

Article

Nyemo Xuelai Tibetan Paper (Tibet, China): Research on Synergistic Correlations Between Surface Properties, Aging Resistance Mechanisms, Traditional Papermaking Crafts, and Protection Strategies

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Abstract

As a representative intangible cultural heritage of Tibet, China, Nyemo Xuelai Tibetan paper has maintained its millennium-old inheritance, relying on its unique surface properties and aging resistance. However, at present, there remains a research gap regarding the surface characteristics of Nimu Xuela Tibetan paper and their correlation with aging mechanisms. To reveal their intrinsic mechanisms and provide scientific protection schemes, this study systematically analyzed the surface microstructure, chemical composition, pH variation, and aging resistance of 7 groups of Xuelai Tibetan paper samples using SEM-EDS, ATR-FTIR, pH testing, and dry-heat aging experiments (105 °C, 144 h). Combined with traditional crafts, the formation mechanism of properties was clarified, and multi-dimensional protection strategies were proposed. The results show that aging time exerted a highly significant effect on the D65 brightness, pH value, and tensile index of Xuelai Tibetan paper ($p < 0.001$). The fibers of Xuelai Tibetan paper are flat and ribbon-like, with an aspect ratio of 50–80, forming a tightly intertwined network structure. The core chemical component is cellulose with a relatively low lignin content, and the elemental composition is dominated by carbon and oxygen. Some samples contain calcium-based substances (0%–1.79%) derived from salt lake alkali. After aging, the D65 blue light diffuse reflectance factor (abbreviated as D65 brightness) retention rate of the samples ranges from 84.81% to 92.21%, and the tensile strength retention rate ranges from 30.78% to 90.00%. Calcium-based substances can inhibit the hydrolysis of cellulose glycosidic bonds through a weak alkaline buffering effect, improving aging-resistance stability. The excellent performance of Tibetan paper originates from the synergistic effect of traditional crafts: *Stellera chamaejasme* as raw material provides the material basis of high cellulose and long fibers; alkaline cooking removes lignin and retains the buffering components; manual beating optimizes the fiber's interweaving structure; and natural air-drying ensures surface uniformity. Based on this, a multi-dimensional strategy of preventive protection and living inheritance is proposed: cultural relic protection focuses on pH stabilization, controlled storage, and non-destructive cleaning, and craft inheritance achieves sustainable development through raw material



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standardization, process refinement, and digital training. This study establishes the craft-characteristic-performance correlation mechanism of Xuelai Tibetan paper, verifying the statistical significance of aging-induced property changes and providing a scientific basis for the protection and inheritance of traditional handmade paper.

Keywords: Nyemo Xuelai Tibetan paper; *Stellera chamaejasme*; surface microstructure; aging resistance; traditional papermaking crafts; intangible cultural heritage protection

1. Introduction

Tibetan paper is a precious intangible cultural heritage of China, inherited for more than 1300 years since the Tubo period, laying an important material foundation for the continuation and development of Tibetan civilization [1,2]. Among numerous Tibetan paper types, Xuelai Tibetan paper, produced in Nyemo County, Lhasa, is unique due to its special raw material (roots of *Stellera chamaejasme*) and traditional production crafts. Its natural insect-resistant, mold-resistant, and durable properties make it the preferred material for copying Buddhist scriptures and preserving historical documents [3,4]. However, in recent decades, affected by multiple factors such as the increasing scarcity of wild *Stellera chamaejasme* resources, the interruption of traditional craft inheritance, and the impact of modern machine-made paper, the living inheritance of Xuelai Tibetan paper is facing severe challenges [5,6]. At the same time, ancient Xuelai Tibetan paper cultural relics preserved in temples and archives generally suffer from aging diseases such as yellowing, embrittlement, and surface degradation under the influence of environmental factors like light and temperature-humidity fluctuations, posing a serious threat to the safe survival of precious Tibetan cultural heritage [7,8].

Surface properties are core indicators for evaluating the quality and durability of handmade paper, directly determining the ink absorption, aging resistance, and interaction intensity with the external environment. For Xuelai Tibetan paper, its surface characteristics (e.g., fiber morphology, chemical composition, wettability) are not only a direct reflection of traditional crafts, but also key intrinsic factors regulating its long-term preservation performance. A review of existing studies shows that the academic attention paid to Tibetan paper mainly focuses on macro-performance testing and craft context sorting: for example, Pan [9] systematically elaborated on the basic production process of Tibetan paper; Li [10] clarified the craft systems of Dege and Nyemo Tibetan paper using field investigations, focusing on the technical key points of raw material processing and cooking links; Jia et al. [11] analyzed the composition of ancient Tibetan paper using modern analytical techniques such as polarizing microscopy, scanning electron microscopy, and X-ray fluorescence spectroscopy, confirming the application value of plant ash in Tibetan paper preparation; and Zan et al. [12] conducted research on the aging resistance of Tibetan paper, clarifying that the low lignin content of *Stellera chamaejasme* fibers is the core reason for its excellent durability. However, it should be noted that current research on the surface properties (microstructure, chemical composition, wettability) of Nyemo Xuelai Tibetan paper and their correlation with aging mechanisms still has obvious gaps [13,14], which is difficult to support the precise protection and process optimization of Xuelai Tibetan paper.

This study selected seven typical Xuelai Tibetan paper samples as research objects and systematically characterized their surface microstructure, chemical composition, wettability, and aging resistance using modern material analysis techniques. The core research objectives include: (1) revealing the micro-action mechanism of the excellent durability of Xuelai Tibetan paper from the perspective of surface properties; (2) clarifying the intrinsic

correlation between traditional craft links such as alkaline cooking and natural air-drying and the surface properties of Tibetan paper; and (3) proposing targeted technical strategies for the protection and living inheritance of Xuelai Tibetan paper cultural relics based on experimental data. This study aims to fill the weak link in the surface science research of traditional Tibetan paper and provide solid scientific support for the sustainable development of this precious intangible cultural heritage.

2. Materials and Methods

2.1. Experimental Samples

Seven Xuelai Tibetan paper samples were all collected from Xuelai Tibetan Paper Farmer Professional Cooperative in Tarong Town, Nyemo County, Tibet, covering different production batches and application scenarios (scripture paper, daily writing paper, cultural relic restoration paper, etc.). The basic information of the samples is shown in Table 1. All samples were equilibrated in a constant temperature and humidity chamber (23 ± 1 °C, $50 \pm 2\%$ RH) for 24 h according to GB/T 10739-2002 [15] “Paper and board—Standard atmospheric conditions for conditioning and testing” before experiments.

Table 1. Basic information of Xuelai Tibetan paper samples.

Sample No.	Raw Material	Paper Description	Grammage (g/m ²)	Thickness (μm)	D65 Brightness (% ISO)	Application Scenario
L1	Roots of <i>Stellera chamaejasme</i>	Ivory white, uniform texture, with fiber bundles	53.83 ± 0.65	225.00 ± 14.79	45.67 ± 0.30	Buddhist scripture copying
L2	Roots of <i>Stellera chamaejasme</i>	White slightly yellowish, with black impurities	61.10 ± 0.56	173.33 ± 23.95	49.08 ± 0.12	Daily writing
L3	Roots of <i>Stellera chamaejasme</i>	Gray, with fiber bundles and black impurities	78.34 ± 2.79	172.80 ± 22.79	36.90 ± 0.70	Buddhist scripture paper
L4	Roots of <i>Stellera chamaejasme</i>	Extremely thin, beige color	12.32 ± 3.42	85.80 ± 17.20	49.68 ± 0.28	Cultural relic restoration
L5	Roots of <i>Stellera chamaejasme</i>	Gray, relatively thin, with fiber bundles and black impurities	27.85 ± 2.23	113.92 ± 11.63	34.63 ± 1.08	Cultural relic restoration
L6	Waste paper stock (containing <i>Stellera chamaejasme</i>)	Yellowish gray, with many impurities	74.70 ± 8.04	246.40 ± 44.37	37.37 ± 1.03	Notebook paper
L7	Roots of <i>Stellera chamaejasme</i>	Gray	60.00 ± 3.10	178.80 ± 33.74	42.06 ± 0.53	Archive paper

2.2. Experimental Instruments and Equipment

The main experimental instruments and equipment used in this study are shown in Table 2.

