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A Review of Research Literature on the Conservation of Grottoes in China Based on Keyword Clustering Analysis

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Abstract

Based on keyword clustering, this paper systematically reviews the development trajectory and hot trends of research on the protection of grottoes in China. The study reveals that a research system centered on "deterioration mechanism-micro-environment monitoring-digital protection-human impact regulation" has been established in this field, and the research focus has gradually shifted from single disease control to systematic and preventive protection. Keyword clustering and emergent analysis indicate that hot topics include grotto art, Buddhist culture, and digitalization of cultural heritage, reflecting the characteristics of multi-disciplinary integration. However, current research still suffers from "fragmentation", lacking an overall understanding of the coupling mechanism of environmental, biological, and human factors, and the integration of multiple disciplines remains superficial. The ability to monitor and warn, as well as to convert digitalization achievements, is insufficient. In the future, it is necessary to construct a systematic research framework, deepen the exploration of mechanisms, promote intelligent monitoring and the establishment of digital standards, to achieve a fundamental transformation in grotto protection from "emergency restoration" to "preventive, precise and sustainable".

Keywords

Cultural Relics Protection, Grottoes, Keyword Clustering, CiteSpace

1. Introduction

Grotto temple heritage in China embodies both cultural-artistic value and archaeological-scientific significance. As a quintessential medium integrating stone artifacts with painted murals, their conservation practices are undergoing a paradigm shift from "emergency restoration" [1] to "preventive conservation," [2] urgently requiring the development of systematic research frameworks and interdisciplinary support. These grottoes not only materialize ancient religious beliefs, engineering craftsmanship, and societal civilization but also serve as pivotal specimens for deciphering historical climate evolution, craft dissemination routes, and cross-regional cultural interactions. However, their immovable nature and unique geological conditions subject them to long-term coupling effects from multiple stressors in the cave micro-environment, including temperature-humidity fluctuations [3], salt migration [4], pollutant infiltration [5], and biological colonization [6]. These induce comprehensive deterioration phenomena such as powdering, pigment flaking, and biogenic crust formation [7]-[9], severely threatening the structural safety [10], material integrity [11], and artistic value of cultural relics.

With the escalation of conservation needs, the field of grotto heritage preservation has developed an interdisciplinary research framework, and the volume of related literature continues to grow. However, existing research still faces a significant "fragmentation" bottleneck:

(1) Research perspectives predominantly focus on single-disease mechanisms or localized environmental factors [12] [13], lacking a macro-level grasp of the holistic research framework encompassing "environmental drivers—technology application—conservation practices";

(2) The application of interdisciplinary technologies (e.g., monitoring sensors, microbial regulation, numerical simulation) remains fragmented [14]-[16], with the evolutionary patterns and core hot spots of technical methodologies within the field yet to be clearly defined;

(3) Predictive and regulatory capabilities are weak [17]. In the face of micro-environmental evolution and cultural heritage responses potentially triggered by conservation engineering interventions (e.g., installing rain shelters, adjusting visitor flow routes) or future environmental changes (e.g., climate change, increasing tourism pressure), effective predictive tools and evaluation methods are still lacking, resulting in a lack of foresight in conservation decision-making.

Traditional review methods struggle to efficiently integrate massive volumes of literature and visually present the developmental dynamics of a field. As a core tool in bibliometrics, CiteSpace overcomes these bottlenecks with its unique advantages in analyzing research hot spot evolution, interdisciplinary pathways, collaboration networks among core authors or institutions, and literature clustering [18]. To address the mismatch between the "fragmented" nature of grotto conservation research and the demand for a paradigm shift toward preventive conservation—where traditional literature reviews fall short in synthesizing the macro-level research landscape—this review adopts a phased retrieval strategy based on the China National Knowledge Infrastructure (CNKI) database: beginning with broad-topic searches (e.g. "grottoes," "grottoes + conservation/restoration") to map the overall scope of the field, followed by precise composite queries focusing on core topics (e.g. "deterioration mechanism," "digital conservation"). The disciplinary coverage includes archaeology, cultural heritage conservation, architecture, materials science, environmental science, digital technology, and other cross-disciplinary fields, and the literature screening is limited to academic publications such as journal articles, conference papers, and theses. By analyzing domestic and international literature on grotto conservation over the years, this review systematically reveals the temporal evolution of the field from empirical-qualitative to scientific-quantitative approaches, along with shifting research hot spots across five core directions (e.g. deterioration mechanisms, micro-environment monitoring).

2. General Overview of Chinese Grotto Studies

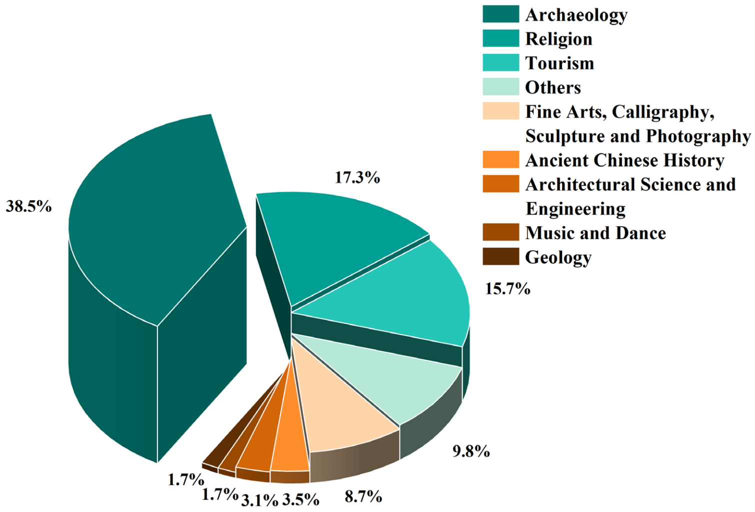


Figure 1. Proportion of various disciplines in Chinese grotto research.

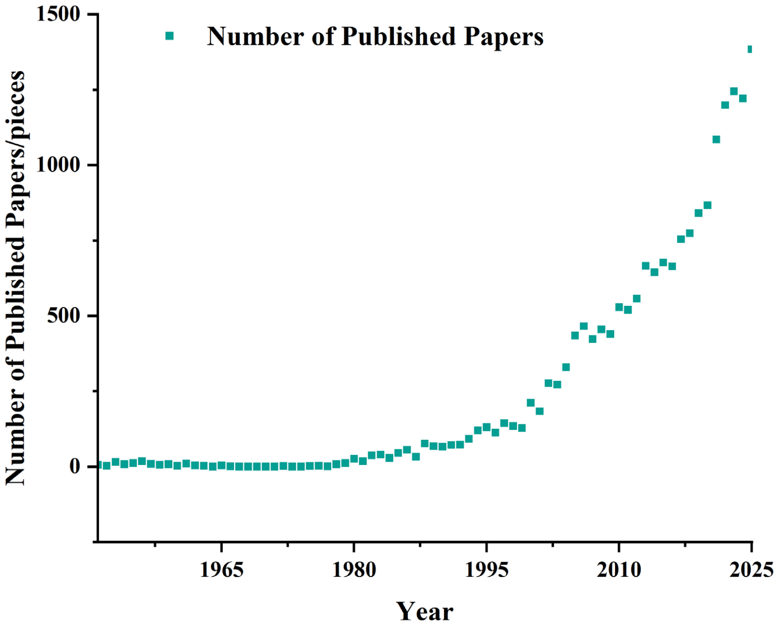


Figure 2. Publication trends in Chinese grotto studies.

The research plan retrieved the term "grottoes" from the CNKI database, yielding a total of 10,300 documents spanning 74 years from 1951 to 2025. The content primarily covers eight disciplinary fields, with archaeological research accounting for 38.5% (**Figure 1**). In terms of publication trends, around 1999, the number of publications began to increase sharply year by year (**Figure 2**). This surge is attributed to the launch of the "Dunhuang Conservation Plan," which established a systematic and comprehensive conservation philosophy along with large-scale investments, thereby promoting the development of grotto research.

