Research on Deacidification Treatment for Addressing the Acidification Crisis of Map Archives

Ming Li[1], Fen Hu[2], Ju Bai[1], Lifei Feng[3], Hao Yu[1],Yunlu Peng[1]

[1] National Geomatics Center of China, Beijing 100830, China – (liming, baiju, yh, pengyunlu)@ngcc.cn
[2] Land Satellite Remote Sensing Application Center, Ministry of Natural Resources of P.R. China, Beijing 100048, China – 154948273@qq.com
[3] Sichuan Ruili Heritage Preservation Technology Co., Ltd., Chengdu, Sichuan 610225, China – 18086918809@163.com

Keywords: Map Archives, Acidification, Deacidification, Cultural Conservation.

Abstract

Map archives, serving as crucial cultural heritage documenting historical spatial information, face severe challenges in long-term preservation. To evaluate the feasibility of deacidification technology in the conservation of map archives, this study utilized 41 severely acidified early 20th-century map archives as samples. These were treated using a specific non-aqueous deacidification technology, and changes in pH value, color difference (ΔE), and inks stability before and after treatment were analyzed. The results indicate that after deacidification, the paper pH value significantly increased from an average of 4.48 to a range between 8.24 and 8.87. The color change was minimal, with an average color difference ΔE of only 1.62. This study verifies that the deacidification technology is suitable and effective for the deacidification treatment of acidified paper-based map archives, providing a safe and reliable method for preserving their cultural value.

1. Introduction

Map archives, as unique and irreplaceable cultural carriers, contain a wealth of historical and humanistic information from different periods, profoundly reflecting the developmental trajectories and spatial patterns of political territories, economic networks, military deployments, cultural changes, livelihood conditions, and natural ecology across various eras.(Uhl et al., 2018;Jiang et al., 2017.) They are not merely records of geographical coordinates but also "spatial witnesses" to historical processes, possessing immense historical, artistic, and scientific value. However, over time, the paper carriers bearing this information are facing inevitable aging and deterioration, among which acidification is the most predominant and widespread internal factor leading to the drastic shortening of paper-based archival lifespans(Zou et al., 1994;Area et al., 2011).

The deterioration of paper results from the combined effects of internal and external factors. External factors, such as inappropriate temperature and humidity, biological pests, light radiation, dust pollution, and acidic gases (e.g., sulfur dioxide, nitrogen oxides), can all accelerate the material's aging process. Internal factors are more fundamental, rooted in the raw materials used in paper production (such as wood pulp which has high lignin content prone to oxidation and acid production), processes (such as the widespread use of alum-rosin sizing, which hydrolyzes to produce sulfuric acid in humid environments), and additives(Erhardt et al., 2005;Missori et al., 2006). These internal and external factors collectively cause the hydrolysis and oxidative degradation of cellulose, the main component of paper, leading to a decrease in its degree of polymerization, breakage of molecular chains, and ultimately resulting in paper embrittlement, yellowing, and loss of mechanical strength(Jablonsky et al., 2021;Conio, 2001.). This process continuously erodes the material foundation and informational integrity of map archives. Without intervention, precious historical maps will become brittle and may even crumble, with the information they carry facing irreversible loss.

In recent years, although significant progress has been made in preservation methods such as digital archiving, which facilitates information access and dissemination, the physical conservation of the map archives' "original objects"—that is, extending the lifespan of their material entities—remains the core and foundation of cultural heritage preservation(Ericson, 2024;Almeida et al., 2024). Digital technology cannot replace the materiality, historical traces, and value as authentic evidence of the original artifacts. Crucially, the physical stability of the original maps is a fundamental prerequisite for high-quality digitization, accurate georeferencing, and ensuring the long-term accessibility and usability of the historical spatial data they contain. Therefore, establishing more targeted deacidification protocols and scientific evaluation systems to address the core threat of acidification is a critical issue urgently needing resolution in current map archive conservation work(Hubbe et al., 2017;Ahn et al., 2013).