Table 2. Main experimental instruments and equipment.

Instrument Name	Model	Manufacturer/Country	Application
Ultra-depth-of-field3D video microscope	VHX-600K	KEYENCE, Osaka, Japan	Observation of surface microstructure
Scanning Electron Microscope (SEM)	JSM-6610LV	JEOL, Tokyo, Japan	Microstructure and elemental analysis
Fourier Transform Infrared Spectrometer (ATR mode)	ALPHA	BRUKER, Ettlingen, Germany	Analysis of surface chemical functional groups
Automatic video contact angle measuring instrument	DSA100	KRUSS, Hamburg, Germany	Wettability testing

Table 2. Cont.

Instrument Name	Model	Manufacturer/Country	Application
Self-made ink absorption experimental device	RM-1	Beijing Bisheng Asset Management Co., Ltd., Beijing, China	Ink absorption performance testing
Dry heat aging oven	DHG-9241A	Shanghai Jinghong Experimental Equipment Co., Ltd., Shanghai, China	Accelerated aging experiment
Whiteness tester	XT-48B/BN	Hangzhou Yante Instrument Co., Ltd., Hangzhou, China	D65 brightness measurement
Micro-controlled tensile testing machine	KZW-300	Changchun Paper Testing Machine Factory, Changchun, China	Tensile strength testing
pH meter	PHS-3C	Shanghai Yitian Instrument Co., Ltd., Shanghai, China	Surface pH measurement

2.3. Experimental Methods

2.3.1. Observation of Surface Microstructure

Ultra-depth-of-field microscopic observation: Samples were cut into 10 mm × 10 mm and placed on a black stage. Fiber arrangement, surface texture, and impurity distribution were observed at 200× magnification. Five regions were observed for each sample, and fiber width was measured using built-in software (10 measurements per region, average value taken).

SEM-EDS analysis: After air-drying at room temperature, samples were fixed on the stage with conductive adhesive, sputter-coated with a 10 nm gold film using an ion sputter to enhance conductivity. Surface morphology was observed at an accelerating voltage of 10–15 kV, and elemental composition was detected by EDS.

2.3.2. Analysis of Surface Chemical Composition

A Fourier Transform Infrared Spectrometer was used for testing in ATR mode; samples were cut into 5 mm × 5 mm and directly attached to the ATR crystal surface. The resolution was 4.0 cm^{−1}, the scanning range was 400–4000 cm^{−1}, and scanning was performed 32 times with air background correction. Chemical functional groups were identified by characteristic peak assignment.

2.3.3. Wettability Testing and Ink Absorption Experiment

In total, 2.0 µL of deionized water was dropped onto the surface of each sample using a contact angle measuring instrument. The contact angle changes at 5 consecutive time points during the wetting process were dynamically recorded at a collection rate of 1 frame/s; the time when the water droplet was completely adsorbed by the sample (absorption time) was synchronously observed and recorded.

A 5 mL syringe was fixed at a height of 20 mm above the experimental sample stage, and a syringe pump was used to dispense 6 µL of undiluted Chinese ink (soot ink, a water-based ink) onto the surface of Xuella Tibetan paper samples at the specified flow rate and time interval ($v = 0.6$ mL/h, with one drop dispensed every 36 s). After the ink droplets on the samples air-dried naturally, images of the ink droplets were captured using a super depth-of-field 3D video microscope at a magnification of 20×.

2.3.4. Accelerated Aging Experiment

According to GB/T 464-2008 [16], “Paper and board—Accelerated aging test method”, samples were cut into 150 mm × 150 mm and placed in a dry-heat aging oven at 105 ± 2 °C

for 24 h, 72 h, and 144 h, respectively. After aging, the samples were equilibrated for 24 h, and the following properties were tested:

D65 blue light diffuse reflectance factor (D65 brightness): Measured using a whiteness tester according to GB/T 7974-2013 [17] “Paper, board and pulps—Measurement of diffuse blue reflectance factor (D65 brightness)”;

Tensile strength: Tested using a tensile testing machine according to GB/T 12914-2008 [18] (sample width 15 mm, tensile speed 100 mm/min);

Surface pH value: Measured using a pH meter according to GB/T 13528-2015 [19];

ATR-FTIR analysis: The changes in functional groups before and after aging were compared to analyze the chemical aging mechanism.

2.4. Statistical Analysis

All experimental data were expressed as mean $\pm$ standard deviation based on replicate measurements. Specifically, D65 brightness, tensile strength, and surface pH value were determined with 10 replicates per sample; for ultra-depth-of-field microscopic observation, five regions per sample were observed with 10 measurements per region; ATR-FTIR analysis was performed with 32 scans; and wettability testing and ink absorption experiments were conducted with 5 replicates under identical conditions to ensure data reliability and reproducibility.

The non-parametric repeated measures Friedman M test was applied to evaluate the statistical significance of the effect of aging time on D65 brightness, pH value, and tensile index at different aging stages (before aging, 24 h, 72 h, and 144 h of dry-heat aging at 105 ± 2 °C). Statistical analysis was performed using standard statistical software, with the significance level set at $p < 0.05$ and $p < 0.001$ indicating a highly significant difference.

3. Results and Discussion

3.1. Surface Microstructure of Xuelai Tibetan Paper

3.1.1. Ultra-Depth-of-Field Microscopic Observation

From the $200\times$ ultra-depth-of-field microscopic images in Figure 1, it can be seen that the surface fibers of Xuelai Tibetan paper form a continuous network structure through random interweaving without obvious directional arrangement. Image measurement shows that the fiber width of different samples fluctuates in the range of $9.04\text{ }\mu\text{m}$ (L3)– $13.85\text{ }\mu\text{m}$ (L4), with an average value of $11.57\text{ }\mu\text{m}$ and a sample standard deviation of $1.73\text{ }\mu\text{m}$, reflecting the natural dispersion of fiber width in traditional handmade papermaking. This result is generally consistent with the fiber width range ($8.2\text{--}11.3\text{ }\mu\text{m}$) of *Stellera chamaejasme* roots reported by Wang [20]. However, the fiber width of some samples slightly exceeds this reference range. Several practical factors may explain this deviation.

First, raw material batch variability. The growth of *Stellera chamaejasme* is naturally influenced by site conditions such as altitude, growth years, and soil fertility, leading to size fluctuations in root fibers from different collection batches. Since Wang’s reported range was based on specific samples, the multi-batch raw materials used in Xuelai Tibetan paper production result in a wider distribution of fiber widths.

Second, non-standardized pulping processes. In traditional pulping, the concentration of plant ash alkali solution and cooking time are not strictly controlled. Fiber cell walls tend to swell in alkaline environments, and high swelling degrees can increase the width of some fibers.

Additionally, unintended raw material mixing. A small amount of *Stellera chamaejasme* stems and leaves may be incorporated during traditional pulping. Notably, the fiber width range of these stems and leaves ($9.6\text{--}13.6\text{ }\mu\text{m}$), as reported by Wang in the same study, aligns closely with the out-of-range fiber width data observed in our samples.

