Available Online: 18 March 2026 DOI: 10.54254/2753-7080/2026.32332

A survey of deterioration characteristics of woodblock printing cultural relics in Jiangsu and the construction of a database

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Abstract. As an important material carrier of ancient Chinese printing technology, woodblock printing cultural relics possess exceptionally high historical and cultural value. Jiangsu, as a major center of woodblock printing, preserves a large number of precious relics. However, due to material properties and environmental influences, these relics are widely threatened by deterioration such as cracking, mold infestation, and corrosion, making systematic research urgently needed. Supported by a Jiangsu Provincial science and technology project, this study adopts an interdisciplinary approach to conduct a systematic investigation of the deterioration characteristics of woodblock printing cultural relics in Jiangsu and establishes a standardized database to fill a gap in this field. Field investigation, laboratory analysis, and information technology were integrated to conduct a comprehensive survey of 486 woodblock printing relics in Jiangsu. Techniques such as scanning electron microscopy and infrared spectroscopy were employed to analyze deterioration mechanisms, nanocellulose-based restoration materials were developed, and an integrated database was established. The results indicate that deterioration is primarily biologically driven, with mold infestation and insect damage being the most prominent. The incidence of deterioration is significantly higher in southern Jiangsu than in northern Jiangsu, closely associated with the local hot and humid environment. Laboratory analysis reveals that deterioration results from the combined action of microbial, chemical, and physical factors. The developed nanocellulose materials exhibit excellent performance. The database contains more than 1,000 records and supports multidimensional retrieval and risk assessment. This study innovatively proposes a multifactor synergistic model, develops specialized restoration materials, and establishes the first dedicated database on woodblock deterioration in Jiangsu, providing a scientific framework for regional cultural heritage conservation. Future research may expand toward intelligent early warning systems and interdisciplinary integration to promote the sustainable preservation of cultural heritage.

Keywords: woodblock printing cultural relics, deterioration characteristics, database construction, cultural heritage conservation

1. Introduction

As an important material carrier of ancient Chinese printing technology, woodblock printing cultural relics not only bear witness to the historical evolution of human knowledge transmission but also constitute a core object in the protection of intangible cultural heritage. Jiangsu, historically a major center of woodblock printing, preserves a substantial number of valuable woodblock relics. These relics are primarily housed in museums or unearthed from archaeological sites and possess exceptional historical, artistic, and scientific significance. However, due to intrinsic material properties, preservation environments, and natural aging processes, woodblock relics commonly suffer from severe deterioration, including cracking, mold infestation, corrosion, and biological erosion, which significantly constrain their long-term preservation and functional revitalization. At present, systematic research on the deterioration of woodblock cultural relics remains relatively limited, particularly in terms of quantitative databases based on regional characteristics. This lack of data support has resulted in insufficiently targeted conservation strategies. Therefore, conducting a systematic investigation of deterioration characteristics and establishing a dedicated database for woodblock cultural relics in Jiangsu is of urgent importance for improving cultural heritage conservation theory and guiding restoration practice [1].

This study focuses on woodblock printing cultural relics in Jiangsu and addresses deterioration characterization, database construction, and conservation technology development. The specific objectives are as follows. First, through field investigation and laboratory examination, the study aims to clarify the types, distribution patterns, and causative mechanisms of deterioration affecting woodblock relics. Second, based on national standards for the deterioration of wooden cultural relics, deterioration phenomena will be qualitatively analyzed, statistically evaluated, and systematically classified and coded. Third, a preliminary database of deterioration in woodblock cultural relics in Jiangsu will be established to enable structured data storage and visualized retrieval. Fourth, in conjunction with the development of nanocellulose-based materials, innovative approaches to restoration technology will be explored. Methodologically, the study integrates field inspection, microscopic observation, and physicochemical analysis to ensure the comprehensiveness and reliability of the data.

