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Scientific Analysis and Investigation of Song-Dynasty Paper

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Abstract: This study focuses on the scientific analysis of Song-dynasty Song-dynasty paper (sutra paper). Using optical microscopy, fiber identification, Py-GC/MS, UPLC-QTOF MS, and visible–near infrared multispectral imaging, the paper was identified as kozo-based, dyed with huangbo (Phellodendron bark), sized with animal glue, and coated with beeswax. The results confirm the structure and composition typical of high-quality sutra paper from the Song period. Multispectral imaging further revealed traces of Buddhist texts, proving the reuse of ancient sutra fragments in Qing imperial production. This research provides new scientific evidence for the study of Song papermaking technology and offers valuable references for the conservation of ancient papers and imperial artworks.

1. Introduction

The Hall of Mental Cultivation is located in the western section of the Inner Court of the Forbidden City. It was built in the sixteenth year of the Jiajing reign (1537) of the Ming dynasty, and since the Yongzheng period of the Qing dynasty, it has served as the principal residence and administrative center for the emperors. The architectural complex is renowned for its exquisite craftsmanship and spatial hierarchy, possessing high historical and artistic value. On the west side of the central hall lies the Western Warm Chamber, divided into several rooms. Among them, the "Hall of Diligent Governance and Respect for the Worthy" was where the emperor reviewed memorials and met officials; adjacent rooms such as the Sanxitang, the small Buddhist chapel, and Meiwu were used by the Qianlong Emperor for reading, Buddhist rituals, and leisure.

The imperial hanging screen Kuihua dian, inscribed by Emperor Qianlong in the 31st year of his reign (1766), originally hung on the east wall of the main room in the Western Warm Chamber. The square hanging screen measures 123.36 cm in height and 123.27 cm in width, and bears a 144-character poem explaining Qianlong's interpretation of the "Zhongzheng Renhe" plaque written by Emperor Yongzheng. The screen features a wooden frame covered with brocade, with the paper painting mounted within the brocade borders. The craftsmanship is delicate, and the overall preservation is good, except for partial damage to the character yi. Microscopic observation shows that the paper structure consists of a painting layer → backing paper → two layers of "Qianlong

Korean paper." The main paper is composed of multiple joined pieces of yellow paper, on which a red seal can be partially seen—likely identifying it as paper made by Ni Renbing, a type of Song-dynasty paper from the Song dynasty[1].

Song-dynasty sutra paper—was a type of paper specially made for copying Buddhist scriptures since the Song and Yuan dynasties. Later, it was widely used by the imperial court and literati, especially popular during the Qianlong reign. Such papers were typically dyed with Phellodendron bark and burnished with wax, giving them a resilient texture and warm tone. They often bore red seals such as "Jinsushan Song-dynasty paper" or "Faxi Dazang," and sometimes the maker's name. Among these, Ni Renbing Song-dynasty paper was a representative variety highly favored by Emperor Qianlong, who frequently ordered its reproduction by the Ministry of Works and used it extensively for calligraphy, painting, mounting, and decoration[2].

This study focuses on the Song-dynasty paper used for the Kuihua dian hanging screen(Figure 1). Using paper fragments detached during the restoration process, a systematic examination was conducted employing optical microscopy, fiber analysis, pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS), ultra-performance liquid chromatography–quadrupole time-of-flight mass spectrometry (UPLC-QTOF MS), and visible–near infrared multispectral imaging. The research analyzes the paper's structural layers, fiber composition, dyes and coating materials, jointing methods, and underlying inscriptions. The goal is to reveal the raw materials and processing techniques of Song-dynasty paper, providing fundamental data and scientific support for the study of sutra paper production since the Song–Yuan period and for understanding Qing imperial mounting techniques for calligraphy and painting.