Although deacidification technology has advanced considerably since its proposal in the early 20th century, leading to various technical approaches such as liquid-phase (aqueous, non-aqueous) and gas-phase methods, and the development of multiple deacidifying agents (e.g., magnesium bicarbonate, calcium\magnesium hydroxide, aminoalkylalkoxysilanes), finding a deacidification technology that balances effectiveness, safety, and specificity is crucial for map archives(Tan et al., 2013;Ipert et al., 2006;Jablonsk et al., 2023). These are special objects with complex material compositions (pot including tracing paper, coatings, various types of machine-made paper) and rich informational characteristics (e.g., multi-color printing, hand-drawn elements, different inks and scripts). Deacidification treatment must not only effectively neutralize acidic substances and endow the paper with an alkaline reserve to resist future acid attacks but also ensure that the process does not cause secondary damage to paper fibers, original colors, or various pigments and inks, such as bleeding, fading, paper distortion, or strength loss(Wojciak, 2016;Yang et al., 2023;Ahn et al., 2012).

https://doi.org/10.5194/isprs-annals-XI-4-2026-421-2026

To this end, this study evaluated the acidification status of a batch of representative early-20th-century map archives through systematic field investigation and scientific sampling. Based on this, a specific non-aqueous deacidification technology was selected, focusing on verifying its comprehensive effects in elevating paper pH to a weakly alkaline range, controlling color stability, and ensuring the safety of diverse ink materials(Weng et al., 2019;Adam, 2015). The aim is to provide scientific evidence and reliable technical support for the systematic and refined deacidification conservation of map archives.

2. Experimental Methods

2.1 Field Investigation

This study began with an in-depth field investigation to comprehensively understand the overall condition of a specific batch of paper-based map archives. The survey covered the total volume of archives, main categories (e.g., topographic maps, administrative division maps, engineering drawings), distribution of creation periods, and the current damage extent and manifestations (such as yellowing, embrittlement, edge damage, mold spots, etc.). Preliminary findings revealed that these archives were predominantly created in the early 20th century and commonly exhibited typical signs of acidification, including yellowing of the paper and a brittle texture, indicating a concerning preservation condition.

2.2 Sampling

Scientific sampling is crucial for ensuring the accuracy and representativeness of research findings. During the sampling process, we comprehensively considered multiple factors including the diversity of paper materials, representativeness of storage environments, and varying degrees of acidification to ensure the selected samples could comprehensively reflect the overall condition of the entire batch of archives. For this study, 41 map archives were selected from the target collection for detailed investigation of their acidification status. The specific sampling proportions are presented in Table 1 below.

Total Quantity / Volumes or Items	Sampling Percentage
＜100	50%
100～1000	20% to 50%
1001～5000	10% to 30%
5001～9999	5% to 10%
10,000～100,000	1% to 5%
Over 100,0000	Below 1%

Table 1 Sampling Ratio for Paper-based Archives

2.3 Deacidification Procedure

After completing the preliminary acidification assessment, two map archives (labeled as Sample A and Sample B respectively) were selected from the 41 items as test specimens for deacidification treatment. The selection criteria were their high representativeness of acidification (pH values close to the average) and their inclusion of various types of inks that required verification in the study. The specific deacidification procedure was as follows: the samples were laid flat on a clean, dry work surface. Using a specialized aerosol spray bottle containing a non-aqueous deacidification agent with magnesium oxide (MgO) particles, the solution was evenly applied to the paper surfaces. During spraying, the distance between the nozzle and the paper surface was strictly maintained within 15-25 cm, with uniform movement from top to bottom and left to right to ensure complete coverage without missed areas or localized over-wetting. The deacidification agent was allowed to naturally permeate and evaporate from the paper surface, with no additional heating or mechanical drying processes required throughout the procedure, so as to avoid potential damage to the fragile paper from thermal or mechanical stress.

3. Characterization Methods

The overall deacidification requirements for the map archives needed to comply with ISO/TS 18344 "Effectiveness of paper deacidification processes".

3.1 pH

The surface pH of the paper was measured using a calibrated portable pH meter (HANNA HI 99171) in accordance with the TAPPI T 529 standard, "Surface pH Testing of Paper." Multiple measurements were taken at different locations on each sample (e.g., corners and center), and the average value was calculated to minimize error.