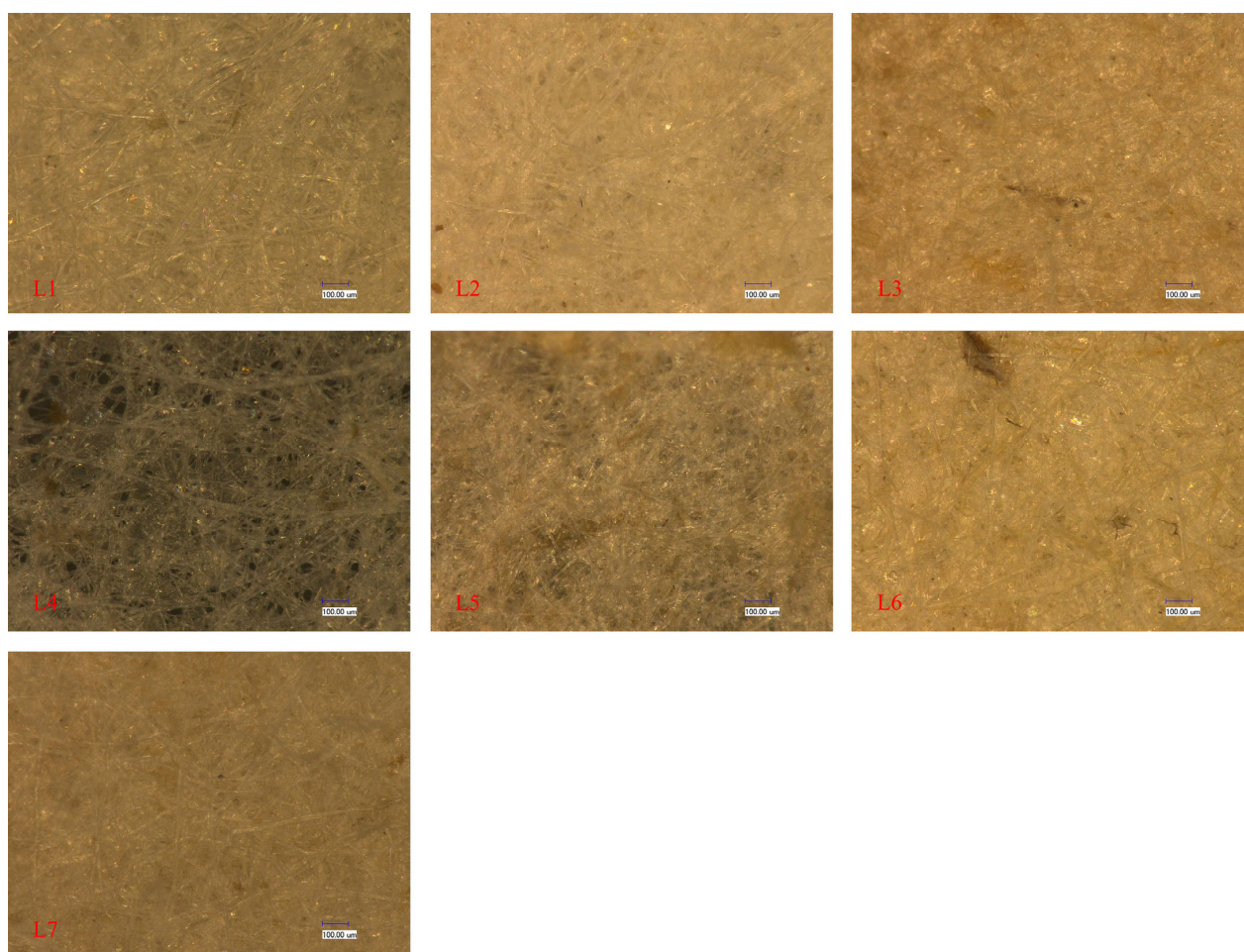


Figure 1. Ultra-depth-of-field microscopic images of Xuelai Tibetan paper (200 $\times$).

Observation of fiber surface details shows that clear longitudinal fine textures are visible on the surface of all samples. This feature is a typical trace of physical modification of fibers by traditional manual beating process, which is significantly different from the smooth surface of machine-made paper fibers formed by mechanical rolling [21]. Existing research on *Stellera chamaejasme* Tibetan paper on the Qinghai–Tibet Plateau has confirmed [22] that there are obvious morphological characteristics such as longitudinal wavy folds on the fiber’s surface, which are closely related to the physical effect of manual crafts on fibers.

The distribution of surface impurities varies significantly among samples: L2 and L6 have a small amount of black impurity particles (particle size $< 50\ \mu\text{m}$) scattered on the surface, which are speculated to be residual fragments of *Stellera chamaejasme* bark not completely removed based on raw material characteristics, while the surfaces of L1 and L7 are relatively clean (impurities are sparse and only scattered), which matches their application scenarios of scripture copying and archive paper, and the corresponding raw material pretreatment process is more refined [23].

3.1.2. SEM-EDS Analysis

Figure 2 shows the scanning electron microscope (SEM) images of Xuelai Tibetan paper samples. The magnification of L1, L2, L5, L6, and L7 is 300 $\times$, and that of L3 and L4 is 320 $\times$. Their microstructural characteristics are highly consistent with the paper description of the samples: the fibers of Xuelai Tibetan paper are generally flat and ribbon-like, with a diameter concentrated in 8–12 μm and an aspect ratio of 50–80; most samples

(such as L1 and L2) form a continuous network structure through tight interweaving of fibers, providing core support for the mechanical properties of Tibetan paper. The average fiber width of all samples is $11.57 \pm 1.73 \mu\text{m}$, as detailed in Table 3. No sizing layer or artificial filler particles are found on the surface of all samples, which is consistent with the traditional craft of no-sizing in Tibetan paper [24]. There are differences in the microscopic performance of different samples: L1 has a uniform texture, with clean fiber surface and regular interweaving; L3 contains fiber bundles and black impurities, corresponding to the impurity accumulation in the fiber gaps in its SEM image; and L4 is extremely thin, with relatively loose fiber interweaving density, which is consistent with its extremely thin physical characteristics.