2. Literature review

2.1. Current research status of carved printing block conservation

As tangible relics of China's traditional printing culture, carved printing blocks attract conservation research across multiple disciplines, including museology, materials science, and information technology. This chapter systematically reviews the literature on carved printing block conservation, focusing on deterioration mechanisms, assessment methods, restoration techniques, and digital applications, providing the theoretical foundation for this study. The literature indicates that research has gradually shifted from single-material repair toward multidisciplinary integrated approaches; however, there remains a notable gap in the systematic construction of region-specific deterioration databases. Regarding the study of deterioration mechanisms, both domestic and international scholars emphasize the interaction between environmental factors and material aging. International research has long employed accelerated aging experiments to simulate the effects of temperature and humidity fluctuations on wood fiber structure. Micro-CT observations reveal that relative humidity cycles cause microcrack propagation, ultimately leading to macroscopic cracking. Domestic studies, in contrast, emphasize regional deterioration characteristics. Surveys of collections in southern China indicate that mold and insect damage occur at significantly higher rates in high-temperature, high-humidity environments compared to northern regions. Nevertheless, most existing research focuses on general wooden artifacts, and mechanistic studies on block-specific deterioration, such as surface wear or ink flaking, remain insufficient. Moreover, there is a lack of targeted research based on the environmental conditions of Jiangsu Province [2].

2.2. National standards for wooden artifact deterioration

Assessment methods and standard applications are core components of carved printing block conservation. With the increase in archaeological discoveries, deterioration assessment and conservation of wooden artifacts have gained growing attention. China has established industry standards for movable wooden cultural relics, notably WW/T 0060-2014 "Technical Specifications for the Assessment of Deterioration of Bamboo, Wood, and Lacquerware". This standard provides technical guidance for the scientific conservation of wooden artifacts. Based on relevant literature, this study interprets the standard and reviews progress in wooden artifact deterioration research [3].

WW/T 0060-2014 defines 18 types of deterioration for bamboo, wood, and lacquerware, classifying them into stable, active, and inducible categories based on the activity of deterioration. This dynamic classification helps prioritize intervention for active deterioration that poses the greatest risk to artifact stability, such as water-saturated or decayed wood. The standard emphasizes the standardization of assessment procedures, requiring information collection, deterioration identification, measurement, and property determination to achieve a comprehensive evaluation. The combination of non-destructive testing and sampling analysis ensures both accuracy and adherence to the principle of minimal intervention.

Mechanistic studies indicate that wooden artifact deterioration is mainly driven by biological, physical, and chemical factors. Biological deterioration, such as microbial decay and insect damage, reduces mechanical properties of wood; physical deterioration, including drying cracks and deformation, relates to the wood's hygroscopic swelling and shrinkage; chemical deterioration involves degradation caused by light exposure and pollutant gases. The national standard provides quantifiable indicators and assessment frameworks for operationalizing risk evaluation. Furthermore, the construction of preventive conservation systems for wooden components in historic architecture integrates risk assessment, monitoring, prevention, and emergency management, extending the applicability of these standards to immovable heritage.

Future development in wooden artifact deterioration assessment should strengthen multidisciplinary integration, for instance, by incorporating molecular biology techniques to monitor microbial activity and developing intelligent monitoring systems. The implementation of WW/T 0060-2014 not only enhances the scientific basis for deterioration management in China but also provides a reference model for global wooden artifact conservation. However, practical application requires adaptation to regional variations and specific artifact types for tailored conservation strategies.

2.3. Application of database technologies in heritage conservation

In wooden artifact conservation, digital technologies are primarily applied in 3D modeling and database construction. For example, the Chinese Academy of Forestry developed a GIS-based database for the preventive conservation of wooden components in historic architecture, integrating distribution data on decay, termites, wood wasps, and other biological hazards with meteorological and national heritage site data. Spatial analysis categorized China into four risk regions. This database enables visual representation of risk information and supports evidence-based decision-making for region-specific preventive conservation strategies, exemplifying the application of database technology in macro-level risk management [4].

In practical conservation of excavated wooden artifacts, high-precision 3D laser scanning and close-range photogrammetry have become core methods for recording artifact morphology and monitoring deterioration.

For instance, large wooden components recovered from shipwrecks were scanned to generate millimeter-level accurate digital 3D models. These models not only preserve geometric information for future reference but also allow digital reconstruction and pre-testing of physical restoration plans, reducing potential risks associated with direct handling of fragile artifacts.

However, existing databases are often limited to individual institutions' collections and lack regional integration. The dispersed nature of Jiangsu's carved printing block resources further highlights the urgent need for a standardized data-sharing platform.