Using CiteSpace, a cluster analysis was conducted on the 10,300 documents, with the average silhouette value (S-value) and clustering modularity value (Q-value) serving as core indicators for evaluating clustering effectiveness. An S-value > 0.7 indicates high credibility, while a Q-value >0.3 suggests a significant clustering structure in the network. In this study, S = 0.9302 and Q = 0.694, demonstrating highly convincing clustering results. The analysis categorized the keywords from the documents into five clusters (**Figure 3**), with the content coverage of each cluster detailed in the accompanying table.

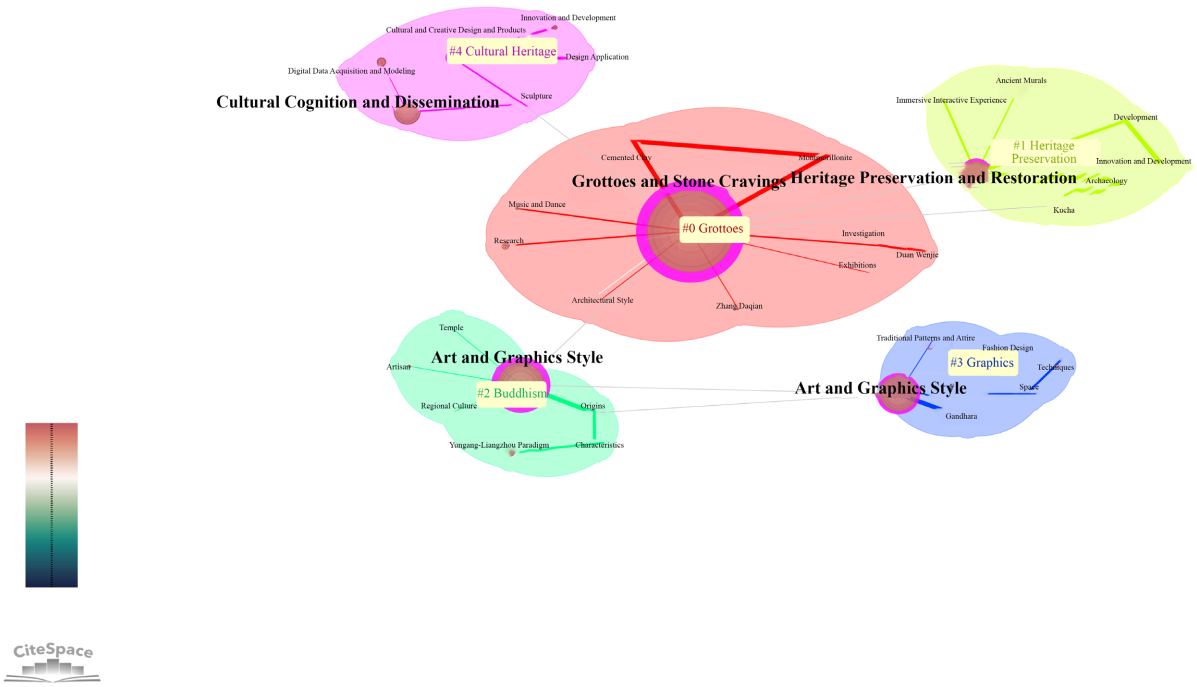


Figure 3. Keyword cluster analysis of Chinese grottoes research.

Cluster #0 exhibits a significant correlation with Cluster #2, which is manifested in viewing grottoes as carriers of the integration between Buddhism and political power. Gu Yanfang [19] revealed grottoes as a combination of religious rituals and political symbols through analyzing the Buddhist worship scene in the Huangfu Cave; Yang Yang [20] elucidated the localization process of Buddhist culture using the Yungang Grottoes as an example. Scholar Chang Qing's research approach is particularly systematic. By treating the grottoes at Longmen [21] and in Shaanxi

[22] as "stone evidence" [21], he spent years deepening his studies from stylistic analysis to political iconography [23] [24], uncovering how medieval imperial authority manipulated Buddhist narratives through cave excavation and statue destruction, thereby establishing the research paradigm of grottoes as "Buddhist political media."

Furthermore, Cluster #0 and Cluster #4 are inherently connected due to their shared category of "cultural heritage." The research by Wei Qi [25] is pivotal in this shift. Through his analysis of the royal statues and Sinicization style of the Longmen Grottoes, he characterized them as "a treasure of national carving art," thereby pioneering the conceptual leap of the research object from the physical "grotto" to the cultural "heritage."

Table 1. Content covered by keyword clustering of Chinese grottoes.

Cluster name	Covering keywords and aspects
0# Grotto	Grotto and stone carving art, music and dance, architectural forms, exhibitions, investigations, argillaceous cementation, montmorillonite, etc.
1# Heritage Preservation	Cultural heritage preservation and restoration, immersive and interactive experiences, ancient murals, development, archaeology, etc.
2# Buddhism	Temples, artisans, regional culture, origins, Liangzhou paradigm, Buddhist culture and iconography, etc.
3# Graphics	Art and image style, traditional patterns and decorations, costume design, techniques, Gandhara, etc.
4# Cultural Heritage	Innovation and development, design and application, digital collection and modeling, cultural and creative design and products, cultural cognition and communication, etc.

As shown in **Table 1**, the 82 publications related to Cluster 0 and Cluster 1 can be categorized into the following four research directions:

(1) Art History and Iconography Studies. This direction systematically examines the themes, styles, and chronology of visual materials such as cave sculptures and murals to establish "core value carriers" for conservation practices. For example, Li Jinyang [26] interprets the imperial legitimacy embodied in the "Dual Seated Buddhas" statues of the Yungang Grottoes, emphasizing that their preservation status directly correlates with the continuity of critical historical information. Li Jingjie [27] clarifies the origins of the iconographic compositions and pigments in the Nirvana Sutra transformation scenes at Dunhuang, providing an original historical and technical basis for mural restoration.

(2) Conservation Science and Technology, focusing on the deterioration mechanisms and intervention techniques for cave sites, adopting a research approach that integrates "experimentation, monitoring, and engineering." Liu Xiangfeng [28] identified the critical conditions for macroscopic crack formation in Yungang

sandstone through freeze-thaw cycle tests. Meng Tianhua [29] applied terahertz nondestructive testing technology to predict the onset of hollow detachment in painted layers, advancing the shift from "emergency repairs" to "preventive conservation." Li Zuixiong [30] developed PS-C grouting materials that significantly improved the strength and salt resistance of crack repairs, successfully applied in reinforcement projects at the Yungang Grottoes.

(3) Digitalization and Information Applications, primarily utilizing technologies such as 3D laser scanning and digital twins to establish a closed-loop digital workflow of "high-precision acquisition—scientific archiving—public dissemination." Related studies create permanent digital archives for cave sites, providing essential data support for physical conservation. For instance, Zhou Wensheng [31] created a "digital twin" for Cave 12 of the Yungang Grottoes using mobile laser scanning, offering a precise reference for construction reinforcement. Huang Zeyu [32] employed digital twin technology to enable real-time monitoring of environmental and structural changes within the caves.