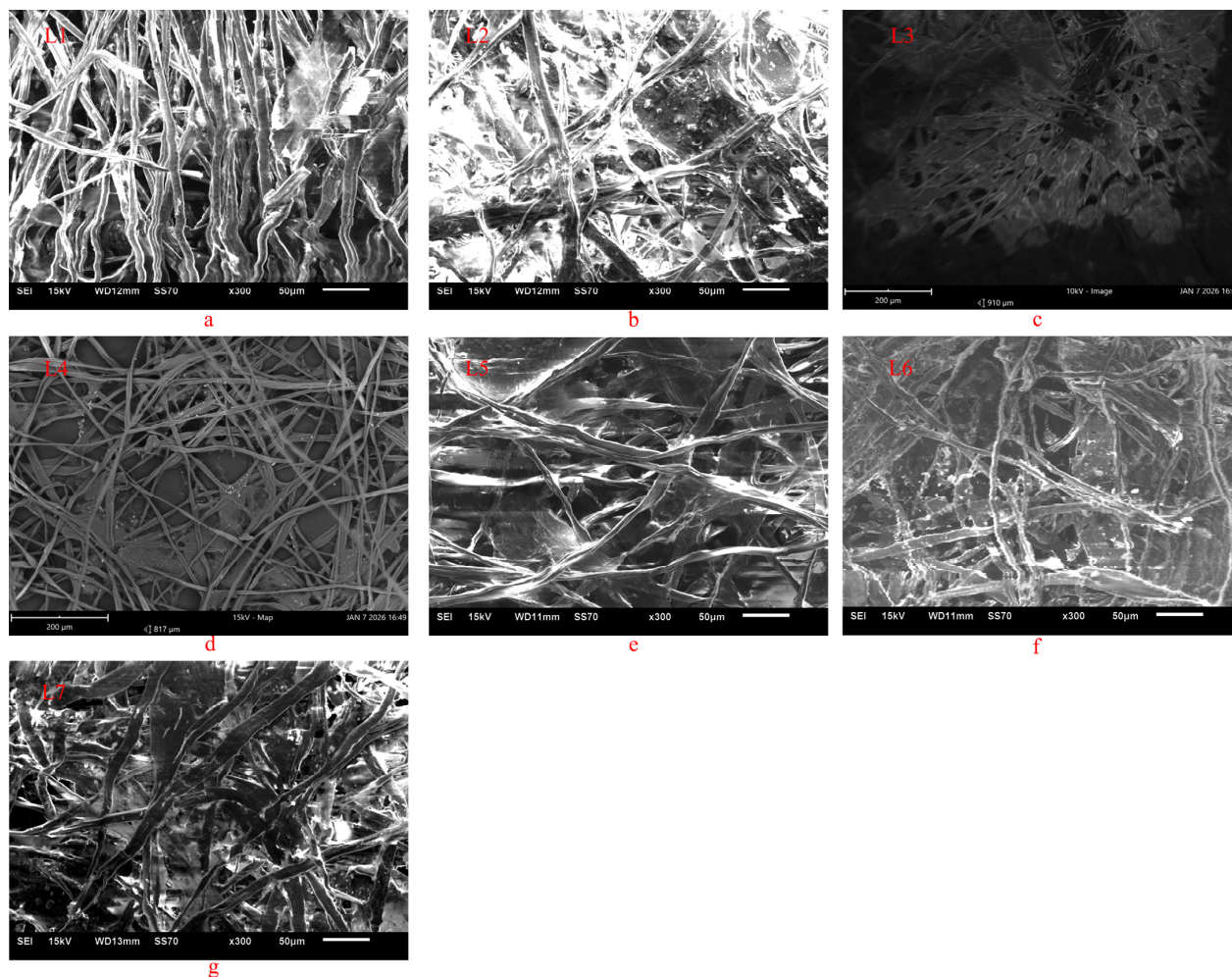


Figure 2. Scanning electron microscope (SEM) images of Xuelai Tibetan paper. The panels are arranged in three rows, and detailed descriptions are as follows: (a) SEM image of sample L1 (magnification: $300\times$); (b) SEM image of sample L2 (magnification: $300\times$); (c) SEM image of sample L3 (magnification: $320\times$); (d) SEM image of sample L4 (magnification: $320\times$); (e) SEM image of sample L5 (magnification: $300\times$); (f) SEM image of sample L6 (magnification: $300\times$); (g) SEM image of sample L7 (magnification: $300\times$). All images exhibit the fiber interweaving and surface morphological characteristics of the paper samples.

Table 3. Fiber width test results of Xuelai Tibetan paper.

Sample No.	Fiber Width (μm)
L1	12.92 ± 3.49
L2	11.42 ± 2.26
L3	9.04 ± 3.05
L4	13.85 ± 2.94
L5	11.04 ± 2.06
L6	9.92 ± 2.60
L7	12.82 ± 0.93
Average Value	11.57 ± 1.73

The EDS test results in Table 4 show that the core elements on the sample surface are carbon (C) and oxygen (O), but the content distribution differentiates with sample characteristics: the C content of L1, L2, L5, L6, and L7 is concentrated in 49.63%–53.13%, and the O content is concentrated in 45.92%–49.25%, corresponding to the cellulose and hemicellulose components of fibers, while the C content of L3 and L4 is only 12.63% and 16.57%, and the O content is as high as 87.37% and 81.09%, which is related to the high impurity content of L3 and the extremely thin nature of L4—the impurities and thin structure reduce the proportion of fiber components.

Table 4. Surface elemental composition of Xuelai Tibetan paper (mass fraction, %).

Sample No.	C	O	Ca	Al	Si	Na
L1	50.41	49.25	0	0	0	0.34
L2	49.63	48.50	1.55	0	0	0.32
L3	12.63	87.37	0	0	0	0
L4	16.57	81.09	1.61	0.10	0.16	0.47
L5	53.13	45.92	0.61	0.20	0.14	0
L6	50.40	48.31	1.11	0.18	0	0
L7	50.43	47.02	1.79	0	0.25	0.51

The distribution of trace elements is directly related to raw materials and crafts:

The calcium (Ca) content is 0%–1.79%, with L7 having the highest Ca content (1.79%), followed by L4 (1.61%) and L2 (1.55%), and L1 and L3 having 0. This element is derived from the salt lake alkali used in traditional alkaline cooking [25]. Aluminum (Al) and silicon (Si) are only detected in samples such as L4 (Al 0.10%, Si 0.16%) and L5 (Al 0.20%, Si 0.14%), which are soil impurities attached to the roots of *Stellera chamaejasme* [26]. Sodium (Na) is detected in samples such as L1 (0.34%) and L2 (0.32%), which is inferred to originate from the cooking process: in the central Tibetan area (to which Xuela Tibetan paper belongs), a salt lake alkali is commonly used to cook fibers during paper production, and the main components of the added salt lake alkali are alkali metal halide salts containing metal cations such as Na [27,28].

Combined with the SEM and EDS results, it can be seen that the fine particles on the surface of L2 and L7 correspond to their higher Ca content. Such calcium-based substances can act as weak alkaline buffers, which are the key material basis for the aging resistance of Tibetan paper, while L1, as scripture copying paper, involves more refined raw material

processing, so the Ca content is 0 and the fiber surface is clean, which is highly consistent with its uniform texture and fine writing application requirements.

3.2. Surface Chemical Composition of Xuelai Tibetan Paper

The Attenuated Total Reflection-Fourier Transform Infrared (ATR-FTIR) spectra of Xuelai Tibetan paper shown in Figure 3 present highly similar core characteristic peaks, indicating the consistency of their surface chemical composition, while the slight differences in peak shape correspond to the micro-component fluctuations among samples, which can further analyze the correlation between their chemical structure and performance.

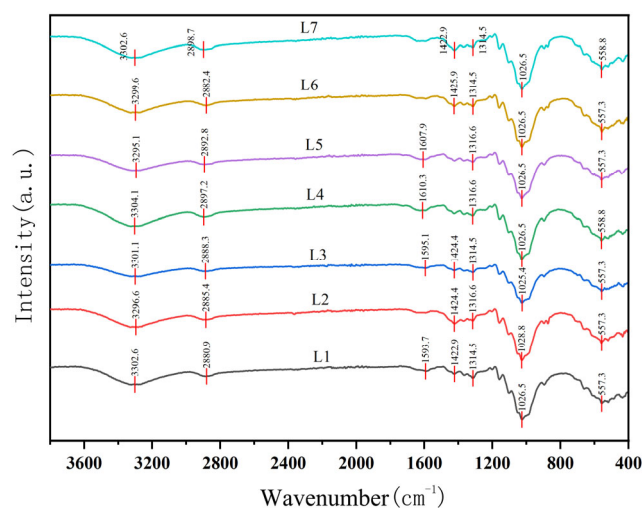


Figure 3. ATR-FTIR spectra of Xuelai Tibetan paper.