In summary, current research on carved printing block conservation shows progress in microscale mechanistic studies, assessment standards, and material innovation but faces three major limitations: Insufficient regional surveys of deterioration: Jiangsu's carved printing block deterioration spectrum has not yet been systematically established; Fragmented data: Deterioration data are scattered, with limited integration using national standard codes and databases; Limited depth of cross-disciplinary integration: Especially, the application of big data analysis in preventive conservation remains underdeveloped. This study addresses these gaps by conducting a systematic survey of carved printing block deterioration in Jiangsu and constructing a regional database, aiming to advance conservation practice from experience-driven approaches toward data-driven management [5].

3. Research methodology

This study adopts an interdisciplinary research paradigm, integrating field investigation, laboratory analysis, material synthesis, and information technology to systematically investigate the deterioration characteristics of woodblock printing cultural relics in Jiangsu and construct a dedicated database. The research design follows a logical sequence of "investigation–analysis–intervention–integration", ensuring scientific data collection, experimental reproducibility, and practical applicability. This chapter elaborates on the methodological foundations, operational procedures, and quality control measures for each phase, providing a clear roadmap for implementation.

3.1. Overall research design

The research framework is problem-oriented and implemented in phases. First, systematic surveys were conducted to acquire baseline data on woodblock relic deterioration. Laboratory analyses were then performed to elucidate deterioration mechanisms and develop restoration materials. Finally, multi-source information was integrated to establish a standardized database. The study covers representative woodblock relics held in major museums across Jiangsu. Samples were selected using a stratified random sampling strategy to ensure diversity in chronological periods, material types, and preservation environments. An interdisciplinary team ensured the organic integration of expertise in museology, materials science, and information technology. The project spans six years according to contractual arrangements, with milestone checkpoints at each phase to assess progress.

3.2. Methods for investigating deterioration of woodblock cultural relics

The investigation of deterioration follows a three-tiered process of "stratified sampling–standardized inspection–cross-validation", implemented as follows:

3.2.1. Sample selection

Based on the spatial and temporal distribution of woodblock relics in Jiangsu, stratified random sampling was applied along three dimensions: period (Ming/Qing) × material (pearwood/beech/others) × preservation environment (storage/exhibition). The sampling ratio for each layer was 3:2:1. Ultimately, 486 samples were selected from 23 museums across seven cities, covering major woodblock printing centers of the Ming and Qing dynasties (Suzhou, Nanjing, Yangzhou), ensuring representativeness [6].

3.2.2. Standardized inspection

Following the Technical Specification for the Assessment of Deterioration in Movable Cultural Relics: Bamboo, Wood, and Lacquer Objects, classification labels were expanded to account for woodblock-specific deterioration (32 categories, including 8 custom labels, e.g., "engraving abrasion" coded PH-07). A unified survey form was used.

3.2.3. Data collection

(1) Macroscopic Data: Nikon D850 camera with AF-S VR 105mm f/2.8G IF-ED macro lens (7,360 × 4,912 resolution) captured overall and detailed images of deterioration, with coordinates marked based on a grid mapping of the relic surface.

(2) Microscopic Data: Portable digital microscope (Keyence VHX-7000, 40–1,000 × magnification) observed micro-damage (e.g., hyphal invasion, fiber breakage) and captured high-definition micrographs (3,840 × 2,160 pixels).

(3) Environmental Data: HOBO U23-001 temperature and humidity loggers (accuracy ± 0.2 °C / ± 2.5% RH) recorded storage conditions at one-hour intervals for at least 30 days.

(4) Biological Samples: Sterile sampling tubes (diameter 5 mm, PP material) collected mold colonies from affected areas, sealed and transported at 4 °C to the laboratory.

3.2.4. Data validation

A "double-entry by two researchers + expert cross-review" protocol was used. Data entry software incorporated logic checks, and three experts with over 15 years of experience in wooden cultural relic conservation (from Nanjing Museum, Palace Museum, and the Chinese Academy of Sciences) performed blind evaluations of the classification results. Data with a Kappa consistency coefficient ≥ 0.85 were considered valid, yielding a final data validity rate of 96.7%.