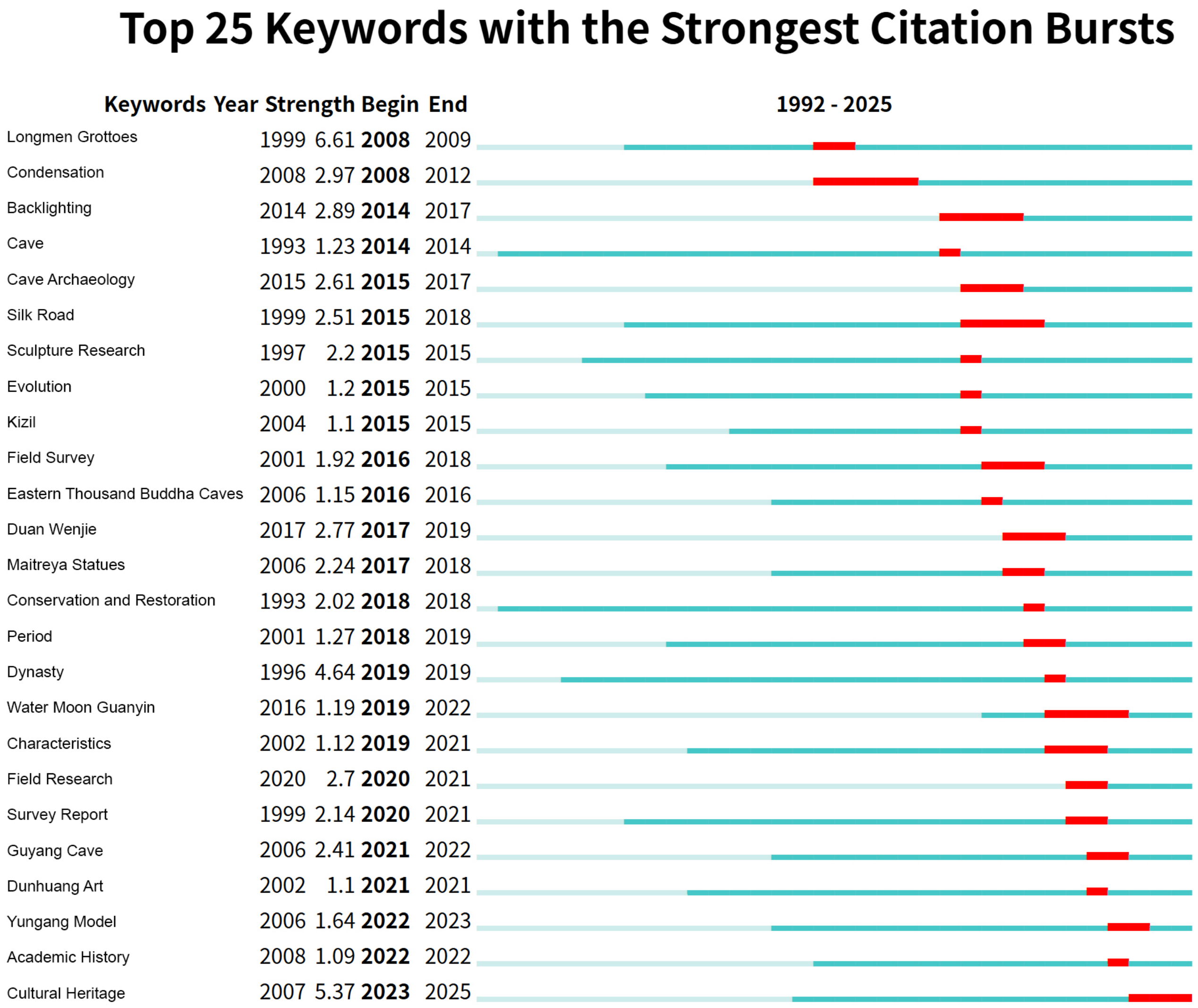
(4) Cultural Exchange and Mutual Learning among Civilizations. This direction explores the reinterpretation of the cultural value of cave sites in contemporary contexts, emphasizing their interaction with cultural tourism integration, public education, and social identity.

Cluster 2 and Cluster 3 form a profound connection through the "visual translation of Buddhist thought" and the "adaptation of imagery for dissemination." Representative studies demonstrate that the stylistic evolution of cave art vividly reflects the localization process of Buddhism: Chen Shaofeng [33] noted that from the Northern Dynasties to the Sui Dynasty, the sculptural techniques shifted from "shallow stepped relief" to fluid and natural forms, aligning with the need for the popularization of Buddhist rituals and doctrines; Zhao Liya [34] categorized the Buddha statues in the Kizil Caves into three styles—"Indian-Kizil-Han," clearly illustrating the cultural fusion path during Buddhism's eastward transmission; the study <Cultural Blending in the Northern Wei Dynasty as Seen in the Yungang Grottoes> [20] systematically outlines the stylistic sequence of Yungang sculptures, transitioning from early Western Regions styles to the sinicized "broad robes and wide belts" imagery of the middle period, and finally to late-period styles incorporating folk elements, thereby bridging the connection between Cluster 2 and Cluster 3. These studies collectively establish a comprehensive interpretive framework of "caves as vessels—sculptures conveying doctrines—styles manifesting fusion," deepening the systematic understanding of how Buddhism in the Northern Wei period utilized visual arts to achieve localization and ethnic integration.

3. Analysis of Keyword Emergence in Chinese Grotto Studies

As shown in **Figure 4** (Top 25 burst terms generated based on CiteSpace), the research hotspots and frontier evolution in this field exhibit distinct characteristics. In terms of burst strength, the top three keywords are "Longmen Grottoes," "cultural heritage," and "dynasty." Among these, "Longmen Grottoes" primarily showed high activity during 2008-2009, with research focusing on protection and restoration technologies, particularly addressing engineering challenges such as water leakage control [35], grouting materials [36], and the repair of collapsed niches [37]. This trend stems from both the prominent natural deterioration faced by the Longmen Grottoes as an open-air stone heritage site and the heightened conservation demands following its designation as a national 5A-level scenic area in 2007 [38]. The related achievements mark a significant shift in grotto conservation from empirical maintenance to scientific and systematic restoration [39]. "Cultural heritage" was mainly prominent during 2023-2025, driven by dual forces: first, national cultural strategies such as the "14th Five-Year Plan" elevating cultural heritage protection to a strategic level [40]; second, the maturation of digital technologies like 3D scanning, VR, and digital twins, which have facilitated high-precision archiving, virtual restoration [32], and immersive dissemination [41], significantly expanding its pathways and impact in preservation and transmission. "Dynasty" primarily surged during 2018-2019, with academic attention centered on Northern Dynasties grotto art, delving into the interplay between grotto excavation and Buddhist thought, as well as political contexts during the Northern Wei, Northern Qi, and Northern Zhou periods [42] [43]. Research themes included the spread of the "Decline of the Dharma" concept and scripture engraving [43], as well as the origins of sacred tree imagery [44]. This trend may have been influenced by significant archaeological discoveries at the time (e.g., the Ye City ruins [43] [45]) and the promotion of related academic conferences and projects, reflecting a research orientation that interprets the evolution of Buddhist art from a dynastic perspective.

In terms of sustained keyword popularity, "backlight," "Silk Road," and "water Guanyin" have maintained research attention for approximately four years, while "condensation water" has the longest burst period (five years), indicating the academic community's continued emphasis on this topic. Condensation water, as a significant moisture source leading to the weathering of stone cultural relics, has been systematically studied since 2008. Zhu Hua [46] *et al.* were among the first to analyze its formation mechanism and its impact on cave weathering, sparking initial academic focus. By 2012, significant progress had been made in related research regarding observation, mechanisms, and prevention: Wan Li [47] proposed quantitative observation methods and revealed its temporal dynamic characteristics; Zhang Ao [48] clarified the chemical weathering effect of condensation water coupled with CO_2 on carbonate rocks through simulation experiments; Ren Jianguang [49] explored the inhibitory mechanisms of cave construction features on condensation water; Huang Jizhong [50] emphasized the critical role of condensation water in water-related hazards through investigations into moisture sources. These achievements collectively promoted the sustained deepening of this topic. Subsequently, research on condensation water further advanced toward technological development. For instance, Ma Ce [51] applied infrared thermal imaging technology in 2022 to reveal the dynamic formation patterns and infiltration mechanisms of condensation water during rainfall, expanding the application pathways of non-destructive monitoring methods.