3.2 Colorimetric measurement

Colorimetric data of the paper in the CIE ($L^*a^*b^*$) system was measured using a 3nh NR10QC spectrophotometer, following the ISO 5631:2022 standard. In this color space, L^* represents lightness (from black to white), a^* represents the red-green axis (+a for red, -a for green), and b^* represents the yellow-blue axis (+b for yellow, -b for blue). The color difference ΔE was used to quantify the overall color change before and after deacidification, calculated using the following formula (1):

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{1}$$

where ΔL^* = difference in L^* before and after treatment
Δa^* = difference in a^* before and after treatment
Δb^* = difference in b^* before and after treatment

3.3 Imaging records

A high-resolution digital microscope was used to document different types of inks (such as blue-black ink, black printing ink, pencil, red seals, etc.) before and after deacidification (all images were captured at a uniform magnification of 200x). The observation focused on comparing the edge clarity of the ink materials after deacidification, checking for any bleeding, diffusion, fading, or flaking of the ink, to assess the impact of the deacidification treatment on the ink materials.

3.4 Results and Analysis

3.4.1 Investigation and Test Results

The 41 map archives selected for sampling in this study predominantly date back to the early 20th century—a period when machine-made paper was largely replacing traditional handmade paper, and acidic sizing agents (such as rosin-alum) were commonly used in papermaking processes. All sampled papers are machine-made, including some tracing papers used for drawing or reproduction. The pH measurement results are shown in Figure 1.

https://doi.org/10.5194/isprs-annals-XI-4-2026-421-2026 |

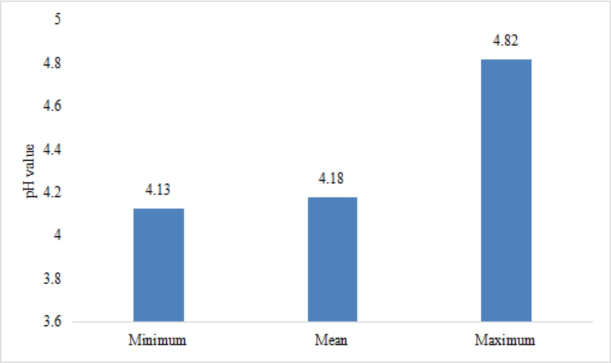


Figure 1. pH Values of Sampled Map Archives

The test results indicate that the pH values of all examined map archives are below 5.0, with an acidification rate of 100%. The pH values specifically range from 4.13 to 4.82, with an average as low as 4.48, indicating a severe overall acidification condition of this batch of map archives. From the perspective of paper chemistry, when the environment becomes acidic, the hydrolysis of cellulose accelerates significantly. Under strongly acidic conditions, extensive acid-catalyzed hydrolytic cleavage of cellulose molecular chains occurs. This degradation directly leads to a continuous decrease in the paper's degree of polymerization and a substantial reduction in mechanical properties (including folding endurance and tear resistance), thereby pushing archival materials into a critical stage of accelerated deterioration. This widespread and deep acidification not only reveals a profound aging crisis of the map archive papers but also signifies that the precious historical and geographical information they carry—such as detailed contour lines, annotated place names, and special symbols—faces the risk of irreversible loss due to the physical collapse of the carrier. Therefore, implementing scientific, timely, and effective deacidification protection for these archives has become an urgent rescue task.

3.4.2 pH Value Changes

The deacidification technology employed in this study operates on a core mechanism based on the deposition of alkaline buffer substances within the paper fibers and subsequent chemical reactions. The active component in the deacidification agent, MgO particles, is evenly sprayed onto the paper surface and penetrates the fiber network. Subsequently, MgO reacts with moisture (H_2O) from the air to form magnesium hydroxide [$Mg(OH)_2$]. The magnesium hydroxide further reacts with atmospheric carbon dioxide (CO_2), converting into the more stable magnesium carbonate ($MgCO_3$). Acting as a mild alkaline substance, magnesium carbonate neutralizes free acids (represented by H^+) present in the paper, producing harmless magnesium salts, water, and releasing carbon dioxide. This series of chemical reactions can be briefly represented as follows:

$$\begin{aligned} & MgO + H_2O \rightarrow Mg(OH)_2 \\ & Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O \\ & MgCO_3 + 2H^+ \rightarrow Mg^{2+} + H_2O + CO_2 \uparrow \end{aligned} \tag{2}$$

Through this mechanism, not only are the existing acidic substances in the paper immediately neutralized, but more importantly, the residual magnesium carbonate and potentially other incompletely converted alkaline substances form an "alkaline reserve" within the paper matrix. This alkaline reserve can continuously neutralize acidic substances that may be introduced from the environment (e.g., atmospheric pollutants) or slowly released by the paper itself during long-term storage, thereby providing sustained protection.