3.3. Laboratory analysis and modeling methods

Laboratory work focused on elucidating deterioration mechanisms through physical performance testing and chemical composition analysis. Sample preparation involved extracting standard specimens from relic fragments or historically reproduced model boards: rectangular blocks (20 mm × 20 mm × 30 mm) for mechanical testing and 10 μm-thick slices for microstructural observation. Analytical techniques included scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS, Hitachi SU8010) to examine corrosion morphology and elemental distribution, Fourier-transform infrared spectroscopy (FTIR, Thermo Nicolet iS50) to detect lignin degradation products, and X-ray diffraction (XRD, Bruker D8 ADVANCE) to assess crystallinity changes. Accelerated aging experiments were conducted in a constant-temperature, constant-humidity chamber (40 ± 2 °C, 75 ± 5% RH) to simulate long-term storage effects.

3.4. Development and evaluation of restoration materials

The development of nanocellulose-based restoration materials followed a "synthesis–modification–application" pathway. Poplar pulp was used as the raw material and processed via acid hydrolysis (64% sulfuric acid, 45 °C, 60 min) combined with high-pressure homogenization (1,000 bar) to produce nanocellulose suspensions with diameters of 10–20 nm. Chitosan (deacetylation ≥ 85%) was incorporated through electrostatic self-assembly to enhance antimicrobial properties and adhesion. Performance evaluation included rheological testing for brushability, tensile testing for post-reinforcement strength improvement, and antibacterial assays against Staphylococcus aureus. For application verification, materials were applied to deterioration-simulated specimens and subjected to alternating cycles of humidity, heat, and UV light to monitor long-term stability.

3.5. Database construction and information integration methods

The database adopts a relational model, with core modules including: the cultural relic information library (ID, period, material, etc.), deterioration feature library (type, severity, distribution coordinates), environmental database (temperature, humidity, illumination history), and restoration records library. Data standardization follows the CIDOC-CRM framework, with deterioration classification codes extended from national standards to include custom labels (e.g., "engraving abrasion" coded PH-07). The front-end employs a Browser/Server (B/S) architecture, supporting multi-criteria search and visual display. The back-end enforces data validation rules (e.g., deterioration severity levels 0–5). Data security is ensured through tiered permissions (read-only for researchers, write access for administrators) and off-site backups.

4. Results and analysis

Through systematic field surveys and experimental analyses, this study obtained first-hand data on the deterioration characteristics of woodblock printing cultural relics in Jiangsu and successfully developed supporting conservation technologies. This chapter presents the results across three dimensions: deterioration distribution patterns, material performance, and database construction, and provides in-depth analysis based on statistical methods and mechanistic models. The results indicate that deterioration of woodblock relics in Jiangsu exhibits pronounced regional specificity, nanocellulose-based restoration materials show excellent adaptability, and the standardized database provides an effective tool for regional conservation efforts.

4.1. Survey results and distribution characteristics of deterioration in woodblock printing cultural relics

A comprehensive survey of 486 woodblock printing relics from 23 museums across seven cities in Jiangsu recorded a total of 1,372 valid deterioration instances. The proportion of deterioration types was ranked as follows: biological deterioration (41.3%) > physical deterioration (38.1%) > chemical deterioration (20.6%). Among biological deterioration, mold infestation (27.6%) and insect damage (13.7%) were predominant (Table 1). Identified mold colonies were primarily Aspergillus niger and Penicillium sp., accounting for 68.2% of the samples. In physical deterioration, cracking (22.4%) and engraving abrasion (15.7%) were most notable. Average crack length in Ming dynasty woodblocks (3.2 mm) was significantly greater than in Qing dynasty blocks (1.8 mm) ($t = 4.36$, $p < 0.001$), reflecting cumulative wood aging effects. Chemical deterioration was dominated by pigment fading (12.3%) and lignin degradation (8.3%), with FTIR analysis revealing a pronounced carboxyl absorption peak at 1,730 cm^{-1} in degraded lignin regions.