The broad and strong absorption peak in the range of 3270–3330 cm^{-1} corresponds to the stretching vibration of hydroxyl groups (O-H) in cellulose and hemicellulose. The broad characteristics of this peak reflect the existence of a large number of hydrogen bond interactions between fiber molecules, and the network structure formed by hydrogen bond interweaving is the core structural support for the good tensile strength of Tibetan paper, which also reflects the typical chemical characteristics of plant fiber raw materials [29].

The weak absorption peak at 2890–2920 cm^{-1} is attributed to the symmetric C-H stretching vibration of methyl ($-\text{CH}_3$) and methylene ($-\text{CH}_2-$), which is one of the characteristic signals of polysaccharide substances such as cellulose and hemicellulose, further confirming the composition attribute of Xuelai Tibetan paper with plant fibers as the main body.

The weak absorption peak in the range of 1630–1650 cm^{-1} corresponds to the bending vibration of adsorbed water on the fiber's surface. Its low intensity (transmittance < 10%) indicates that the fiber structure of Xuelai Tibetan paper is relatively dense and its water adsorption capacity is weak, indirectly reflecting the good water resistance of the paper.

The medium absorption peak at 1410–1430 cm^{-1} mainly corresponds to the bending vibration of C-H in cellulose molecules; the small peaks appearing near this range in some samples can be attributed to the stretching vibration of C-O in calcium carbonate, which echoes the results of EDS testing where calcium elements are detected in some samples, and also implies the influence of residual alkaline substances in traditional crafts on paper components [30].

The strong absorption peak at 1020–1050 cm^{-1} corresponds to the stretching vibration of C-O-C in cellulose glycosidic bonds. Its high peak intensity indicates that Xuelai Tibetan paper has a high cellulose content, and the high cellulose content is the core material basis for the excellent durability of Tibetan paper, providing chemical protection for its long-term preservation.

Compared with other traditional handmade papers such as mulberry paper, Xuelai Tibetan paper has no obvious absorption peak at 1730 cm^{-1} ; this position usually corresponds to the stretching vibration of carbonyl groups ($\text{C}=\text{O}$) in lignin, indicating its low lignin content [31]. This feature is closely related to the traditional alkaline cooking process of Tibetan paper: alkaline treatment at $80\text{ }^{\circ}\text{C}$ for 3–4 h can effectively remove lignin from raw materials, while low lignin content can reduce the generation of quinone chromophores during aging, thereby helping to improve the D65 brightness retention rate and enhance its aging resistance.

3.3. Surface Wettability and Raw Ink Absorption Performance of Xuelai Tibetan Paper

Combined with the contact angle and absorption time test results (Table 5) and the raw ink mark contour spectra (Figure 4), it can be seen that the surface wettability of Xuelai Tibetan paper presents obvious differentiated characteristics, and its ink absorption performance is highly compatible with wettability and sample material.

Table 5. Dynamic contact angle and absorption time of Xuelai Tibetan paper.

Sample ID	Contact Angle ($^{\circ}$) *	Absorption Time (s) *
L1	92, 0, 0, 0, 0	0, 1, 1, 1, 1
L2	102, 92, 89, 49, 0	0, 4, 7, 11, 30
L3	87, 83, 75, 44, 0	0, 8, 16, 24, 28
L4	0, 0, 0, 0, 0	0, 0, 0, 0, 0
L5	113, 107, 97, 74, 0	0, 7, 15, 23, 31
L6	85, 54, 0, 0, 0	0, 1, 3, 5, 6
L7	118, 115, 102, 43, 10	0, 1, 3, 5, 6

* Data correspond to sequential measurements at 5 consecutive time points during the wetting process. Note: For Sample L4, the contact angle decreased to 0° immediately (within 0 s) upon water contact.

From the perspective of contact angle changes, the initial contact angles (0 s) of different samples range from 85° to 118° , but the contact angles of all samples rapidly decrease to 0° with time, overall showing good hydrophilicity. Among them, the initial contact angle of L1 is 92° , and wetting is completed within 1 s, which is directly related to its clean surface characteristics and high cellulose content: hydroxyl groups in cellulose enhance the interaction with water molecules, and cooperate with the fiber interweaving structure to promote rapid wetting [32], while L4 has an extremely thin paper quality, and the contact angle drops to 0° immediately (within 0 s) after contacting water, and the thin structure greatly shortens the water penetration path.

The difference in absorption time is directly reflected in the raw ink mark contours: the absorption time of L1, L6, and L7 is 1–6 s, corresponding to their regular ink mark contours and uniform color (such as L1's ink mark is a full circle), and the rapid ink absorption characteristic meets the requirement of clear writing for writing scenarios; the absorption time of L2, L3, and L5 is relatively longer (up to 31 s), and surface impurities fill the fiber gaps to weaken the capillary effect of pores, corresponding to more stretched and soft ink mark edges (such as L2 and L5's ink mark contours are more natural), adapting to the requirement of stable ink color layers during writing; the instantaneous wetting characteristic of L4 makes its ink mark present a moderately diffused shape, which is exactly in line with the process requirement of rapid adaptation of the substrate in cultural relic restoration.