To precisely quantify the effect of the deacidification treatment, this study conducted multiple pH measurements on Sample A and Sample B before and after processing, and calculated their mean values and standard deviations. The specific data are presented in Table 2.

Sample	Before Deacidification		After Deacidification		
	pH Values	Mean pH	pH Values	Mean pH	Standard Deviation
A	4.63	4.48	9.3	8.87	0.39
	4.38		8.78		
	4.42		8.54		
B	4.6	4.74	8.35	8.24	0.13
	4.9		8.09		
	4.71		8.27		

Table 2. Changes in Paper pH Values Before and After Deacidification

Data analysis reveals the highly significant effectiveness of the deacidification treatment in neutralizing paper acidity. Before treatment, all measured points in both samples showed strongly acidic characteristics. Specifically, the three measurement points of Sample A registered values of 4.63, 4.38, and 4.42, while Sample B showed values of 4.60, 4.90, and 4.71. These consistently low pH values clearly demonstrate a severe acidification state. In such a strongly acidic environment, the hydrolysis and breakage of cellulose molecules are continuously catalyzed, critically threatening the long-term preservation of the archives. Following deacidification treatment, each measurement point exhibited a substantial increase in pH. In Sample A, the values rose to 9.30, 8.78, and 8.54, while in Sample B, they increased to 8.35, 8.09, and 8.27. This notable elevation signifies a successful transition for the paper from an acidic to a weakly alkaline state. This shift indicates not only the effective neutralization of existing free acids within the paper but also, more importantly, suggests the formation of a valuable "alkaline reserve" by alkaline substances (such as magnesium carbonate) deposited inside the paper fibers. This alkaline buffer layer provides continuous protection against new acidic substances potentially generated by environmental factors or the paper's own aging process, thereby offering a fundamental guarantee for the long-term chemical stability of the paper.

Furthermore, observation of the standard deviation of pH values after deacidification reveals information about the uniformity of the treatment. The relatively low standard deviation for Sample B (0.13) suggests a very even distribution and penetration of the deacidification agent on the paper surface, resulting in good consistency of the treatment effect. In contrast, Sample A showed a somewhat higher standard deviation (0.39), with pH values across measuring points fluctuating between 8.54 and 9.30. This variation may stem from the microstructural heterogeneity of the paper fibers themselves, slight differences in the distribution of the deacidification agent during spraying, or a combination of both factors. Despite this slight fluctuation, all measured pH values firmly remain within the ideal weakly alkaline range (7.0-10.0). There is no risk of localized excessive alkalinity (pH > 10), which avoids the potential for alkaline degradation of cellulose. Simultaneously, no areas of insufficient neutralization were detected, ensuring comprehensive protection. Therefore, overall, this technology demonstrates exceptional effectiveness and good treatment uniformity, proving it to be a safe and reliable deacidification solution for precious paper-based archives.

The changes in the average pH values before and after deacidification, as shown in Figure 2, allow for a clearer observation of the effectiveness of the deacidification treatment.

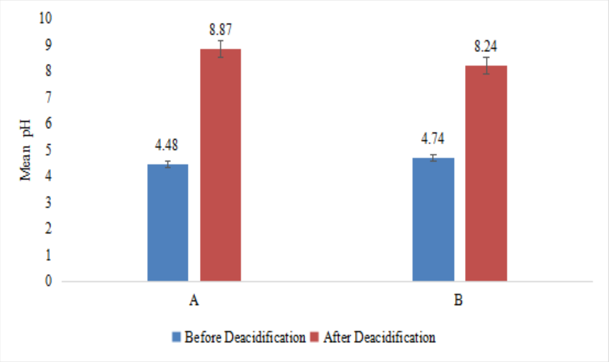


Figure 2. Changes in Average pH Before and After Deacidification

Before deacidification, the average pH values at various measuring points for Sample A and Sample B were 4.48 and 4.74, respectively, clearly indicating an acidic state and signaling a high risk of rapid deterioration for the paper. Long-term storage under such conditions would lead to continued acceleration of cellulose chain scission until the paper completely loses its strength. After deacidification treatment, the average pH values of the two samples increased significantly to 8.87 and 8.24, stabilizing within the weakly alkaline range. This remarkable change fully demonstrates that the deacidification technology used effectively penetrates the paper and sufficiently neutralizes the free acidic substances, transitioning the paper's overall environment from acidic to weakly alkaline. This transformation fundamentally inhibits the acid-catalyzed hydrolysis reaction, providing the crucial chemical assurance for significantly slowing the paper's aging rate and markedly extending its preservation lifespan. Furthermore, the elevation of the pH to the 8-9 range (weakly alkaline) instead of a strongly alkaline level also avoids the potential risk of alkaline degradation to cellulose, highlighting the mildness and safety of this technology.