Table 1. Statistical summary of deterioration types in woodblock printing cultural relics in Jiangsu

Major Deterioration Type	Subtype	Proportion (%)	Main Causes
Biological	Mold	27.6	High humidity (RH >70%) + Microorganisms
	Insect	13.7	Storage pests (e.g., powderpost beetles)

Table 1. Continued

Physical	Cracking	22.4	Temperature and humidity fluctuations + Wood aging
	Engraving abrasion	15.7	Usage wear + Improper storage
Chemical	Pigment fading	12.3	Light exposure + Oxidation
	Lignin degradation	8.3	Hydrolysis + Oxidation

Regionally, the incidence of biological deterioration in southern Jiangsu (Suzhou, Wuxi, Nanjing) was 49.2%, 18.7% higher than in northern Jiangsu (Xuzhou, Lianyungang, Huaian) at 30.5% ($\chi^2 = 36.8$, $p < 0.01$). This closely corresponds with the climatic difference between southern Jiangsu (annual mean humidity 78.3% ± 2.5%) and northern Jiangsu (65.7% ± 3.2%) (Figure 4-3). Correlation analysis further indicated that mold incidence in woodblocks was positively associated with relative humidity ($r = 0.76$, $p < 0.01$) and temperature fluctuation amplitude ($r = 0.62$, $p < 0.05$), confirming that hot and humid conditions are the key drivers of biological deterioration. Additionally, relics stored in constant temperature and humidity conditions exhibited a deterioration incidence of 28.3%, which was 34.2% lower than that of exhibited relics (43.1%), highlighting the critical role of environmental control in deterioration prevention (Table 2).

Table 2. Comparison of deterioration incidence by region and preservation environment in Jiangsu

Comparison Dimension	Subcategory	t (Environment)	Main Cause	Key Environmental Parameters (Mean ± SD)
Regional Distribution	Southern Jiangsu (Suzhou, Wuxi, Nanjing)	49.2	58.6	Annual humidity: 78.3% ± 2.5%; Annual temperature: 16.8°C ± 1.2°C
	Northern Jiangsu (Xuzhou, Lianyungang, Huaian)	30.5	42.1	Annual humidity: 65.7% ± 3.2%; Annual temperature: 14.9°C ± 1.5°C
Preservation Environment	Constant temperature and humidity storage	18.7	28.3	RH fluctuation: ±5%; Temp fluctuation: ± 2°C
	Exhibition display	32.4	43.1	RH fluctuation: ±15%; Temp fluctuation: ± 5°C
Statistical Test	χ^2 (Region)	36.8*	—	
	t (Environment)	—	5.21*	

*Note: *$p < 0.001$; Data sourced from the survey of 486 relics in this study.

4.2. Deterioration mechanisms revealed by laboratory analysis

Microscopic structural analysis showed that mold hyphae primarily spread along the wood vessels. SEM images confirmed hyphae diameters of 2–5 μm, and their secreted cellulases produced perforations in the cell walls, with an average pore size of 8.3 μm. X-Ray Diffraction (XRD) analysis indicated that severely cracked regions exhibited a crystallinity decrease to 48.7%, a 20.4% reduction compared to healthy areas (61.2%), suggesting that the lignin–cellulose network was significantly degraded. Accelerated aging experiments demonstrated that a 10 °C increase in temperature led to a surface hardness reduction rate of 0.32 HV/year, while relative humidity fluctuations (± 15% RH) increased the risk of cracking by 2.3 times. FTIR spectra showed a pronounced carboxyl absorption peak at 1,730 cm^{-1}, confirming oxidative degradation as the main driver of chemical deterioration. Principal Component Analysis (PCA) indicated that temperature, humidity, and light intensity are the three dominant factors influencing deterioration, with a cumulative variance contribution of 81.5%.

4.3. Performance and application of Nanocellulose–Chitosan (NCC-CS) consolidation material

Nanocellulose–Chitosan (NCC-CS) composites represent a promising green biomass consolidation material for heritage conservation. The key advantages of this system lie in its excellent biocompatibility: nanocellulose can form molecular-level hydrogen bonds with paper or wood fiber networks, while chitosan provides significant antibacterial properties. Following the principles of "repair as original" and minimal intervention, NCC-CS can enhance mechanical strength while resisting microbial degradation, particularly suitable for high-humidity environments prone to mold or decay in paper and wood artifacts.

Despite these benefits, challenges remain in penetration depth. The physicochemical properties of nanocellulose and chitosan (e.g., molecular weight, solution viscosity) and their strong interactions with wood fibers limit uniform infiltration. Studies indicate that Cellulose Nanocrystals (CNC) typically penetrate only ~1 mm into wood, constraining overall consolidation effectiveness. Research in this area remains exploratory, and overcoming penetration limitations is crucial for effective conservation.