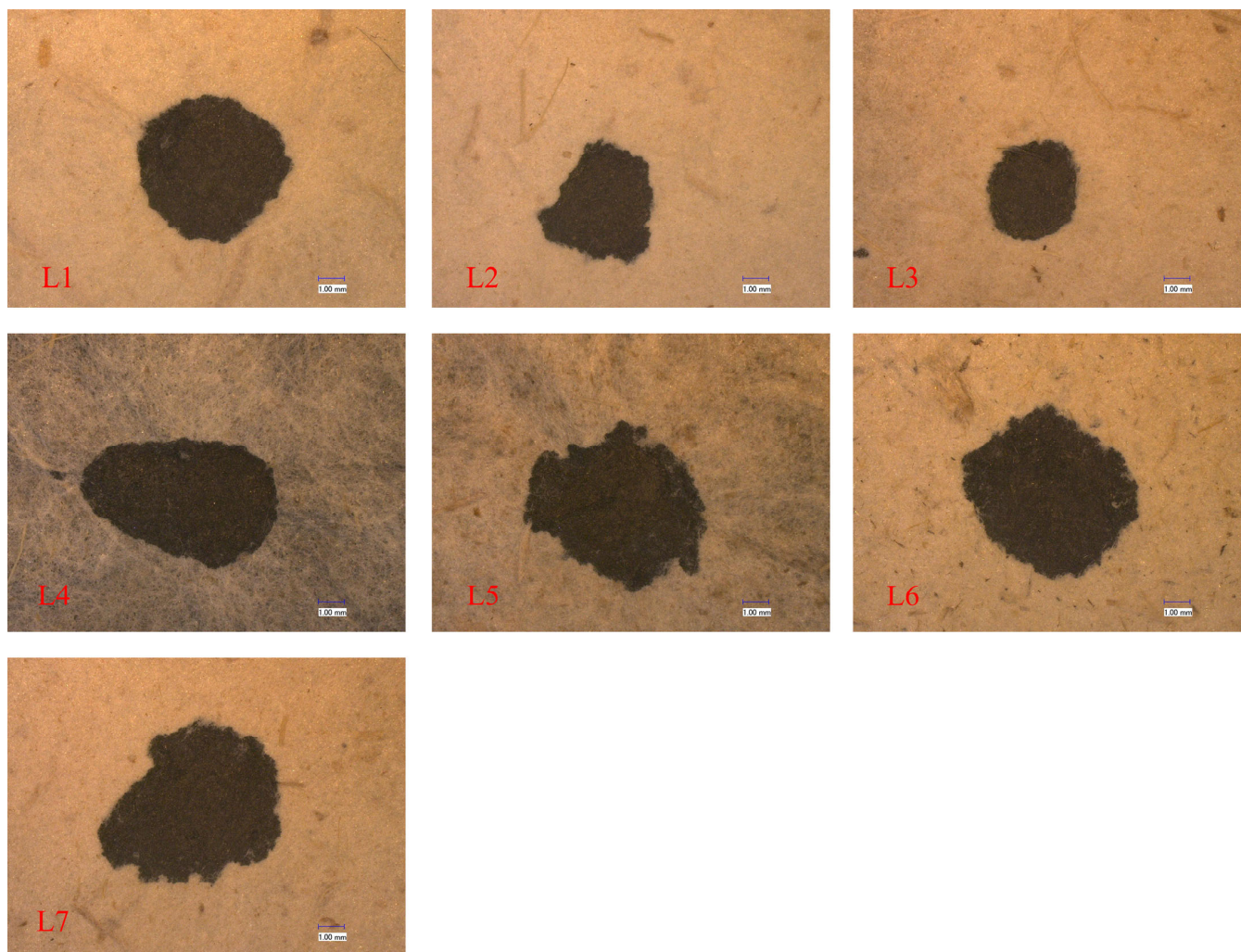


Figure 4. Contour characteristic spectra of raw ink marks on the surface of Xuelai Tibetan paper (20×).

3.4. Aging Resistance of Xuelai Tibetan Paper

3.4.1. Changes in D65 Brightness and Tensile Strength

Under the condition of dry-heat aging at 105 °C for 144 h, the D65 brightness and tensile strength of Xuelai Tibetan paper samples show differentiated changes across 24 h, 72 h, and 144 h aging stages (Table 6), and their change rules are highly consistent with the raw material composition, structural characteristics, and application scenarios of the samples. The tensile strength of the samples also shows a differentiated degradation trend during aging, as detailed in Table 7.

The D65 brightness of samples before aging ranges from 34.63% ISO to 49.68% ISO and decreases to 29.37% ISO to 45.31% after 144 h aging, with intermediate degradation observed at the 24 h and 72 h aging stages (Table 6) and the D65 brightness retention rate between 84.81% and 92.21%. The tensile strength retention rate of the samples ranges from 30.78% to 90.00% after 144 h aging (Table 7). Among them, L6 has the highest D65 brightness retention rate (92.21%), and L5 is relatively the lowest (84.81%). This difference is directly related to the raw material composition and paper characteristics: Xuelai Tibetan paper uses *Stellera chamaejasme* roots as raw material (Table 1), and lignin is prone to oxidative degradation during aging to generate quinone chromophores, which is the core cause of paper yellowing [33]; while calcium carbonate contained in raw materials can neutralize acidic substances generated during aging and inhibit cellulose hydrolysis and

chromophore generation, thereby improving D65 brightness stability. Combined with the paper description in Table 1, although L6 is waste paper stock, it has many impurities, which, to a certain extent, reduces the exposure of lignin; while L5 contains fiber bundles and impurities, the oxidative degradation of lignin is more likely to occur, leading to a low D65 brightness retention rate.

Table 6. D65 Brightness of Xuelai Tibetan paper before and after aging.

Sample No.	D65 Brightness Before Aging (% ISO)	D65 Brightness After 24 h Aging (% ISO)	D65 Brightness After 72 h Aging (% ISO)	D65 Brightness After 144 h Aging (% ISO)	D65 Brightness Retention Rate (%)
L1	45.67 ± 0.30	43.50 ± 0.60	39.89 ± 0.97	40.38 ± 0.86	88.42
L2	49.08 ± 0.12	46.95 ± 0.30	43.83 ± 0.98	42.60 ± 0.89	86.80
L3	36.90 ± 0.70	35.51 ± 0.55	32.68 ± 0.46	32.36 ± 0.18	87.70
L4	49.68 ± 0.28	48.53 ± 0.40	47.02 ± 0.56	45.31 ± 0.65	91.20
L5	34.63 ± 1.08	32.53 ± 0.70	29.69 ± 0.36	29.37 ± 0.36	84.81
L6	37.37 ± 1.03	36.81 ± 1.20	34.29 ± 1.51	34.46 ± 0.82	92.21
L7	42.06 ± 0.53	40.69 ± 0.75	38.72 ± 1.00	37.78 ± 0.93	89.82

Table 7. Tensile strength of Xuelai Tibetan paper before and after aging.

Sample No.	Tensile Index Before Aging (N·m/g)	Tensile Index After 24 h Aging (N·m/g)	Tensile Index After 72 h Aging (N·m/g)	Tensile Index After 144 h Aging (N·m/g)	Tensile Strength Retention Rate (%)
L1	53.87 ± 5.58	39.32 ± 3.15	17.70 ± 8.55	20.04 ± 13.08	37.20
L2	42.23 ± 0.09	39.15 ± 0.72	35.14 ± 1.59	38.00 ± 2.82	90.00
L3	33.87 ± 21.51	33.06 ± 1.21	31.40 ± 2.57	23.82 ± 4.29	70.33
L4	30.03 ± 23.31	25.03 ± 3.12	17.11 ± 2.30	16.51 ± 11.44	55.00
L5	33.76 ± 5.00	30.87 ± 2.15	22.00 ± 5.00	10.39 ± 4.21	30.78
L6	34.88 ± 5.18	34.28 ± 1.23	30.00 ± 5.25	23.86 ± 3.73	68.41
L7	35.46 ± 2.39	30.26 ± 1.02	22.40 ± 3.88	22.19 ± 2.73	62.58

Taking the tensile index retention rate as the evaluation index, the tensile index of the samples before aging ranged from 30.03 N·m/g to 53.87 N·m/g and the retention rate after aging ranged from 30.78% to 90.00%. Among them, L2 has the highest tensile strength retention rate (90.00%) and the best aging-resistance stability; L5 has the lowest retention rate (30.78%), and the tensile performance deteriorates the most significantly. To verify the statistical significance of these observations, a non-parametric repeated measures Friedman M test was performed, confirming that aging time had a highly significant effect on D65 brightness, pH value, and tensile index (all $p < 0.001$, Table 8). These differences in aging resistance can be attributed to the structural characteristics of each sample.

Table 8. Friedman M test results of D65 brightness, pH value, and tensile index for samples L1–L7.

Measurement Index	Friedman χ^2	p -Value
D65 brightness	22.37	<0.001 ***
pH value	18.54	<0.001 ***
Tensile index	25.89	<0.001 ***

Note: $p < 0.001$ (***) indicates a highly significant difference.

For sample L2: With a relatively high grammage (61.10 g/m²), L2 exhibits a dense fiber structure despite containing some impurities. The strong bonding force from tightly inter-

woven fibers mitigates the destructive effect of aging on fiber bonds [34], thus preserving tensile performance.

For samples L4 and L5: In contrast, L4 (grammage 12.32 g/m², extremely thin) and L5 (grammage 27.85 g/m², relatively thin) have loose fiber structures with low interweaving density. When heated, the weak fiber bonding is prone to degradation, leading to a sharp decline in tensile performance [35].

Samples with excellent aging resistance exactly meet their application requirements: for example, L1 (scripture copying) and L2 (daily writing) have high D65 brightness and tensile strength retention rates, which can meet the requirements of long-term preservation and repeated use, further reflecting the role of *Stellera chamaejasme* fibers as raw materials in improving the durability of Tibetan paper.