3.4.3 Color Changes

For cultural artifacts such as map archives, which hold significant visual research value, preserving their original appearance, including the stability of paper color, is one of the key criteria for evaluating the success of any conservation treatment. This study utilized the CIE ($L^*a^*b^*$) system—an approximately uniform three-dimensional color space represented by rectangular coordinates—to assess paper color before and after deacidification treatment. The corresponding data is presented in Table 3.

Sample	Before Deacidification		After Deacidification		Color Difference (ΔE)
	L^*	80.52	L^*	78.8	
A	a^*	6.01	a^*	4.47	2.88
	b^*	16.88	b^*	15.16	
	L^*	78.32	L^*	78.65	
B	a^*	4.01	a^*	3.96	0.35
	b^*	13.93	b^*	13.83	

Table 3. CIE ($L^*a^*b^*$) system Data of Maps Before and After Deacidification

The results show that the L^* value of Sample A slightly decreased from 80.52 to 78.80, a change of 1.72, while the L^* value of Sample B remained almost unchanged (from 78.32 to 78.65, a change of 0.33). The minor decrease in L^* values may be attributed to the deposition of solid particles (e.g., MgO) from the deacidification agent within the paper fibers, causing slight scattering or absorption of light. However, the magnitude of this change is minimal and imperceptible to the naked eye, thus having a negligible impact on the overall visual brightness of the paper.

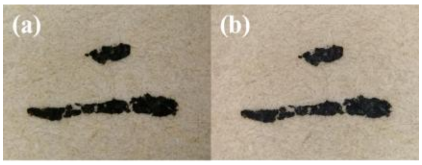
The a^* value of Sample A decreased from 6.01 to 4.47, a change of 1.54, while the a^* value of Sample B exhibited an extremely minor change (0.05). A positive but reduced a^* value indicates a slight decrease in the red component of the paper, which may be related to the deacidification process subtly altering certain chromophores responsible for yellowing/reddening of the paper, or to the alkaline environment mildly affecting residual dyes or impurities in the paper. Again, the extent of change is very small and did not cause any noticeable color shift.

The b^* value of Sample A decreased from 16.88 to 15.16, a change of 1.72, while the b^* value of Sample B changed by only 0.10. A positive but reduced b^* value suggests a slight weakening of the yellow component in the paper. This may occasionally be associated with the alkaline environment inducing reversible or irreversible changes in substances that originally caused yellowing (such as acidic degradation products or certain oxidation by-products).

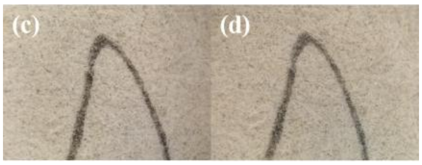
The calculated color difference values (ΔE) for Sample A and Sample B were 2.88 and 0.35 respectively, with a mean value of 1.62. This overall average ΔE of 1.62 is imperceptible to the naked eye. These results strongly demonstrate that the applied deacidification technology has minimal impact on the visual appearance of the map archive papers, successfully maintaining high color stability. This represents a crucial advantage for archival conservation work where authenticity preservation is paramount.

3.4.4 Ink Changes

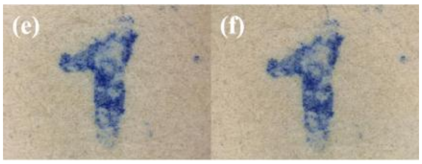
The value of map archives lies not only in their paper substrates but, more importantly, in the diverse graphic and textual information they carry. The significant variation in the types of these handwritten texts, pigments, printing inks, etc., along with their complex chemical compositions, makes their compatibility with the deacidifying agent another critical factor determining the safety of the technology. This study focused on examining six common types of inks, including printing ink, pencil, blue seals, red seals, red ink, and blue-black ink. A detailed observation was conducted by comparing high-resolution microscopic images (at 200x magnification) taken before and after deacidification (Figure 3).



