Journal of Materials, Processing and Design (2025)
Clausius Scientific Press, Canada
DOI: 10.23977/jmpd.2025.090118
ISSN 2516-0923 Vol. 9 Num. 1

Scientific Study on the Traditional Evaluation Criterion "Fire Qi" in Chinese Painting and Calligraphy Restoration Paper

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Keywords: Fire Qi; Paper Aging; Chinese Painting Restoration; Cellulose Degradation; Material Properties; Physicochemical Performance; Restoration Paper Evaluation

Abstract: The concept "fire qi" is an essential yet empirically defined notion in traditional Chinese painting and calligraphy restoration, referring to the usability and stability of newly manufactured versus aged papers. Despite its widespread application among restorers, the scientific basis of *fire qi* remains poorly understood. This study systematically investigates the physicochemical mechanisms underlying paper aging and their relationship with the observed phenomenon of *fading fire qi*. Through an analysis of the degradation pathways of cellulose, hemicellulose, and lignin—including hydrolysis, oxidation, and acid-catalyzed reactions—the research reveals how early-stage aging leads to moderate structural rearrangement in the fiber network. These microstructural adjustments enhance folding endurance, improve pore uniformity, and optimize water absorbency and ink receptivity, thereby corresponding to the empirically recognized "fading" of *fire qi*. Conversely, prolonged aging results in irreversible degradation characterized by reduced tensile strength, yellowing, and loss of chemical stability. The findings demonstrate that *fire qi* represents a comprehensive reflection of multiple paper properties—mechanical, chemical, and operational—and can be quantified through measurable parameters such as tensile strength, folding endurance, pH, degree of polymerization, and ink receptivity. By integrating traditional experience with modern materials science, this study provides a theoretical foundation for quantifying *fire qi* and establishing a standardized evaluation framework for restoration papers used in cultural heritage conservation.

1. Introduction

The conservation and restoration of Chinese calligraphy and painting are deeply rooted not only in modern scientific techniques but also in long-standing traditional practices. In the field of Chinese painting restoration, there exists a widely accepted belief among conservators and mounting specialists that newly produced paper often possesses excessive fiery energy, making it unsuitable for immediate use. It is therefore customary to store such paper for a period of time to allow the huoqi to dissipate—a process referred to as "removing fire energy" or "reducing dryness" before it can be properly applied.

This traditional understanding reflects both a long-term empirical observation of the physical behavior of paper and an aesthetic–technical appreciation of its stability, ink absorbency, and maturity. However, huoqi remains an empirical term lacking a precise scientific definition. Previous studies have suggested that paper stored under ambient conditions for a certain period exhibits improved dimensional stability [1] and may be associated with changes in hygroscopic expansion behavior [2]. Practitioners also report that aged paper with reduced huoqi performs better in handling and application. Therefore, huoqi should not be viewed as a single measurable property but rather as a comprehensive manifestation of multiple physicochemical characteristics, the nature of which warrants systematic scientific analysis.

From the perspective of materials science, paper is primarily composed of cellulose and hemicellulose—plant-derived polysaccharide polymers whose aging processes involve complex chemical and physical transformations under the combined influence of light, heat, moisture, acids, and oxidizing agents. These changes lead to macroscopic degradation phenomena such as loss of mechanical strength, reduction in brightness, cellulose depolymerization, and overall deterioration of performance [3–4]. Cellulose chains are susceptible to hydrolytic and oxidative cleavage, while lignin may undergo photooxidation to form phenoxy radicals and colored quinonoid compounds, contributing to yellowing and embrittlement. Furthermore, the weakening of inter-fiber bonding results in reduced folding endurance and tensile strength.

The absorbency, ink receptivity, and dimensional stability of paper are closely related to fiber morphology, filler distribution, and micro-porous structure. Interestingly, certain types of xuanzhi (traditional Chinese paper) exhibit an initial increase in folding endurance during early stages of natural aging. This transitional phase may correspond to the traditional notion of tui huoqi, during which paper undergoes microstructural and physicochemical adjustments that enhance its overall usability [5].

Building on this background, the present study aims to investigate the intrinsic meaning of huoqi in traditional restoration papers by analyzing the physicochemical changes that occur during early storage and aging. The goal is to establish a scientific interpretation of this traditional concept, linking empirical knowledge with modern materials science. Ultimately, this research seeks to provide a theoretical framework for the selection and evaluation of restoration papers, offering quantifiable performance indicators for their application in the conservation of Chinese calligraphy and painting.

2. Mechanisms of Paper Aging

During long-term storage, paper inevitably undergoes deterioration induced by the intrinsic aging of its constituent materials. As the primary support for Chinese calligraphy and painting, paper experiences a complex, multi-phase physicochemical degradation process driven by multiple environmental factors, including light, heat, humidity, acidic pollutants, oxidizing agents, and metal ions [6]. The aging process not only affects the mechanical performance of paper but also alters its color, chemical properties, and ink receptivity, ultimately leading to visible forms of deterioration such as discoloration, embrittlement, cockling, and surface fibrillation [7].