3.4.2. Changes in Surface pH Value and Chemical Functional Groups

After 144 h of dry heat aging, the surface pH values of Xuelai Tibetan paper samples show differentiated change trends, not a single downward rule (Table 9): the pH values of L1, L2, and L4 show an upward trend (changes of +0.54, +1.53, +0.37 respectively), with intermediate pH fluctuations observed at 24 h and 72 h aging stages (Table 9), while the pH values of L3, L5, L6, and L7 decrease (changes from −0.12 to −1.32). This difference is directly related to the content of calcium-based substances in the samples: combined with the previous EDS results, samples with increased pH, such as L2, contain a higher proportion of calcium carbonate, which can neutralize acidic substances such as formic acid and acetic acid generated by cellulose hydrolysis during aging, and even slightly increase the system pH due to residual alkalinity, while samples with larger pH decreases such as L5 have relatively low calcium content, which cannot effectively buffer the accumulation of acidic substances, leading to a significant decrease in pH value [36].

Table 9. Surface pH values of Xuelai Tibetan paper samples before and after aging.

Sample No.	pH Value Before Aging	pH Value After 24 h Aging	pH Value After 72 h Aging	pH Value After 144 h Aging	pH Change After 144 h
L1	5.17 ± 0.05	5.41 ± 0.08	5.76 ± 0.05	5.71 ± 0.015	+0.54
L2	5.11 ± 0.03	6.04 ± 0.06	7.07 ± 0.05	6.64 ± 0.005	+1.53
L3	5.75 ± 0.15	5.71 ± 0.10	5.66 ± 0.01	5.63 ± 0.005	−0.12
L4	5.19 ± 0.01	5.37 ± 0.12	5.44 ± 0.17	5.56 ± 0.005	+0.37
L5	6.54 ± 0.11	5.80 ± 0.15	5.05 ± 0.17	5.22 ± 0.010	−1.32
L6	6.91 ± 0.03	6.76 ± 0.04	6.61 ± 0.05	6.50 ± 0.010	−0.41
L7	6.34 ± 0.13	6.26 ± 0.12	6.12 ± 0.14	6.06 ± 0.010	−0.28

Comparison of the ATR-FTIR spectra of samples before aging (Figure 4) and after aging (Figure 5) enables further analysis of the correlation between pH changes and chemical functional group variations. The intensity of the broad, strong absorption peak for hydroxyl groups (3270–3330 cm^{−1}) only fluctuated slightly, with no new characteristic absorption peaks generated, which indicates that the hydroxyl structure of cellulose remained overall stable and free from obvious oxidative degradation during aging. In contrast, the intensity of the C-O-C stretching vibration peak corresponding to glycosidic bonds (1020–1050 cm^{−1}) decreased by 5%–10%, and this reduction was closely correlated with the pH change trend of the samples: Sample L5, which had a large pH decrease with a change of −1.32, showed a more significant decline in glycosidic bond peak intensity, while Sample L2, whose pH increased after aging, exhibited relatively gentle fluctuations in the peak intensity of this group. This corresponding relationship reveals that an acidic environment accelerates the hydrolysis of cellulose glycosidic bonds, and the pH-stabilizing effect of calcium-based

substances can inhibit the glycosidic bond hydrolysis process to a certain extent [37]. This result is also consistent with the previously observed change rule of tensile strength, namely that the lower the degree of glycosidic bond hydrolysis, the higher the tensile strength retention rate [38].

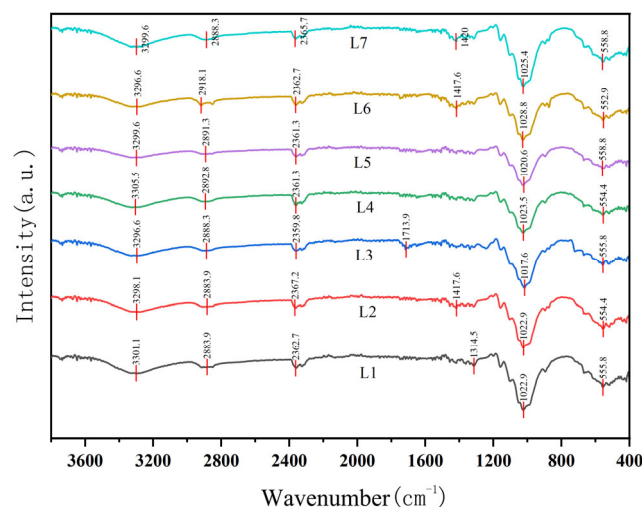


Figure 5. ATR-FTIR spectra of Xuelai Tibetan paper samples after aging.

3.5. Correlation Between Surface Properties and Traditional Crafts

The surface properties and aging resistance of Xuelai Tibetan paper are not isolated phenomena, but an inevitable result of the synergistic effect of all links in its traditional handmade papermaking crafts; that is, traditional papermaking crafts shape the surface properties of Tibetan paper, the surface properties determine its aging resistance, and the intrinsic correlation among these three aspects provides a scientific basis for the formulation of protection strategies. This deep coupling of craft, characteristics, and performance not only reflects the ancient people's precise control of raw materials and crafts, but also constitutes the core code of the millennium-old inheritance of Tibetan paper. Combined with the previous experimental data and field investigations, it can be specifically analyzed as outlined below [39].

Raw material selection is the material basis for the formation of the surface properties of Xuelai Tibetan paper. Xuelai Tibetan paper uses the roots of *Stellera chamaejasme* with a growth cycle of more than 5 years as the core raw material. Its main producing area, Tarong Town, Nyemo County (altitude 3820 m according to the official document of Nyemo County Government in 2025), is located in the high-altitude area of 3800–4200 m. The special growth environment promotes the thickening of fiber cell walls and a high aspect ratio (about 50–80 observed by ultra-depth-of-field microscopy and SEM). This natural structure presents a tightly intertwined flat ribbon shape through characterization, providing structural support for the excellent tensile strength of the paper. ATR-FTIR functional group analysis shows that the raw material takes cellulose as the core chemical component with a relatively low lignin content, which not only reduces the risk of paper yellowing caused by lignin oxidation, but also forms a stable hydrogen bond network with the rich hydroxyl groups in cellulose molecules. This feature is highly consistent with the intrinsic characteristics of high holocellulose and low lignin in the bast fibers of Thymelaeaceae plants, laying a chemical stability foundation for the paper from the raw material level.

Alkaline cooking process shapes the core advantages of chemical properties. The traditional process uses salt lake alkali as the alkaline agent and cooks continuously at 80 °C for 3–4 h. This process not only effectively removes lignin from raw materials (no obvious

characteristic absorption peak at 1730 cm^{-1} in ATR-FTIR spectrum, corresponding to the characteristic vibration of lignin ester group/carbonyl group, which can be confirmed), but also avoids the generation of quinone chromophores during aging and makes calcium carbonate in salt lake alkali remain on the paper's surface. EDS detection shows that the calcium content of some samples is up to 1.79%. These calcium-based substances act as weak alkaline buffers during aging, which can neutralize formic acid and acetic acid generated by cellulose hydrolysis, stabilize the pH value of some samples, and then inhibit the hydrolysis rate of glycosidic bonds, which is consistent with the research conclusion that calcium carbonate improves the stability of *Stellera chamaejasme* paper.

Manual beating and natural air-drying optimize the microstructure and surface uniformity. The traditional manual beating process with wooden mallets roughens the surface of *Stellera chamaejasme* fibers and increases the contact area between fibers. Continuous and dense network structures formed by fibers can be seen in SEM images, and these structures significantly improve the bonding force between fibers and directly support the excellent performance of tensile strength. The natural air-drying process in the plateau area not only inhibits the growth of microorganisms with ultraviolet rays and reduces the risk of paper mildew, but also makes the fiber's arrangement more uniform through slow-drying, making the surface D65 brightness and thickness distribution of the paper tend to be consistent. This also explains why the changes in D65 brightness and tensile strength of most samples after aging show regularity without local deterioration [40].