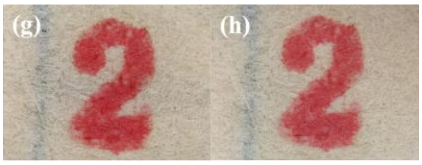
Printing Ink



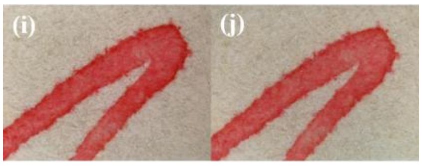
Pencil



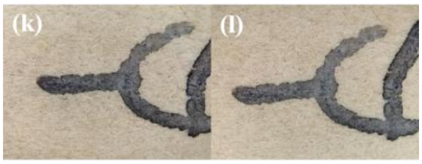
Blue Seal



Red Seal



Red Ink



Blue-Black Ink

Figure 3. Images of Different Inks Before and After Deacidification.; (a), (c), (e), (g), (i), and (k) show the condition before deacidification; (b), (d), (f), (h), (j), and (l) show the condition after deacidification.

Comparative analysis before and after treatment revealed no adverse changes in any of the tested inks following deacidification. There was no dissolution or diffusion observed, nor any bleeding of ink, blurring of edges, or color spreading, indicating that the non-aqueous solvent system of the deacidifying agent is inert to these materials. No fading or discoloration due to chemical reactions was detected. All contours remained sharp without any signs of bleeding after deacidification. Additionally, no flaking, peeling, or powdering of the inks was observed, demonstrating that the deacidification treatment did not compromise their physical adhesion to the paper fibers.

These results fully confirm that the deacidification technology validated in this study exhibits excellent chemical compatibility and physical safety with a variety of common historical inks. Its mechanism appears to selectively react with acidic substances in the paper without damaging the colorants, binders, or carriers of the inks. This provides strong technical assurance for the safe treatment of paper map archives containing complex and sensitive graphic and textual information, significantly reducing the risks associated with the process.

3.5 Conclusion

Through systematic investigation and experimentation, this study has reached the following conclusions:

Severe Acidification Status: Sampling and testing of 41 early 20th-century map archives revealed an acidification rate of 100%, with an average pH value as low as 4.48. This indicates a seriously acidic condition overall, necessitating urgent rescue conservation.

Significant Deacidification Effectiveness: Following treatment with the specific deacidification technology, the pH value of the paper increased notably (8.24-8.87), reaching a weakly alkaline range. This effectively neutralized the existing acidity and is likely to have deposited an alkaline reserve, providing a fundamental assurance for the long-term stability of the paper.

Minimal Visual Impact: The color changes induced by the deacidification treatment were very slight, with an average color difference (ΔE) of only 1.62. This falls within a range imperceptible to the human eye, thereby maximally preserving the original appearance and visual authenticity of the archives.

Reliable Ink Safety: The treatment process caused no adverse effects—such as dissolution, diffusion, fading, or flaking—on the various common ink materials tested, demonstrating the technology's excellent material compatibility.

In summary, this deacidification effort has verified that the employed technology offers both remarkable effectiveness and high safety for paper-based map archives. It not only addresses the core issue of paper acidification but also successfully avoids potential secondary damage risks during treatment. Consequently, this technology can be considered a viable and reliable option for the deacidification of paper map archives, particularly those similar to early 20th-century machine-made paper maps.

By integrating advanced deacidification technology with rigorous cultural conservation principles, we can not only effectively extend the physical lifespan of map archives, allowing for their longer transmission, but more importantly, we safeguard their unique cultural value as irreplaceable witnesses to historical spaces and carriers of civilization. This study provides concrete scientific data and a practical case for the preventive conservation and rescue restoration of such precious cultural heritage. It holds significant reference value for future development of standardized deacidification operating procedures for map archives. Future research could further investigate the impact of this deacidification technology on the long-term mechanical properties of map archives, as well as assess the depletion rate of the alkaline reserve and its long-term preservation effectiveness under different environmental conditions.

Acknowledgements

This study was funded by the National Key Research and Development Program of China(2023YFC3209101). The authors would like to thank Fen Hu of Land Satellite Remote Sensing Application Center, Ministry of Natural Resources of P.R. China and Ju Bai of National Geomatics Center of China as corresponding author for his contribution related to this work.

References

Adam Wójciak., 2015. Washing, spraying and brushing. a comparison of paper deacidification by magnesium hydroxide nanoparticles. *Restaurator*, 36(1), 3-23.