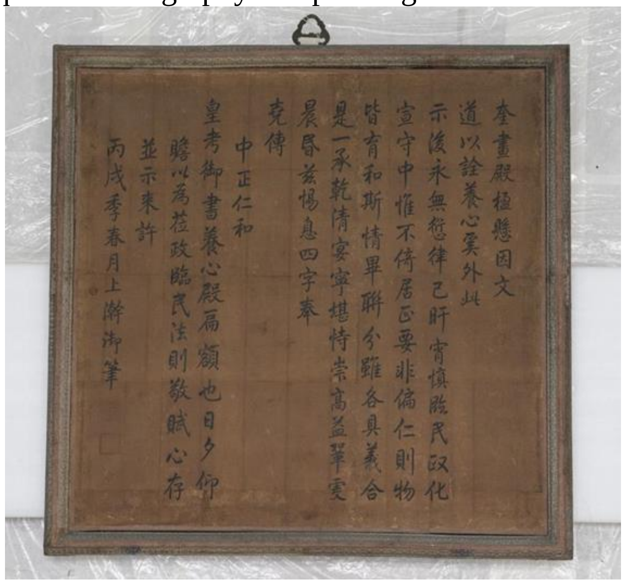

Figure 1: Song-dynasty sutra paper

2. Sample Information and Analytical Methods

2.1 Sample Information

Table 1: Sampling locations

Sample ID	Sampling location	Condition
KYD-1	Detached paper fragment, lower right corner of the painting	With yellow-dye layer
KYD-2	Backing joint paper fragment	No pigment coverage
KYD-3	Fiber layer from backing paper	No wax gloss, slightly soiled

Samples were collected from detached edge fragments and minor backing pieces of the Song-dynasty Song-dynasty paper (Table 1), all from non-decorative areas of the artwork. The sampling mass was controlled within 1–2 mg.

2.2 Analytical Methods

Layer structure analysis: Olympus BX51 microscope with U-RFL-T UV light source and DP73 digital camera. Cross-sections of detached fragments were observed under UV light to examine structural layering.

Optical microscopy (OM): Leica DM2700P polarized microscope, 100–400× magnification, used to observe fiber morphology, fillers, and impurities.

Fiber identification: Herzberg staining method to determine fiber species by color reaction.

Py-GC/MS: Agilent 7890B/5977B system, pyrolysis temperature 500 ℃, for identifying organic coatings and sizing materials.

UPLC-QTOF MS: Waters Xevo G2-XS QTOF, positive-ion ESI mode, for detecting dyes and organic pigments.

Visible–near infrared multispectral imaging: 400–1000 nm wavelength range, to identify underlying inscriptions and coating features.

3. Results

3.1 Structural Layer Analysis

Cross-sectional observation under UV light revealed a distinct multilayer structure (Figure 2). The sutra paper fragment could be divided into two main layers.

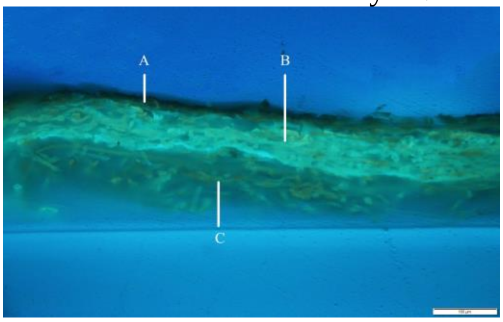

Figure 2: Cross-section of sutra paper fragment (UV illumination, 200×)

The upper layer consists of two visually distinct parts (A and B), with differing color tones but continuous fiber distribution, indicating they belong to the same paper sheet. The difference in fluorescence suggests varying surface treatments such as glue, wax, or soiling. Under UV light, the entire upper layer exhibits bright yellow-green fluorescence, indicative of organic coatings like animal glue or wax.

The lower layer (C) shows looser fiber distribution and weaker fluorescence, typical of an undyed support paper adhered with animal glue.

This layered structure—dyed and waxed surface paper combined with an undyed backing—matches the characteristics of hard yellow paper commonly used in the Qing imperial court. It is inferred that the Song-dynasty paper here was made by laminating two sheets: a yellow-dyed, wax-polished facing paper and a supporting base paper, tightly pressed together to form a dense, moisture-resistant composite sheet.

3.2 Optical Microscopy and Fiber Analysis

Microscopic examination shows long, straight fibers, 18–25 μm wide, with fine transverse striations and occasional wavy shapes, interspersed with minor vegetal fragments (Figures 3–6). Herzberg staining produced reddish-purple coloration, identifying the fibers as kozo (paper mulberry, Broussonetia papyrifera). Blue granules observed among fibers suggest starch or mineral fillers. The uniform fiber distribution and smooth surface correspond to high-grade bast paper.