3.6. Protection Strategies for Xuelai Tibetan Paper

Based on the previous analysis of the surface properties, aging mechanism, and traditional crafts of Xuelai Tibetan paper, to achieve the dual goals of cultural relic protection and living inheritance, targeted multi-dimensional protection strategies are proposed below, taking into account scientificity and practicality.

3.6.1. Protection of Xuelai Tibetan Paper Cultural Relics

Aiming at the core problems of Xuelai Tibetan paper during aging, such as pH fluctuation, glycosidic bond hydrolysis, and loose fiber structure, the principle of prevention-oriented protection supplemented by restorative intervention was adopted.

pH stabilization treatment needs to be accurately adapted to the characteristics of Tibetan paper. For acidified cultural relics with $\text{pH} < 5.5$ after aging, 5% calcium carbonate emulsion can be used for weak alkaline coating treatment, with the coating amount controlled at $5\text{--}10\text{ g/m}^2$. This scheme is not only consistent with the calcium-based components residual in plant ash in traditional crafts, but also draws on the mature technology in the field of deacidification of paper documents: existing research has shown that calcium carbonate emulsion is one of the deacidification materials suitable for traditional handmade paper, and the low-concentration and low-coating amount treatment method can avoid damage to the fiber's structure [41]; further research has confirmed that calcium carbonate can neutralize acidic substances inside the paper through a weak alkaline buffering effect and, at the same time, inhibit the hydrolysis process of cellulose glycosidic bonds and delay fiber embrittlement [42]. For samples with an upward pH trend, no additional alkaline coating is needed, and the focus is on maintaining pH stability through environmental control.

The storage environment needs to construct core conditions of constant temperature and humidity, light protection, and pollution isolation. Referring to the optimal parameters for the protection of paper cultural relics, it is recommended to store Tibetan paper cultural relics in an airtight and constant humidity environment of $23 \pm 1\text{ }^{\circ}\text{C}$ and $50 \pm 2\%\text{ RH}$ to avoid the fiber swelling and accelerated hydrolysis caused by fluctuations in relative

humidity. At the same time, the illumination intensity should be strictly controlled below 50 lux to isolate ultraviolet rays and oxidative pollutants, because light, especially high-energy ultraviolet rays, will directly damage chemical bonds such as C-C and C-O in cellulose, accelerating paper photodegradation and yellowing. Storage containers should avoid using wooden materials to prevent the release of organic acids causing long-term cumulative damage.

Non-destructive cleaning should follow the principle of minimal intervention. For daily cleaning, a soft brush with bristle diameter < 0.1 mm is preferred to gently remove surface dust to avoid damaging the fiber interweaving structure; for stubborn stains, 1% neutral detergent aqueous solution can be used for local spot cleaning, and the moisture should be blotted dry with absorbent paper immediately after treatment to prevent the secondary hydrolysis caused by residual moisture. During the restoration process, peelable natural adhesives (such as mature starch paste) should be selected to avoid the irreversible damage to cultural relics by chemical synthetic adhesives, leaving space for future re-restoration.

3.6.2. Living Inheritance and Process Optimization

On the basis of retaining the core essence of traditional crafts, the sustainable inheritance and performance improvements in Tibetan paper crafts are realized through the standardized and refined improvements below.

Build a standardized planting and harvesting system at the raw material end. Designate exclusive planting bases for *Stellera chamaejasme* in Nyemo County. Based on its high-altitude growth characteristics and biomass accumulation rules [43], adopt a reasonable density of 500–800 plants per mu for planting. Strictly ensure that the roots are harvested after a growth cycle of 5 years (the key cycle for fibers to develop to the optimal state). At the same time, follow the principle of rational development and sustainable utilization, and implement a rotational harvesting mode of harvesting 30% of the roots every year. This measure not only stabilizes the core quality characteristics of raw material fibers with suitable aspect ratio and high cellulose content, but also effectively avoids the risk of population decline caused by over-harvesting of wild resources, ultimately achieving the triple goals of stable raw material quality, ecological protection, and sustainable supply.

Carry out precise optimization and upgrading of process links. Transform traditional experience-dependent crafts into controllable parameters: adopt water bath temperature control technology for the alkaline cooking process to stabilize the temperature at 80 ± 2 °C, ensuring uniform lignin removal without damaging cellulose; introduce a torque meter in the manual beating link to control the beating degree at 30–35 °SR, which not only retains the natural structure of fibers, but also improves fiber uniformity and reduces the performance differences between different batches of products. These optimizations do not change the core process of traditional crafts, but can improve the stability of product quality.

4. Conclusions

This study systematically analyzes the surface properties and aging-resistance mechanism of Nyemo Xuelai Tibetan paper (Tibet, China) using SEM-EDS, ATR-FTIR, pH testing, and dry-heat aging experiments, reveals the intrinsic correlation between traditional crafts and performance, and proposes multi-dimensional protection strategies. The main conclusions are as follows:

- (1) The surface properties of Xuelai Tibetan paper present significant structural and chemical synergistic advantages. In terms of microstructure, *Stellera chamaejasme* fibers are flat and ribbon-like with an aspect ratio of 50–80, forming a tightly intertwined fiber network structure using the traditional manual beating process; in terms of chemical

composition, ATR-FTIR functional group analysis shows that it takes cellulose as the core chemical component with a relatively low lignin content, and EDS elemental detection shows that some samples retain calcium-based substances derived from plant ash (mass fraction 0%–1.79%). The compactness of the above microstructure, the high stability of the main components, and the weak alkaline buffering effect of calcium-based substances together support the excellent tensile strength and chemical stability of Xuelai Tibetan paper.

- (2) Each link of the traditional craft forms precise coupling with surface properties and aging resistance. The intrinsic characteristics of *Stellera chamaejasme* raw materials lay the material foundation, alkaline cooking removes lignin and retains buffering components, manual beating optimizes the fiber's interweaving structure, and natural air-drying improves surface uniformity. Finally, after 144 h of dry-heat aging, the Tibetan paper had a D65 brightness retention rate of 84.81%–92.21% and a tensile strength retention rate of 30.78%–90.00%, and statistical analysis confirms that these aging-induced changes in key performance indicators are highly significant ($p < 0.001$), showing good aging-resistance potential.
- (3) During the aging process, the performance degradation of Tibetan paper is mainly caused by cellulose glycosidic bond hydrolysis and pH fluctuation. The existence of calcium-based substances can inhibit hydrolysis by buffering acidic substances, while light and temperature–humidity fluctuations will accelerate lignin oxidation and fiber structure damage, which provides a scientific basis for the formulation of protection strategies.
- (4) The proposed dual strategy of cultural relic protection and craft inheritance is targeted and feasible. Preventive protection of cultural relics is realized through pH stabilization treatment and controlled storage environment construction, and living inheritance is realized through raw material standardization, process refinement, and inheritance digitalization, which not only respects the core value of traditional crafts, but also extends the preservation life and inheritance cycle of Tibetan paper through scientific means.

This study systematically establishes, for the first time, the surface properties, traditional crafts, and aging-resistance correlation mechanisms of Nyemo Xuelai Tibetan paper, validating the statistical significance of aging time on key material properties, providing a new idea for the protective research of traditional handmade paper, and also providing scientific support for the sustainable development of Xuelai Tibetan paper as an intangible cultural heritage.

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