Traditional Chinese painting papers are mainly composed of cellulose, hemicellulose, and a small amount of lignin. Cellulose, a linear high-molecular polymer with the general formula $(C_6H_{10}O_5)_n$, consists of β-D-glucopyranose units linked by 1,4-β-glycosidic bonds [8]. The integrity of the cellulose chain determines the paper's mechanical strength and flexibility. However, these glycosidic linkages are extremely susceptible to acid hydrolysis under humid or acidic conditions.

Exposure to acidic pollutants such as SO_2 and NO_2, or to acidic additives in the paper itself, can break down the polymeric chains through acid-catalyzed hydrolysis, leading to decreased tensile strength, folding endurance, and inter-fiber bonding [9].

Oxidation reactions constitute another major mechanism of paper aging. In the presence of air, light, atmospheric pollutants, and catalytic metal ions (e.g., Fe^{3+}, Cu^{2+}), reactive C–H and C–O–C bonds in cellulose are cleaved, generating free radicals such as ·OH and ROO·. These radicals initiate chain oxidation reactions, producing carbonyl (–CHO) and carboxyl (–COOH) functional groups [10]. The accumulation of such acidic products reduces the degree of polymerization and disrupts inter-fiber hydrogen bonding, resulting in diminished fiber cohesion, flexibility, and structural stability. In addition, lignin absorbs near-ultraviolet radiation to form phenoxy radicals, which further oxidize into colored quinonoid compounds, causing yellowing and a decline in brightness [11].

Paper aging may also involve cross-linking and hornification phenomena, in which cellulose or hemicellulose chains undergo secondary reactions to form amorphous, glassy phases that increase brittleness [3]. These microstructural alterations directly influence the macroscopic physical properties of paper, including folding endurance, tear strength, and dimensional stability [12]. Changes in fiber porosity and filler distribution further affect water absorption and ink wettability, sometimes leading to cockling or surface fuzzing during ink application and drying. Notably, certain studies have reported an initial increase in folding endurance during the early stages of *xuanzhi* (Chinese handmade paper) aging. This phenomenon may correspond to the traditional notion of *tui huoqi* (the “fire energy dissipation” stage), during which paper undergoes structural optimization and property adjustment that enhance its stability and usability in restoration and painting practices.

Overall, paper aging is an irreversible macroscopic manifestation of microstructural and chemical degradation within the cellulose–hemicellulose–lignin system. It is characterized by reduced mechanical strength (embrittlement and fragmentation), color alteration (yellowing and loss of brightness), chemical modification (increased copper number and decreased viscosity), and functional deterioration. This systematic understanding of paper aging provides a theoretical foundation for interpreting the traditional concept of *huoqi* in restoration papers and offers scientific support for performance evaluation, *tui huoqi* procedures, and practical applications in the conservation of Chinese calligraphy and painting.

3. Correlation Analysis between Paper Properties and the Concept of “Fire Qi”

In traditional Chinese painting restoration practices, huoqi (“fire qi”) serves as an important empirical criterion for evaluating the usability and operational adaptability of paper. Empirical observations indicate that newly produced paper generally possesses strong fire qi, tending to wrinkle, fuzz, or undergo uneven expansion and contraction during humidification or drying. In contrast, paper that has been stored for a certain period exhibits diminished fire qi, showing improved dimensional stability and ink absorbency. However, fire qi lacks a clear scientific definition—its connotation encompasses not only mechanical performance but also chemical stability, hygroscopic behavior, and operational suitability. To interpret fire qi scientifically, it is necessary to establish its correlation with measurable physicochemical properties of paper.

First, the mechanical properties of paper constitute the core indicators of *fire qi*. Tensile strength reflects both the bonding forces between fibers and the intrinsic strength of the fibers themselves. Paper aging leads to cellulose degradation and weakened interfiber bonding, thereby reducing tensile strength [13–15]. Folding endurance, which represents a paper’s resistance to repeated bending, is affected by fiber length, flexibility, and interfiber cohesion. Studies have shown that the folding endurance of some *xuan* papers may temporarily increase during the initial stages of aging [16], likely due to increased hydrogen bonding sites formed after microstructural rearrangements within the fibers. This phenomenon may correspond to the traditional concept of the "fading of *fire qi*," representing an early-stage optimization of fiber structure that enhances stability and usability. Changes in tearing and bursting strength also directly influence the paper's workability and stability, serving as important physical indicators of *fire qi* intensity.