Figure 3: Fiber morphology of surface (100×magnification)

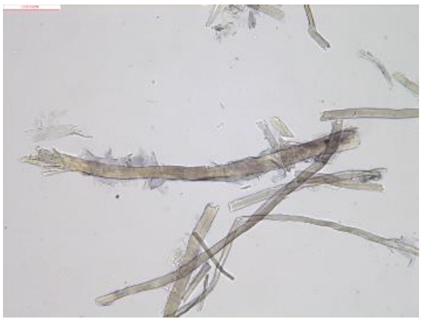

Figure 4: Fiber morphology of surface (200× magnification)

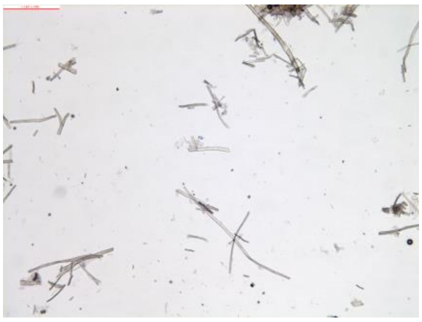

Figure 5: Fiber morphology of backing layers (100× magnification)

Figure 6: Fiber morphology of backing layers (200× magnification)

3.3 Py-GC/MS Analysis

Pyrolysis–GC/MS (at 500 ℃) of samples KYD-1 and KYD-2 revealed the following major compounds (Table 2).

Table 2: Py-GC/MS results

Retention time (min)	Main compound	Classification	Likely source
9.83	Palmitic acid	Saturated fatty acid	Animal fat or beeswax
10.92	Stearic acid	Saturated fatty acid	Animal glue/wax
14.36	Hexacosane	Long-chain alkane	Beeswax/plant wax
16.48	Indole, pyrrole derivatives	Nitrogenous aromatics	Animal protein pyrolysates
18.02	β-Amyrin acid	Triterpenoid acid	Plant resin
19.56	Styrene, phenolic compounds	Aromatics	Organic dye degradation

The coexistence of fatty acids and alkanes indicates the presence of a waxy coating, while nitrogenous compounds confirm animal glue (Figure 7). These results demonstrate a composite glue–wax sizing process: the paper was first sized with animal glue and then burnished with beeswax or plant wax—a traditional technique enhancing moisture resistance, insect repellence, and mechanical strength. Minor resinous and aromatic compounds suggest additional plant-based materials or dyes.

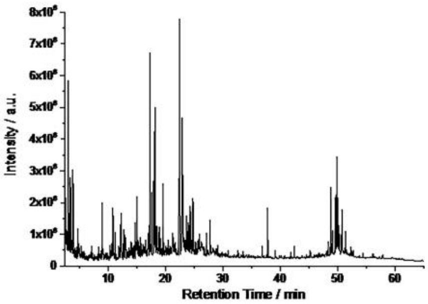

Figure 7: Py-GC/MS total ion chromatogram of the sutra paper

3.4 UPLC-QTOF MS Analysis

UPLC-QTOF MS analysis of the dye extract from KYD-1 (positive-ion mode) revealed prominent peaks at m/z 336.1, 320.1, and 322.1 (Figures 8–9), identified as follows (Table 3).

Table 3: UPLC-QTOF MS results

m/z	Ion	Compound	Source plant	Description
336.1	[M]+	Berberine	*Phellodendron amurense* (Amur cork tree)	Main coloring agent
320.1	[M]+	Palmatine	*Phellodendron* spp.	Secondary component
322.1	[M]+	Coptisine	*Coptis* spp.	Auxiliary dye
338.1	[M]+	Jatrorrhizine	*Fibraurea* spp.	Related alkaloid pigment

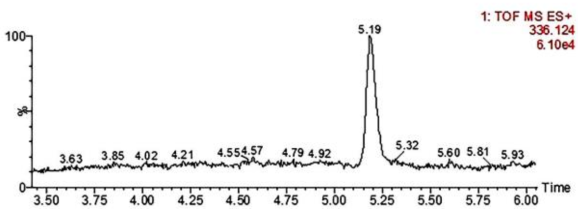

Figure 8: UPLC-QTOF MS chromatogram

These alkaloids were historically used for yellow dyeing, with *huangbo* (Amur cork tree bark) as the primary source. The strong berberine peak confirms natural *huangbo* dyeing, typical of Qing *hard yellow paper*. The relative abundance pattern—berberine > palmatine > coptisine—matches the proportions described in Qing treatises such as *Xiushi lu* and *Zaopi xinfa*, validating the imperial production origin.