Top 25 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End
Longmen Grottoes	1999	6.61	**2008**	2009
Condensation	2008	2.97	**2008**	2012
Backlighting	2014	2.89	**2014**	2017
Cave	1993	1.23	**2014**	2014
Cave Archaeology	2015	2.61	**2015**	2017
Silk Road	1999	2.51	**2015**	2018
Sculpture Research	1997	2.2	**2015**	2015
Evolution	2000	1.2	**2015**	2015
Kizil	2004	1.1	**2015**	2015
Field Survey	2001	1.92	**2016**	2018
Eastern Thousand Buddha Caves	2006	1.15	**2016**	2016
Duan Wenjie	2017	2.77	**2017**	2019
Maitreya Statues	2006	2.24	**2017**	2018
Conservation and Restoration	1993	2.02	**2018**	2018
Period	2001	1.27	**2018**	2019
Dynasty	1996	4.64	**2019**	2019
Water Moon Guanyin	2016	1.19	**2019**	2022
Characteristics	2002	1.12	**2019**	2021
Field Research	2020	2.7	**2020**	2021
Survey Report	1999	2.14	**2020**	2021
Guyang Cave	2006	2.41	**2021**	2022
Dunhuang Art	2002	1.1	**2021**	2021
Yungang Model	2006	1.64	**2022**	2023
Academic History	2008	1.09	**2022**	2022
Cultural Heritage	2007	5.37	**2023**	2025

Figure 4. Keyword burst graph of Chinese grotto studies.

4. Research on the Protection and Restoration of Chinese Grottoes (Past 10 Years)

In the CNKI database, using the search terms "grottoes" & "protection" or "grottoes" & "restoration," a total of 209 articles were retrieved. Through systematic review, the relevant research can be categorized into four main directions: "Research on the Deterioration Mechanisms of Grotto Cultural Relics," "Micro-environment Monitoring and Assessment Techniques for Grottoes," "Research on Homo sapiens Activity Interference," and "Digital Protection Theories and Technologies," accounting for 31.4%, 20.0%, 11.4%, and 37.1% respectively (Figure 5).

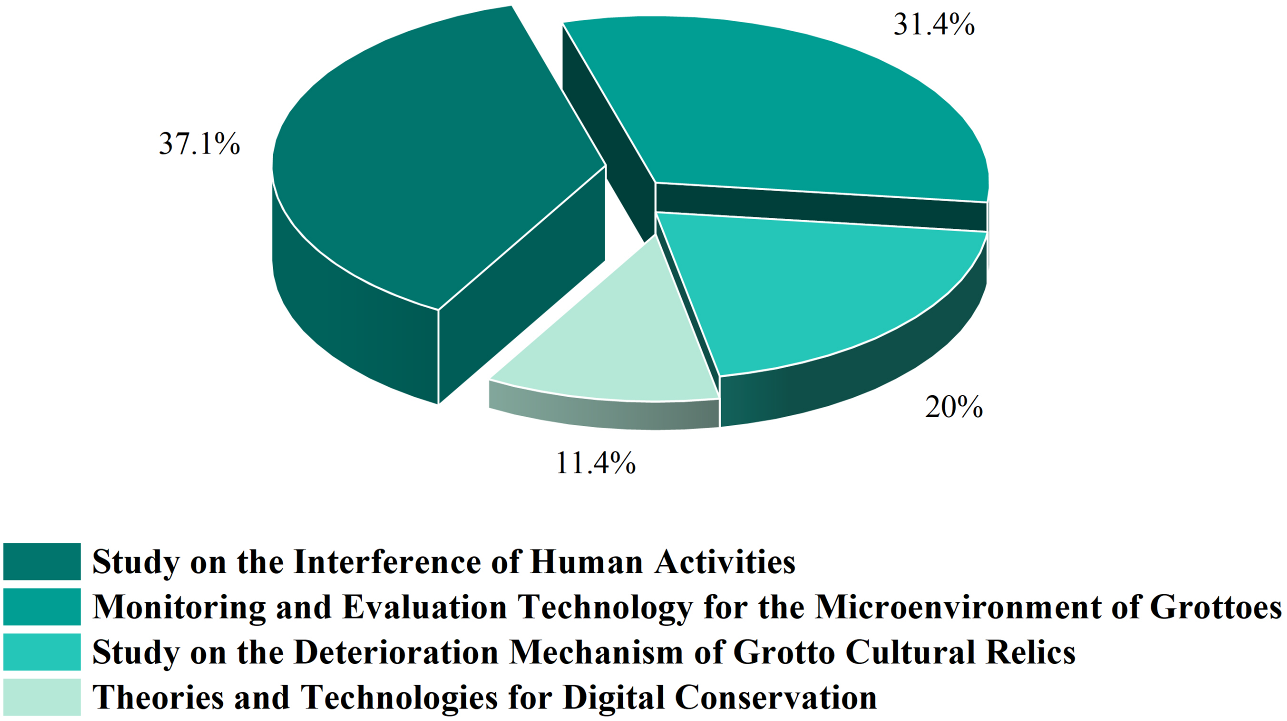


Figure 5. Proportion of research directions in the conservation and restoration of Chinese grottoes.

4.1. Research on the Deterioration Mechanisms of Cave Cultural Relics

Table 2. Causes of deterioration and mitigation strategies for cave temple cultural relics.

Disease type	Causes of formation	Solution strategy
Weathering damage	1. Water Action: Rainwater erosion, capillary water rise, freeze-thaw cycles, condensation water infiltration. [52]-[58] 2. Environmental Action: Temperature fluctuation, wet-dry cycles, wind and sand abrasion. [52] [57] [58] 3. Chemical Action: Acid rain corrosion (from SO_2, NOx), salt crystallization pressure, migration and accumulation of soluble salts. [59]-[62] 4. Biological Effects: Acid production by microbial metabolism, physical damage caused by plant root systems. [52] [58] [59] [63] 5. Material Defects: High rock porosity, susceptibility of cementing materials to dissolution (e.g., clay or calcareous composition), unstable mineral components (e.g., high montmorillonite content). [53] [55] [57]	1. Surface protection: Use permeable reinforcement materials (such as PS materials, silicone resins). [53] [62] [64] 2. Environmental control: Construct cave eaves, install rain shelters, and regulate temperature and humidity inside the caves. [52] [57] [61] [65] 3. Restoration techniques: Structural restoration (e.g., natural hydraulic lime), microbial-induced mineralization repair. [56] [57] [66] 4. Salt damage mitigation: Desalination treatment, control of water and salt migration. [56] [58] [61] 5. Biological control: Physical removal, low-toxicity fungicides. [52] [56] [64]

Continued

Fissure	1. Rock Mass Stress: Gravity, unloading fissures, seismic activity, tectonic movement. [53]-[55] [59] [64] [65] [67] 2. Role of Water: Seepage and piping, frost heave pressure, stress changes induced by wetting-drying cycles. [54] [57] [58] [62] [68] [69] 3. Weathering: Reduction in surface rock mass strength, propagation and connectivity of fissures. [52] [63] [70] 4. Anthropogenic Factors: Engineering vibrations, improper stabilization or support interventions. [56] [59] [69] [71]	1. Grouting Reinforcement: Application of PS grout material, epoxy resin, and metakaolin composite grout using low-pressure grouting techniques. [56] [60] [65] [69] [72] 2. Anchoring Technology: Prestressed anchor rods, BFRP anchor rod reinforcement. [53] [55] [59] [60] [62] [65] [68] 3. Structural Support: Implementation of masonry propping and steel beam support systems. [55] [56] [59] [64] [65] 4. Drainage Measures: Install intercepting ditches, diversion blind ditches. [55] [57]-[59] [61] [67]
Water seepage/water damage	1. Water sources: atmospheric precipitation, groundwater (fissure water, capillary water), condensation water. [55] [56] [58] [59] [62] [64] [68] 2. Pathways: rock mass fissures, pores. [53] [54] [59] [61] [62] [64] 3. Inducing factors: concentrated rainfall, poor drainage systems, failure of the cave roof anti-seepage layer (e.g., cement spraying exacerbates water seepage). [52] [61]-[63] [70]	1. Interception and Drainage: Seal fissures, lay impermeable layers (e.g. GCL waterproof blankets), and construct drainage channels. [57] [58] [61] [73] 2.Cave Dehumidification: Ventilation, use of dehumidifiers, and desiccants. [55] [59] [68] 3. Precise Detection: Employ geophysical methods (e.g., infrared imaging) to trace seepage pathways. [60] [64] [74] 4. Eave Construction: Mitigate direct rainwater erosion. [62] [65]
Biological diseases	1. Microorganisms: Proliferation of bacteria, fungi, and algae in humid environments, which secrete pigments and organic acids. [57] [68] 2. Plants: Penetration of rock masses by root systems of higher plants. [72] 3. Animals: Habitation of birds (causing fecal contamination) and activity of insects. [53] [56] [61] 4. Environment: High humidity and poor ventilation inside the caves, along with the accumulation of organic matter. [57]	1. Physical removal: Mechanical scraping, laser cleaning. [68] 2. Chemical treatment: Spraying disinfectants (e.g. ethanol), applying mildew inhibitors. [56] [68] 3. Environmental management: Improving ventilation and drainage, controlling humidity, installing bird-proof nets. [57] [66] 4. Regular monitoring: Real-time monitoring of temperature, humidity, and microbial activity. [57] [68] [73]
Pollution	1. Anthropogenic pollution: Smoke staining, graffiti, dust accumulation, improper restoration practices (e.g., cement repairs). [52] [53] [56] [58] [62]-[64] [68] 2. Industrial pollution: atmospheric SO_2 and NO_2 forming acid rain. [59] 3. Biological pollution: bird droppings, microbial colonization. [55] [56] [64] 4. Water effects: water seepage carrying pollutants, calcareous crust formation. [53] [59]	1. Cleaning Techniques: Laser cleaning, physical grinding, chemical cleaning (such as sodium hexametaphosphate). [59] [62] [68] [72] 2. Source Control: Regulating industrial emissions, restricting tourist activities. [59] [75] 3. Public Education: Strengthening cultural heritage protection publicity, standardizing tourist behavior. [58] [75] 4. Scientific Restoration: Removing inappropriate restoration materials, adopting compatible materials. [58] [60] [75]