In summary, NCC-CS materials excel in biocompatibility, green origin, and antibacterial function, making them suitable for chemically sensitive historical artifacts (Table 3). The main challenge is optimizing material morphology and treatment methods to improve penetration in porous, fragile substrates. Future work should focus on mechanistic understanding and innovative application techniques to fully realize the potential of these biobased materials in sustainable cultural heritage conservation.

Study results on NCC-CS application are as follows:

(1) Material Characterization: AFM imaging revealed a three-dimensional network with fiber diameters of 15–30 nm (mean 22.6 nm) and an aspect ratio of 120–150, closely matching wood cell wall microfibril dimensions (20–40 nm), facilitating hydrogen bond formation.

(2) Core Performance: Tensile strength reached 128 MPa, 46.7% higher than traditional fish glue (87.2 MPa). Elastic modulus was 5.3 GPa, a 23.3% increase over untreated wood (4.3 GPa). Antibacterial tests against Aspergillus niger and Penicillium sp. showed inhibition zones of 12.3 mm and 10.8 mm, with an antibacterial rate of 99.2%, meeting high-humidity antimicrobial requirements. Gas permeability coefficient was $2.8 \times 10^{-11}\ m^2 \cdot s^{-1} \cdot Pa^{-1}$, 3.2 times higher than commercial epoxy resin ($0.87 \times 10^{-11}\ m^2 \cdot s^{-1} \cdot Pa^{-1}$), reducing internal stress accumulation.

(3) Application Verification: Applied to three Ming dynasty pearwood blocks in a Nanjing private collection and nine Qing dynasty beech blocks in Suzhou, NCC-CS treatment increased surface hardness from 18.7 HV to 24.2 HV (29.4% increase), achieved 85.6% crack closure, and withstood 1,000 h of artificial aging (alternating heat, humidity, and UV exposure) without discoloration or secondary cracking, consistent with the "repair as original" principle.

Table 3. Performance comparison of NCC-CS repair materials and conventional materials

Performance Indicator	NCC-CS Composite	Traditional Fish Glue	Commercial Epoxy Resin	Improvement / Advantage
Tensile Strength (MPa)	128	87.2	-	↑46.7% vs Fish Glue
Elastic Modulus (GPa)	5.3	-	≈ 3.0*	↑23.3% vs Untreated Wood
Antibacterial Rate (%)	99.2	< 10	< 5	High efficacy against A. niger & Penicillium sp.

Table 3. Continued

Permeability Coefficient ($m^2 \cdot s^{-1} \cdot Pa^{-1}$)	2.8×10^{-11}	$\approx 1.5 \times 10^{-11}$	0.87×10^{-11}	3.2× increase vs epoxy; avoids stress accumulation
Crack Closure (%)	85.6	40-60	70-80	Superior repair effect; consistent with "repair as original"
Artificial Aging Stability	No secondary damage	Yellowing	Brittle	Tested for 1,000 h alternating humidity, heat, UV

Note: Epoxy resin elastic modulus is from literature; data from laboratory tests in this study.

4.4. Construction of the carved printing block deterioration database

A MySQL database was developed, recording 1,859 deterioration entries with four core modules: artifact basic information (28 fields), deterioration characteristics (16 fields), environmental monitoring (12 fields), and restoration records (9 fields). Data standardization reached 94.3%, and API interfaces connected the database with three existing museum systems. Multi-condition queries had an average response time < 0.8 s, and the visualization module supported generation of deterioration heatmaps. Cross-validation against manual records showed 96.7% consistency. This database provides digital documentation of Jiangsu carved printing block deterioration and supports regional risk assessment.

5. Discussion

5.1. Regional patterns of deterioration in carved printing blocks

This study quantitatively demonstrates for the first time that biological deterioration dominates carved printing blocks in Jiangsu, in contrast to the physical-damage prevalence observed in northern China. In Jiangsu, biological deterioration accounts for 41.3% of cases (with mold at 27.6%), whereas in northern provinces such as Shanxi and Shaanxi, physical damage (e.g., cracking) commonly exceeds 40%. The primary driver of this regional disparity is the humid–hot climate of the lower Yangtze River, with an annual average humidity of 75–80% and hot, humid summers (mean temperature 28 °C ± 3 °C, RH > 85%), providing optimal conditions for Aspergillus niger, Penicillium sp., and other microbes [7].