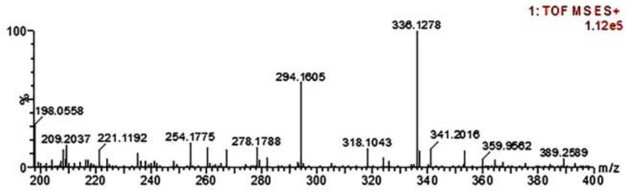

Figure 9: mass spectrum at 5.19 min

3.5 Visible–Near Infrared Multispectral Imaging

Multispectral imaging (400–1000 nm) of the paper's reverse side revealed, under 850–900 nm, faint dark text lines arranged in columnar format consistent with Buddhist sutra scrolls (Figure 10).

Spectral reflectance curves showed a characteristic yellow-dye peak at 550–600 nm (indicative of huangbo dye) and decreased reflectance beyond 700 nm, indicating mild surface carbonization. Localized microcracking of the wax layer observed in the images corresponds with uneven surface gloss noted under microscopy.

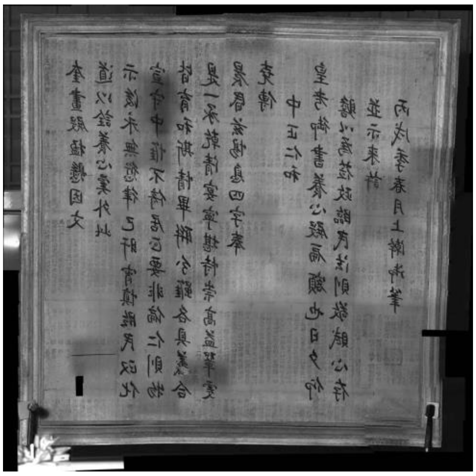

Figure 10: Multispectral imaging result

4. Analysis and Discussion

4.1 Material Composition and Manufacturing Features

Comprehensive analysis indicates that the sutra paper is primarily composed of kozo fibers, dyed with huangbo extract, sized with animal glue, and burnished with beeswax, producing a smooth, moisture-resistant, and durable surface. Structurally, it comprises two tightly bonded layers—a dyed facing paper and an undyed backing sheet—forming a typical imperial hard yellow paper composite. The Py-GC/MS results confirm the glue–wax system; UPLC-QTOF MS identifies berberine as the main dye; multispectral imaging reveals reused sutra inscriptions.

4.2 Reuse of Sutra Paper in the Imperial Court

The reuse of old sutra paper was common in the Qianlong court. Archival records note the emperor's preference for using "aged sutra paper" for his own calligraphy and edicts.

4.3 Preservation Condition and Deterioration Mechanisms

The paper's fiber structure remains stable without significant acid hydrolysis or mold. However, prolonged light exposure, humidity, and dye acidity have caused mild surface yellowing and acidification. Areas with reduced fluorescence correlate with lower pH, indicating deterioration concentrated in the dyed and sized layers. The backing paper, protected by wax, remains relatively intact.

Major degradation mechanisms:Continuous release of organic acids from residual dyes;Thermal oxidation and cracking of wax layers;Moisture absorption of glue layers causing local brittleness.

5. Conclusions

(1) The sutra paper is made of kozo fibers, dyed with huangbo (berberine-based) extract, sized with animal glue, and burnished with beeswax—typical hard yellow paper.

(2) The paper consists of two tightly bonded layers: a fluorescent dyed surface layer and a non-fluorescent backing layer, forming a "dyed + support" composite structure.

(3) UPLC-QTOF MS confirms berberine as the principal dye; Py-GC/MS verifies the glue–wax sizing system.

(4) Multispectral imaging reveals residual sutra inscriptions, proving the paper's reuse and reflecting material recycling in Qianlong's imperial production.

(5) Overall preservation is good, with minor acidification and wax aging; maintaining stable pH, humidity, and avoiding heat/light is essential.

(6) This study clarifies the composition and technology of Song-dynasty sutra paper, providing scientific data for material selection, replica production, and reconstruction of traditional papermaking techniques.

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