Continued

Salinization damage	1. Sources of soluble salts: groundwater transport, dissolution of rock minerals, atmospheric dust. [57] [58] 2. Migration and crystallization: water and salt migrate to the surface, followed by evaporation and precipitation (e.g., sodium sulfate, sodium chloride). [54] [60] [75] 3. Damage mechanisms: crystallization pressure, hydration pressure (e.g., $Na_2SO_4 \rightarrow Na_2SO_4 \cdot 10H_2O$ with a 314% volume expansion). [62] [72] 4. Environmental triggers: temperature and humidity variations drive wet-dry cycles. [57]	1. Blocking water sources: crack grouting and impermeable layer installation to cut off the sources of water and salt. [65] [68] 2. Environmental control: regulating cave humidity to reduce evaporation. [57] 3. Desalination treatment: surface cleaning and the use of desalination materials. [57] [60] 4. Monitoring and early warning: establishing a monitoring system for water and salt migration. [55]
Structural instability	1. Fracture cutting: Formation of unstable rock masses and separation of rock blocks. [65] [68] 2. Gravity effect: Self-weight of rock masses, stress concentration in overhanging structures. [65] [72] [75] 3. External forces: Earthquakes, floods, debris flows. [71] [75] 4. Water effects: Softening of rock masses, freeze-thaw expansion and contraction, seepage-induced piping. [58] [62] [69] 5. Weathering and degradation: Reduction in rock mass strength. [57]	1. Anchorage reinforcement: Prestressed anchor rods, anchor cable systems. [64] [65] [72] 2. Support Structures: Steel beams, concrete struts. [55] [64] [65] 3. Grouting reinforcement: Fracture grouting to enhance integrity. [69] [70] [76] 4. Unstable rock removal: Elimination of loose rock blocks. [69] 5. Drainage and load reduction: Reduction of water pressure and rock mass load. [76]
Partial detachment	1. Surface weathering: Powdering, flaking, warping. [55] [60] 5. Water-salt interaction: Salt crystallization pressure, freeze-thaw cycles. [69] 3. Stress concentration: Crack tip propagation. [57] 4. Biological erosion: Microbial degradation of cementing materials. [57]	1. Bonding Repair: Use epoxy resin mortar, natural hydraulic lime, and other materials for bonding. [53] [56] [65] [72] 2. Void Grouting: Injection of grouting materials to fill hollow detachment areas behind painted layers or within stone substrates. [62] 3. Edge Reinforcement: Penetrate and reinforce the spalling edges. [62] 4. Surface Sealing: Prevent further spalling. [53]
Anthropogenic damage	1. Improper restoration: Use of incompatible materials such as cement. [52] [53] [62] 2. Theft and vandalism: Cultural relic theft, visitor carvings. [62] [72] 3. Tourism pressure: Visitor touching, elevated carbon dioxide levels. [55] [72] 4. Production activities: Surrounding construction altering hydrogeological conditions. [54] [58]	1. Scientific Restoration: Adhere to the principle of minimal intervention and use compatible materials. [58] [60] 2. Regulatory Enforcement: Strengthen security measures and surveillance systems. [62] [63] [71] 3. Protective Facilities: Install barriers and glass enclosures. [52] 4. Public Participation: Conduct public education and standardize tourism management. [75] 5. Environmental Assessment: Conduct cultural heritage impact assessments before major projects. [75]

Systematic progress has been made in the study of deterioration typology and condition surveys of Chinese grotto temples, leading to the establishment of a comprehensive disease classification system and the accumulation of extensive regional survey data. At the level of mechanistic research, related studies show a deepening trend from macroscopic description to microscopic investigation. For example, micro-analysis techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) have been used to reveal the microscopic mechanisms of material hydration reactions and mural degradation processes, significantly enhancing the scientific understanding of deterioration causes. The specific types and origins of various deterioration phenomena are detailed in **Table 2** below.

However, current research primarily focuses on the physicochemical processes of grotto deterioration, with insufficient exploration of biodeterioration and its coupling mechanisms with abiotic processes. For instance, Xie Qiang [77] monitored multiple indicators including microorganisms but did not delve into the interactions between biotic and abiotic factors; Yang Zhonglin [78] mentioned biological deterioration, yet their emphasis remained on natural and Homo sapiens-induced damage analysis, with protection measures mainly centered on physical reinforcement, failing to systematically elucidate the biotic-abiotic coupling deterioration mechanisms.

4.2. Cave Microenvironment Monitoring Technology

A review of the aforementioned literature reveals that China has employed diverse methods to address the environmental impacts on grottoes. Table X systematically summarizes the various monitoring methods and technologies applied to immovable cultural heritage sites, specifically grottoes and grotto relics, for monitoring multiple key environmental parameters. The table covers temperature and humidity, water content, gaseous pollutants, particulate matter, light radiation, microorganisms, weathering products, salt content, and other environmental factors. It provides detailed listings of the names of various monitoring devices or methods along with their primary advantages and disadvantages. Comparative analysis indicates that while existing monitoring technologies exhibit strengths in aspects such as precision, real-time capability, or *in-situ* testing, they also commonly suffer from limitations such as limited coverage of monitoring points, susceptibility to environmental conditions, reliance on Homo sapiens labor, or potential destructiveness.

Table 3. Types and advantages/disadvantages of cave microenvironment monitoring technologies.

Monitoring subjects	Monitoring methods (techniques)	Advantages and disadvantages
Advantages and disadvantages		
Air temperature, relative humidity	HOBO® U23-001 Temperature and Humidity Monitor [79]	Advantages: High data collection frequency (5 min/time), high precision; Disadvantages: Limited monitoring points, unable to cover all caves.