Second, the chemical properties of paper play a significant role in the manifestation of *fire qi*. A decrease in the degree of polymerization of cellulose, increased acidity, and variations in copper number all indicate molecular-level degradation of fibers. Oxidation products such as carbonyl (–CHO) and carboxyl (–COOH) groups not only weaken fiber strength but also alter intermolecular bonding patterns, reducing paper flexibility. Variations in whiteness or brightness visually reflect photochemical oxidation and lignin degradation, influencing both the aesthetic perception and tactile experience during restoration operations.

In addition, water absorbency, ink receptivity, and dimensional stability are essential components of *fire qi* evaluation. Water absorbency depends on the pore structure and polarity of the fiber network, determining the rate and uniformity of water and ink uptake. Ink receptivity is closely associated with fiber surface morphology, pore distribution, and filler dispersion, directly affecting artistic expression. Paper stability—its ability to remain flat without wrinkling or fuzzing after wetting—is the most intuitive criterion by which restorers perceive the degree of *fire qi*.

In summary, *fire qi* represents a comprehensive expression of multiple performance parameters, including tensile strength, folding endurance, extensibility, tearing resistance, chemical stability, hygroscopic behavior, and ink receptivity. The traditional process of "fading *fire qi*" through long-term storage allows the paper to undergo an initial adjustment of its mechanical and chemical equilibrium, improving stability, flexibility, and surface compatibility. A scientific analysis of *fire qi* and its evolutionary mechanism not only provides a framework for quantifying the performance of restoration papers but also offers theoretical support for traditional practices, bridging empirical craftsmanship with modern materials science.

4. Conclusions

Through an analysis of the mechanisms of paper aging and the corresponding changes in physicochemical properties, the scientific connotation of huoqi ("fire qi") in traditional Chinese painting restoration can be systematically understood. Traditional craftsmanship holds that newly manufactured paper possesses strong fire qi, making it unstable in use, whereas paper that has been stored for a certain period can "fade" its fire qi, exhibiting improved dimensional stability and ink receptivity during practical operations. The present study demonstrates that this phenomenon can be scientifically explained through the comprehensive variation of the paper's physical and chemical properties. In the early stages of natural aging, cellulose and hemicellulose undergo mild hydrolysis and oxidation, leading to the rearrangement of interfiber bonding and an increase in the number of hydrogen bonds. As a result, the folding endurance slightly increases, while the fiber pore structure becomes more uniform, improving both water absorbency and ink receptivity. This stage corresponds to the traditional practice of "fading fire qi," providing a scientific basis for the enhanced controllability of paper used in painting restoration and mounting processes.

Furthermore, paper aging is an irreversible macroscopic process, essentially arising from the microscopic degradation of cellulose, hemicellulose, and lignin molecular structures and the deterioration of the fiber network. This degradation manifests as a decline in mechanical strength, a decrease in whiteness, alterations in cellulose chemical properties, and a loss of functional performance. Such transformations not only account for the embrittlement and yellowing of paper during long-term preservation but also reveal the intrinsic mechanism underlying the temporal evolution of fire qi. It follows that fire qi is not a single measurable index but a comprehensive reflection of multiple properties—mechanical performance, chemical stability, and operational adaptability.

This study emphasizes the integration of traditional empirical knowledge with modern materials science to provide theoretical guidance for the selection and handling of restoration papers. In practical conservation work, allowing paper to undergo an appropriate period of storage—thereby experiencing an initial phase of controlled aging—can optimize its ink receptivity and dimensional stability while maintaining sufficient mechanical strength. This process enhances both the controllability of restoration operations and the safety of cultural heritage preservation. Moreover, this research suggests that measurable performance indicators—such as tensile strength, folding endurance, tearing resistance, extensibility, pH value, degree of polymerization, water absorbency, and ink receptivity—can serve as scientific parameters for quantifying fire qi. These parameters offer measurable and verifiable criteria for guiding restoration practices.

In summary, this study systematically elucidates the scientific connotation of fire qi in painting restoration papers by analyzing the mechanisms of paper aging and the corresponding changes in performance parameters. It reveals the physicochemical basis of the traditional "fading fire qi" practice and provides scientific support for understanding traditional restoration experiences. The findings lay a theoretical foundation for the future development of a quantitative and standardized evaluation system for restoration papers used in the conservation of Chinese paintings.

Acknowledgements

The authors gratefully acknowledge the financial support from the following funding sources: the National Key R&D Program of China (Grant No. 2022YFF0904504); the ByteDance Ancient Books Preservation Special Fund under the China Cultural Relics Protection Foundation and the Palace Museum's "Ancient Books Preservation and Revitalization Public Welfare Project"; and the 2024 National Social Science Fund Special Research Project on Cultural Heritage Protection and Inheritance: Research on Talent Team Development in Cultural Heritage Preservation (No. 24VWB028); Innovative Experimental Projects in Liberal Arts (LDWK202511). Their support has been invaluable for the completion of this work.

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