Ahn, K., Banik, G., Potthast, A., 2012. Sustainability of Mass-Deacidification. Part II: Evaluation of Alkaline Reserve. Restaurator. *International Journal for the Preservation of Library and Archival Material*, 33(1), 48-75. https://doi.org/10.1515/res-2012-0003

Ahn, K., Rosenau, T., Potthast, A., 2013. The influence of alkaline reserve on the aging behavior of book papers. *Cellulose*, 20(4), 1989-2001.

Almeida, P., Teixeira, A., Velhinho, A., Raposo, R., Silva, T., Pedro, L., 2024. Remixing and repurposing cultural heritage archives through a collaborative and AI-generated storytelling digital platform. Proceedings of the 2024 ACM International Conference on Interactive Media Experiences Workshops.

Area, M. C., and Cheradame, H., 2011. Paper aging and degradation: Recent findings and research methods, *BioRes*. 6(4), 5307-5337.

Conio, G., 2001. Hydrolytic and oxidative degradation of paper. *Restaurator*, 22(2), 67-83.

Erhardt, D., Tumosa, C. S., 2005. Chemical degradation of cellulose in paper over 500 years. *Restaurator*, 26(3).

Ericson, K. G., 2024. Re-animating the archive: encountering and transforming historical materials with digital design tools. *Cultural Geographies*, 31(4).

Hubbe, M. A., Smith, R. D., Zou, X., Katuscak, S., Potthast, A., Ahn, K., 2017. Deacidification of acidic books and paper by means of non-aqueous dispersions of alkaline particles: A review focusing on completeness of the reaction, *BioRes*. 12(2), 4410-4477.

Ipert, S., Dupont, A., Lavedrine, B., Begin, P., Rousset, E., Cheradame, H., 2006. Mass deacidification of papers and books. IV – a study of papers treated with aminoalkylalkoxysilanes and their resistance to ageing. *Polymer Degradation & Stability*, 91(12), 3448-3455.

Jablonský, M., Ima, J., 2021. Oxidative degradation of paper – a minireview. *Journal of Cultural Heritage*(11).

Jablonský, M., Ima, J., 2023. The role of magnesium species in paper deacidification. a review. *Journal of Cultural Heritage*, 61, 194-200.

Jiang, L., Liang, Q. Z., Qi, Q., Ye, Y., Liang, X., 2017. The heritage and cultural values of ancient chinese maps. *Journal of Geographical Sciences*, 27, 1521-1540.

Missori, M., Mondelli, C., De Spirito, M., Castellano, C., Bicchieri, M., Schweins, R., et al., 2006. Modifications of the mesoscopic structure of cellulose in paper degradation. *Physical Review Letters*, 97(23), 238001.

Tan, W., Cheng, L. F., Fang, Y. X., 2013. Deacidification of paper using supercritical carbon dioxide containing calcium propionate or magnesium bicarbonate. *Advanced Materials Research*, 781-784, 2637-2640.

Uhl, J. H., Leyk, S., Chiang, Y.-Y., Duan, W., Knoblock, C. A., 2018. Map Archive Mining: Visual-Analytical Approaches to Explore Large Historical Map Collections. *ISPRS International Journal of Geo-Information*, 7(4), 148. https://doi.org/10.3390/ijgi7040148

Weng, J., Zhang, X., Jia, M., Zhang, J., 2019. Deacidification of aged papers using dispersion of $Ca(OH)_2$ nanoparticles in subcritical 1,1,1,2-tetrafluoroethane (R134a). *Journal of Cultural Heritage*, 37, 137–147.

Wojciak, A., 2016. Deacidification of paper with Mg(OH)2 nanoparticles: the impact of dosage on process effectiveness. *Wood Research*, 61(6), 937-950.

Yang, S. J., Wang, H. Q., Liu, S. G., Sun, C. H., Zheng, L., Shi, P. B., et al., 2023. Research on Deacidification and Reinforcement of Archives Paper with Calcium Carbonate Nanoparticles/Modified Hydroxypropyl Cellulose. *Integrated Ferroelectrics*, 234(1), 88–99. https://doi.org/10.1080/10584587.2023.2191553.

Zou, X., Gurnagul, N., Uesaka, T., Bouchard, J., 1994. Accelerated aging of papers of pure cellulose: mechanism of cellulose degradation and paper embrittlement. *Polymer Degradation & Stability*, 43(3), 393-402.