Continued

	Electronic temperature and humidity recorder (Test0175-H2, HOBO U23-001, etc.) [80]	Advantages: High instrument precision and wide testing range; Disadvantages: Seasonal measurements, which cannot represent the annual situation.
	Advanced Mathematics WS2020 Hygrometer [81]	Advantages: *In-situ* testing with intuitive data; Disadvantages: Manual observation with low frequency.
	Meteorological Monitoring [82]	Advantages: Provides environmental background parameters; Disadvantages: Not directly correlated with cultural relic deterioration.
	Temperature and humidity sensor (model not specified) [83]	Advantages: Reveals the poor microenvironment of Parazacco spilurus subsp. spilurus; Disadvantages: May lack real-time capability.
Wall temperature	OBO UX120-014M Wall Surface Temperature Recorder [55]	Advantages: Comprehensive monitoring indicators; Disadvantages: Limitations exist in the monitoring data.
	Wall Temperature Monitor [84]	Advantages: High prediction accuracy; Disadvantages: The model broussonetia papyrifera requires substantial data support for construction.
Rock body temperature degree	TP3001 Multifunctional Thermometer (Borehole Temperature Measurement) [81]	Advantages: Reveals temperature gradients; Disadvantages: Destructive drilling.
Temperature and humidity inside the mural stratigraphy	iButton DS1923 Miniature Embedded Temperature and Humidity Data Logger [85]	Advantages: Miniaturization, can be embedded in mural strata; Disadvantages: Possible accuracy fluctuations.
Surface temperature of murals	Infrared thermal imager [85]	Advantages: Lossless remote monitoring; Disadvantages: Inability to synchronize continuous monitoring at multiple points.
	Moisture/Water content	
Cliff/rock mass moisture content	MW316GD EX Cultural Relic Body Moisture Content Sensor [86]	Advantages: Multi-sensor collaborative monitoring; Disadvantages: Accuracy is limited under high temperatures.
	Microwave moisture measurement method (hf sensor, Moist 350B) [77]	Advantages: Multi-indicator comparative analysis; Disadvantages: Only reflects the moisture content of the shallow surface layer.
	Microwave Moisture Meter (MOIST 300 B) [87]	Advantages: Non-destructive monitoring of moisture inside rock mass; Disadvantages: Accuracy is affected by the Broussonetia papyrifera in the rock mass.
	NECT H7700SP Infrared Thermal Imager [81]	Advantages: Non-contact, rapid detection; Disadvantages: Affected by meteorological conditions.

Continued

Rock water seepage rate	Rubber-clay surrounding pit seepage experiment [81]	Advantages: Simulating natural conditions; Disadvantages: Small experimental scale.
Condensate water	Coagulation Analysis Calculation Model [83]	Advantages: Assessing moisture hazards; Disadvantages: The model may oversimplify actual conditions.
Gas pollutants		
SO_2, NOx, CO_2 etc.	Internet of Things Environmental Monitoring System (Zigbee Network, Electrochemical Sensors) [88]	Advantages: Full coverage, real-time monitoring; Disadvantages: Large equipment size, high cost.
	KC-120E low-noise TSP sampler, KC-6D atmospheric sampler [82]	Advantages: Long-term monitoring with reliable data; Disadvantages: Single monitoring point.
	Atmospheric pollutant monitoring equipment (TSP sampler, SO_2, NOx, CO analyzer) [89]	Advantages: Provides quantitative pollution data; Disadvantages: Lacks long-term dynamics.
	Based on ZigBee wireless sensor nodes (such as the ZE12 electrochemical module, etc.) [90]	Advantages: Full coverage, real-time monitoring, low cost; Disadvantages: Dependent on network stability.
Particulate matter		
TSP (Total Suspended Particulates)	KC-120E Low-Noise TSP Sampler [82]	Advantages: Long-term monitoring with reliable data; Disadvantages: Single monitoring point.
	Dustfall cylinder [89]	Advantages: Directly reflects the amount of dust settlement; Disadvantages: Does not analyze the composition of dust.
PM_{10}	Laser dust sensor [90]	Advantages: High precision and good stability; Disadvantages: Requires regular calibration.
Light/Radiation		
Illuminance	Illuminometer + Numerical Simulation [91]	Advantages: Combination of field measurements and simulations; Disadvantages: Limited range of illuminance measurement.
Solar radiation	Fully Automatic Weather Station [86]	Advantages: Multi-sensor collaborative monitoring; Disadvantages: Limited representativeness of monitoring points.
Microorganism		
Airborne bacterial concentration	Bioaerosol sampler (Bio-Culture Pump™) cultured with R2A medium [92]	Advantages: Traditional cultivation methods are reliable; Disadvantages: Only culturable microorganisms can be detected.
Bacterial community structure	Molecular biology techniques (16S rRNA gene sequencing) [92]	Advantages: Accurate identification of bacterial species; Disadvantages: Dependent on pre-cultivation steps.
Weathering products		

Continued

Weight of weathering products	High-precision electronic balance (BSM-200.4) [79]	Advantages: Precise weighing; Disadvantages: Non-real-time monitoring.
Weathering type	Field investigation and laboratory analysis (camera, microscope, X-ray diffraction, etc.) [89]	Advantages: Intuitive identification of weathering types; Disadvantages: Strong subjectivity, lack of quantitative data.
Sand fall volume	Sand dropping measurement method [77]	Advantages: The method is intuitive; Disadvantages: Temporary shelters may interfere with long-term monitoring.
	Salinity	
Soluble salt ion content	Ion chromatograph (ICS-90) [79]	Advantages: Laboratory analysis is accurate; Disadvantages: Destructive sampling.
	Analysis of Soluble Salt Ions [81]	Advantages: Identifies sources of salt damage; Disadvantages: Limited sampling points.
	Other environmental parameters	
Pore gas pressure	Mack MPM-430 Cavity-Free Micro-Pressure Pressure Transmitter [86]	Advantages: Multi-sensor collaborative monitoring; Disadvantages: Limited representativeness of monitoring points.
Atmospheric pressure	BaroSCOUT atmospheric pressure sensor [79]	Advantages: Assists in water level calculation; Disadvantages: Requires coordination with other sensors for use.
Wind speed, wind direction, rainfall, etc.	Fully automated weather station [86]	Advantages: Multi-sensor collaborative monitoring; Disadvantages: Limited representativeness of monitoring points.

Based on a systematic review of various micro-environmental monitoring technologies for cave temples (**Table 3**), and combined with their practical application feedback in real conservation scenarios, the following critical assessment of their practical effectiveness and core limitations can be condensed:

In terms of temperature and humidity monitoring, electronic data loggers such as the HOBO® U23-001 can provide high-frequency, high-precision data at single points, making them suitable for long-term tracking at key locations. However, their sparse deployment leads to severely insufficient spatial representativeness, making it difficult to characterize the complex thermal and moisture gradients within caves. Wireless Sensor Networks (e.g., Zigbee) enable multi-point coverage but are constrained by network stability and device power consumption, posing challenges for deployment and maintenance in remote environments like mountain cave temples.

In the field of moisture monitoring, microwave moisture measurement (e.g., MOIST 300B) offers the theoretical advantage of non-destructive detection of moisture within rock masses. However, its signal accuracy is highly susceptible to interference from the pore structure and mineral composition of the rock, leading to significantly reduced reliability in argillaceous rocks or those with high montmorillonite content. While infrared thermography can rapidly screen for surface moisture anomalies, it is extremely sensitive to ambient conditions like temperature, humidity, and wind speed. It cannot quantitatively reflect deep moisture content and struggles to differentiate between condensation water and seepage sources.

Regarding gas and particulate matter monitoring, electrochemical sensors (e.g., ZE12 modules) and TSP samplers can accurately capture pollutant concentrations. However, monitoring is often limited to "concentration recording," lacking dynamic correlation with deterioration processes such as surface weathering rates and microbial activity on cave surfaces. The data also fail to effectively support pollutant source analysis, unable to distinguish between contributions from local human emissions, regional transport, or metabolic activities of organisms within the caves, resulting in insufficiently targeted mitigation measures.

Concerning microbial monitoring, traditional cultivation methods (e.g., bioaerosol samplers) can capture less than 1% of cultivable microorganisms, severely underestimating community diversity. Although molecular biology techniques (e.g., 16S rRNA sequencing) can comprehensively analyze species composition, they often stop at a "species inventory." They fail to deeply integrate with microbial metabolic functions (e.g., acid production, biomineralization) and their mechanistic roles in specific deterioration phenomena (e.g., powdering, pigment flaking), leading to a disconnect in the data application chain.

