Chinese lacquer and its gilding effect. *Coatings* **14**, 1379 (2024).
51. Yan, W. T. Collecting the Pei Cen stele in Qing China. *Ming Qing Yanjiu* **24**, 245–278 (2020).
52. Zhou, F. et al. Effects of density on colour and gloss variability changes of wood induced by heat treatment. *Color Res. Appl.* **46**, 1151–1160 (2021).
53. Rocha, M. G. et al. Effect of simulated tooth brushing on surface roughness, gloss and color stability of milled and printed permanent restorative materials. *J. Esthet. Restor. Dent*. https://doi.org/10.1111/jerd.13450 (2025).
54. Standardization Administration of China. *GB/T 4893.7–2013: Furniture – Assessment of surface resistance to mechanical damage (in Chinese)* (Standardization Administration of China, 2013).

Acknowledgements
The authors sincerely thank the Palace Museum and Beijing Yuanshenglongbo Co., Ltd. for their guidance and assistance with the experimental materials and technical procedures.

Author contributions
Qirong Li: Conceptualization, methodology, experimental work, data analysis, visualization, and writing—original draft. Fan Zhang: Methodology, evaluation of experimental feasibility, and supervision, as well as writing—review and editing.Wei Jia: Conceptualization, validation of experimental materials, and writing— review and editing. Yanqiu Xie: Data analysis and visualization.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s40494-026-02376-z.

Correspondence and requests for materials should be addressed to Fan Zhang.