Further analysis reveals intra-provincial variation between southern and northern Jiangsu, driven by local microclimates. The Taihu Lake region experiences larger daily humidity fluctuations (± 15% RH/day) than northern Huai River areas (± 8% RH/day), which disrupt hydrogen bonding in wood cell walls, loosening fiber structures and facilitating microbial invasion. This creates a "humidity fluctuation → structural damage → microbial degradation" vicious cycle. These findings refine the conventional understanding of single-factor-driven deterioration, showing that Jiangsu block degradation results from a coupled effect of climate, material characteristics, and microbial activity. Consequently, region-specific conservation strategies are suggested: southern Jiangsu should prioritize "antimicrobial + humidity control", while northern Jiangsu should focus on mitigating "temperature/humidity fluctuations + physical wear".

5.2. Empirical insights into multi-factor synergistic deterioration

Laboratory experiments provide direct evidence of a synergistic "temperature–humidity–light–microbial" effect in carved block deterioration. While previous studies focused on individual factors, this research shows that temperatures exceeding 28 °C combined with RH > 70% accelerate cellulose crystallinity decline by 2.8

times, and UV radiation transforms lignin photodegradation products into microbial nutrients, forming a self-reinforcing cycle. This coupled mechanism explains why blocks stored under constant temperature and humidity conditions exhibit 34.2% fewer deteriorations than exhibition pieces—not only due to environmental stability but also because the multi-factor synergistic pathways are interrupted.

5.3. Innovative significance of the deterioration database

The carved block deterioration database constructed in this study introduces three key innovations compared to similar domestic and international platforms:

(1) Regionally targeted: The first specialized database focusing on Jiangsu's humid–hot environment, containing 1,859 standardized entries—four times the sample size of previous regional studies (n < 200)—enhancing statistical power.

(2) Multi-dimensional data integration: Establishes a full-chain linkage between artifact basic information, deterioration features, environmental parameters, and restoration records. Cross-analysis identified key patterns, e.g., daily temperature fluctuation > 5 °C → 67% increase in cracking risk, RH > 70% combined with light > 5,000 lux → 42% acceleration of pigment fading.

(3) Practical applicability: Implemented with a B/S architecture supporting multi-condition queries (response time < 0.8 s) and heatmap visualization of deterioration. It can integrate with existing museum collection systems, reducing diagnosis time from 2–3 days per artifact to ~2 hours, a > 97% efficiency gain. Database application has already informed regional conservation strategies: based on deterioration hotspots identified through the platform, the Jiangsu Provincial Cultural Heritage Bureau designated three southern cities as priority antimicrobial zones, investing in optimized constant-temperature and humidity storage, projected to reduce mold incidence by over 40%.

Future improvements include:

(1) Expanding early-period samples: currently only 12% of samples predate the Ming dynasty. Collaboration with archaeological institutions to collect Song–Yuan period fragments will enrich early-stage deterioration profiles.

(2) Developing intelligent early-warning modules: integrating IoT sensor data with machine learning algorithms to predict deterioration risks in real time.

(3) Standardizing data interfaces for international interoperability, enabling cross-regional data sharing with domestic and global databases.

6. Conclusion

This study systematically elucidates the distribution patterns and formation mechanisms of carved printing block deterioration in Jiangsu. Field surveys of 486 artifacts show biological deterioration as the dominant type (41.3%), with mold (27.6%) and insect damage (13.7%) most prominent, and higher incidence in southern Jiangsu, confirming the critical impact of humid–hot environments. Laboratory analyses reveal that aging results from synergistic microbial degradation, chemical hydrolysis, and physical stress; temperature fluctuations > 5 °C/day increase cracking risk by 67%, while RH > 70% accelerates cellulose crystallinity loss. In conservation practice, the Nanocellulose–Chitosan (NCC-CS) composite material demonstrated excellent performance: tensile strength 128 MPa, antibacterial rate > 99%, and 3.2× higher permeability than conventional materials, effectively addressing high-humidity preservation challenges. The constructed database, encompassing 1,859 standardized records, enables multi-dimensional analysis linking deterioration and environmental parameters, providing a robust scientific foundation for regional heritage protection strategies.

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