For monitoring salts and weathering products, laboratory methods like Ion Chromatography (ICS-90) offer high precision but rely on destructive sampling. They cannot achieve *in-situ* continuous observation and cannot capture the dynamic migration and crystallization processes of salts during wet-dry cycles. Portable field devices (e.g., XRF) are significantly affected by surface roughness and humidity, resulting in poor data repeatability and comparability, which makes it difficult to meet the stability requirements for long-term monitoring.

At the level of intelligence and integration, although technologies like the Internet of Things (IoT) and wireless sensing have seen preliminary application, existing systems generally exist as "data silos." They lack cross-parameter, cross-spatiotemporal data fusion and intelligent analysis capabilities. Monitoring largely remains at the "post-event recording" stage, failing to advance towards early-diagnosis models for deterioration risks (based on machine learning), early warning models for condensation or salt damage, or decision support systems for mitigation. This results in a serious disconnect between "monitoring" and "conservation intervention."

In summary, the current technological system for monitoring the micro-environments of cave temples shows continuous refinement at the "point" level but lacks systematic integration at the "surface" level, dynamic tracking of "processes," and intelligent decision support in "application." Future breakthroughs lie in promoting technological integration (building air-ground-cave integrated sensor networks), process-oriented monitoring (enabling synchronous time-series observation of multiple parameters like water, salt, and microbes), and platform intelligence (developing early-warning and mitigation platforms based on digital twins and artificial intelligence), thereby truly supporting a closed-loop decision-making process for preventive conservation.

4.3. Anthropogenic Impact Studies

Through a review of relevant literature, the impact of human activities on the preservation of grottoes can be summarized into two main aspects: first, directly altering the micro-environment and rock mass stability of the grottoes, such as industrial and transportation activities disrupting the water–heat–gas balance, exacerbating salt damage, chemical corrosion, and structural destabilization; second, triggering biological responses through the introduction of substances and environmental disturbances, such as tourist and management activities promoting microbial proliferation and animal habitation, leading to the superposition of risks from biological erosion and chemical degradation.

The direct impacts of anthropogenic activities on the microclimate and rock mass stability of grottoes are primarily manifested in the following four aspects:

Industrial Activities: Industrial emissions, engineering blasting, and excessive groundwater extraction alter the hydrothermal conditions and stress distribution of the surrounding rock mass, inducing acidic chemical corrosion, accelerating the development of rock fractures, and causing dehydration-induced cracking and intensified salt damage due to declining groundwater levels [53] [93] [94].

Agricultural Activities: Flood irrigation leads to persistent water infiltration into the grotto cliffs, significantly increasing humidity within the caves and disrupting the original dry environment. This activates soluble salts in the rock mass and murals, triggering typical deterioration phenomena such as hollow bulging and salt efflorescence through repeated dissolution-crystallization cycles [62].

Transportation: Sulfur oxides, nitrogen oxides, and dust emitted by vehicles diffuse into the grotto area, altering local atmospheric composition. The resulting acidic precipitation and condensation chemically erode sculpted surfaces, leading to the loss of artistic details [95].

Religious Activities: Acidic gases and carbonaceous smoke released by incense burning adsorb moisture to form electrolytic solutions that corrode calcareous cement in the stone matrix. Combined with salts and dust, they form tenacious soot crusts that accelerate weathering and surface exfoliation [61].

Anthropogenic activities, through material input and environmental changes, trigger biological responses primarily manifested in the following aspects: (1) Visitor and resident activities: Tourists carry microorganisms, and their respiration and elevated body temperature increase the humidity and temperature inside the caves, creating favorable conditions for the growth of molds, algae, etc., and attracting birds and insects to inhabit. Related excretions, metabolic acids, and nests collectively cause mechanical blockage and chemical corrosion on the walls, exacerbating damage such as powdering and flaking [56] [94]. (2) Surrounding production and living emissions: Industrial and mining coal combustion, as well as agricultural and pastoral activities, release sulfur-containing pollutants and organic waste, providing nutrients for microorganisms such as Thiobacillus, promoting the frequent proliferation of acidophilic microbial communities. Microbial metabolism converts sulfur-containing substances into strong acids, leading to acid etching of rock masses, resulting in rock loosening, dissolution, and accelerated weathering [53].

4.4. Digital Preservation Theory and Technology

With the deep integration of information technology into the field of grotto conservation, digitization has become a core strategy for addressing the risks of cultural relic aging and achieving permanent archiving and dynamic inheritance. The current technological approaches can be summarized into the following six methodological systems:

(1) 3D Digitization and Modeling Reconstruction: Utilizing technologies such as 3D laser scanning, photogrammetry, and unmanned aerial vehicles, systematically capturing geometric and texture data of grottoes, constructing high-precision digital models, and achieving holographic documentation from overall structures to detailed features, thereby establishing an accurate spatial benchmark for conservation, restoration, and monitoring research [31] [96]-[100].

(2) Virtual Restoration and Reconstruction: Employing technologies such as generative adversarial networks, spectral analysis, and 3D printing to digitally repair and virtually reconstruct damaged murals and fragmented statues. Based on scientific analysis of pigment composition and structural characteristics, this enables stylistically consistent and evidence-based digital reconstructions while providing physical replicas for educational display [101]-[105].

(3) Digital Archiving and Management: Leveraging big data, cloud computing, and distributed storage technologies to establish standardized digital repositories and intelligent management platforms. This facilitates secure storage, efficient retrieval, and systematic management of massive cultural relic datasets, supporting the permanent preservation and tiered sharing of heritage information [2] [106]-[108].

(4) Physical Replication and Texture Reproduction: Using 3D printing and color restoration techniques to create high-fidelity replicas of grotto caves, statues, and murals. This addresses the challenge of relocating immovable cultural relics while preserving the material texture and color gradation of the originals in replicas, thereby expanding exhibition formats and public engagement opportunities [98] [99] [109]-[111].

(5) Digital Display and Immersive Experience: Combining VR/AR, digital cultural creativity, and interactive media to construct perceptible and interactive digital cultural spaces. This transcends physical visitation constraints, enhances public participation and cultural identity, and promotes innovative dissemination of grotto art in contemporary contexts [112]-[115].

(6) Intelligent Monitoring and Regulation: Relying on LOT, wide-area network

transmission, and automated control technologies to enable real-time monitoring, data analysis, and intelligent regulation of grotto micro-environments and structural conditions. This establishes a preventive conservation loop integrating "perception-warning-intervention," enhancing proactive and precise risk response capabilities for grotto conservation [116]-[118].

5. Research Limitations and Problem Examination

Although China has made significant progress in both theoretical and practical aspects of grotto cultural heritage conservation research, particularly accumulating abundant achievements in deterioration mechanisms, micro-environment monitoring, and digital preservation, a systematic review and bibliometric analysis using Citespace still reveal several critical gaps and urgent research needs that require attention in current studies. These are specifically reflected in the following aspects:

(1) The research perspective remains "fragmented," lacking systematic and holistic integration.

Current studies predominantly focus on single disease types, localized environmental factors, or specific technological approaches. While these have yielded in-depth insights at the micro level, they have failed to effectively establish a systematic research framework for rock mass deterioration under the coupled effects of "environmental drivers—biological responses—anthropogenic disturbance." The deterioration of grottoes often results from nonlinear interactions among multiple factors:

Taking the study of the North Grottoes Temple as an example [119], the findings clearly reveal the multi-layered and dynamic interactions between environmental and biological factors. The research confirms that the increase in relative humidity inside the caves (e.g., after the construction of protective shelters) directly promotes the proliferation and metabolic activity of insects and microbial communities on sandstone surfaces. The organic acids secreted by microorganisms accelerate the dissolution of sandstone cement, while the biofilms they form alter the physical properties of the rock surface, collectively establishing a "humidity-driven—bioactivation—accelerated corrosion" coupling cycle. Furthermore, water infiltration and soluble salt migration not only cause physical crystallization damage but also create microhabitats for halophilic microorganisms. Microbial metabolism, in turn, modifies the local chemical environment, influencing the crystallization process and destructive effects of salts, forming a chain reaction intertwined with water-salt transport and biological activity. Notably, external interventions aimed at blocking rainwater (e.g., constructing rain shelters) alter the existing ventilation and drying processes within the caves, potentially leading to microenvironmental reorganization, disrupting the original microbial ecological balance, and triggering new dominant microbial populations and unknown bioerosion risks. This case highlights that analyzing and intervening by isolating environmental and biological factors will make it difficult to comprehensively assess disease mechanisms and may even lead to unintended conservation-induced damage.

Taking the Wanqing Temple Grottoes as an example [17], the study specifically reveals the dynamic coupling between environmental and biological factors: The primary joints and unloading fractures in the grotto rock mass provide initial growth space and water channels for plant roots. For instance, the roots of cypress trees on the southern wall of Cave No. 1 grow downward along fractures, with their physical wedging action continuously expanding the fissures, ultimately leading to the fragmentation of the "V"-shaped rock mass and forming a typical cycle of "fracture—root expansion—rock deterioration." This mechanism further triggers a systemic amplification effect: root penetration alters local water movement, potentially activating the migration of deep soluble salts and creating a humid environment for microbial proliferation. The organic acids and other substances produced by microbial metabolism then weaken the cementation around the fractures, forming a chain-reaction network from macroscopic mechanical damage to microscopic chemical corrosion.

As a complete "geology-ecology-culture" complex, the deterioration process of grottoes is often the result of the interaction of multiple factors. However, current research has not yet established a systematic methodology for the holistic protection of grotto cultural relics, lacking integrated studies across scales and multiple processes. Therefore, based on the findings from the aforementioned literature, the interaction mechanisms among these factors are inferred as shown in **Figure 6** below.

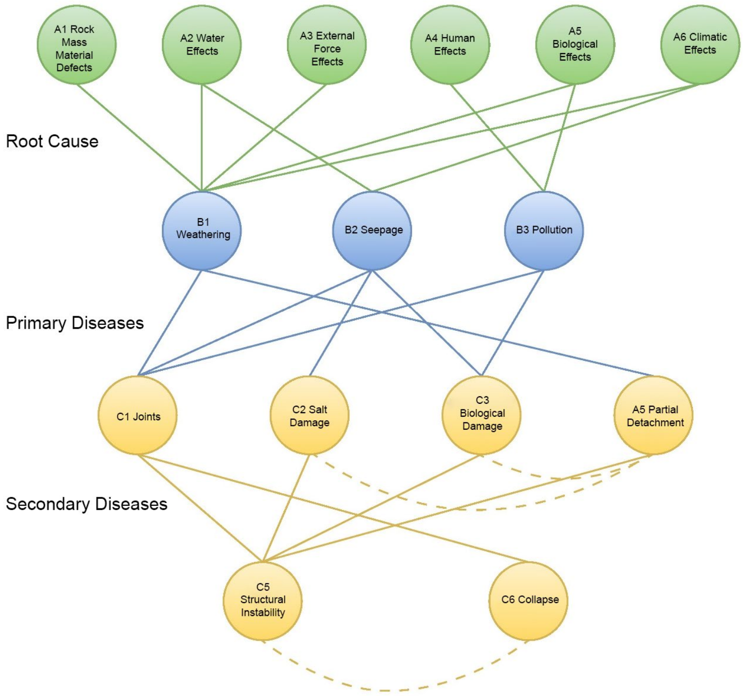


Figure 6. "Environmental drivers-Biological responses-anthropogenic as disturbance" multi-factor coupling mechanism diagram of disease and deterioration in grotto relics.

(2) Interdisciplinary integration remains superficial, lacking deep technical pathways for convergence. Although multidisciplinary technologies such as conservation science, materials science, microbiology, and geographic information science have been introduced into the field of cave conservation, their application still exhibits a "technology stacking" characteristic, lacking deep integration at both theoretical and methodological levels. For instance, the coupling mechanism between microbial communities and rock weathering processes, as well as the application of intelligent algorithms in disease prediction, have yet to form a systematic technical framework and evaluation standards.

(3) Despite the diversity of monitoring technologies, there is a deficiency in intelligence and predictive capabilities. Although current environmental and disease monitoring methods are increasingly varied, they predominantly rely on "post-event responses" and lack the ability to predict and regulate the future state of grottoes. Most monitoring systems have yet to achieve data-driven intelligent diagnosis, risk warning, and adaptive regulation, particularly in the face of dynamic external stressors such as climate change and tourism pressure. There is a lack of long-term trend analysis and decision support tools based on big data.

(4) The transformation of digital preservation outcomes and the development of standardization are lagging. Despite the widespread application of technologies such as 3D modeling, virtual restoration, and digital twins, their practical effectiveness in conservation projects, data sharing mechanisms, and technical standard systems remain inadequate. How digital outcomes can effectively support the entire process of "diagnosis-intervention-evaluation" for physical cultural heritage has not yet formed a closed loop.

Future research should focus on breaking through the current "fragmented" limitations, promoting a paradigm shift in cave temple conservation from "dispersed exploration" to a systematic approach characterized by "holistic correlation," and gradually establishing a comprehensive technical system integrating "mechanism elucidation—intelligent prediction—precise regulation—collaborative operation and maintenance." Key tasks include: establishing a systematic research framework for multi-factor coupling to unravel the complex mechanisms of cave deterioration; bridging interdisciplinary methodological chains to develop integrated technological pathways for processes such as microbial activity and rock weathering; upgrading monitoring systems to develop intelligent disease diagnosis, risk warning, and adaptive regulation platforms based on big data and artificial intelligence; promoting the standardization, sharing, and engineering application of digital conservation outcomes, and establishing their role throughout the entire process of "diagnosis—intervention—evaluation." Through systematic integration and path innovation, the ultimate goal is to drive a fundamental transformation in cave temple conservation toward a "preventive, precise, and sustainable" model.

6. Conclusions

Based on a systematic review of domestic and international research literature on the conservation of cave temples and a visual analysis using CiteSpace, this review employs CiteSpace to reveal the developmental trajectory of the field from empirical and qualitative approaches to scientific and quantitative methods, the evolution of research hotspots, and interdisciplinary characteristics. The study indicates that cave temple conservation in China has established a research framework centered on "deterioration mechanisms—microenvironment monitoring—digital conservation—human impact factors," achieving significant progress in material development, disease diagnosis, and 3D reconstruction. Keyword burst analysis further demonstrates that research focus has gradually expanded from early single engineering technical issues to systemic topics such as the recognition of cultural heritage value, digital inheritance, and preventive conservation.

However, current research still exhibits a pronounced "fragmentation" tendency, with most findings lacking a holistic grasp of the multifactorial coupling mechanisms involving "environment–organism–human interactions"; interdisciplinary integration remains at the level of technical stacking, without achieving deep theoretical and methodological consolidation; although monitoring systems are increasingly refined, the capabilities for intelligent diagnosis, prediction, and regulation remain weak; digital preservation outcomes also lag in standardization, sharing, and engineering transformation.

In the future, research on the conservation of cave temple cultural relics should further emphasize a holistic perspective and systems thinking, promoting a paradigm shift from "fragmented interventions" to "integrated regulation." Key tasks include: establishing a systematic research framework for multi-factor coupling, deepening interdisciplinary exploration in areas such as microorganism-rock mass and artifact interactions; developing intelligent monitoring and early warning platforms based on artificial intelligence to enhance the foresight and precision of conservation efforts; promoting the standardization of digital outcomes and the closed-loop application in engineering, achieving full-process support from "data-decision-intervention-evaluation." Only through deep interdisciplinary integration and innovation in technological pathways can the conservation of cave temple cultural relics achieve a fundamental transformation from "emergency restoration" to "preventive, precise, and sustainable" approaches, providing solid scientific and technological support for the perpetual preservation and revitalization of China's cave temple heritage.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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