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Analyzing the ecologicality and functionality of kiln architecture in China through KH coder data mining algorithm and hierarchical event coding

Runze Liu[1,5], Xiang Wang[2,5], Lin Yuan[2]✉, Yunting Gao[3], Yan Zhang[2], Mengsi Yang[2] & Weicong Li[4]

Recent studies focused on the ecological characteristics, heritage conservation, and economic benefits of kiln architecture, with most studies emphasizing structural analysis while neglecting the interaction mechanisms between architecture and ecological environment. Based on constructing ecologicality-architecture-cultural resilience theory, this study analyzes the structural features, ecological technologies, and conservation status of kiln architecture across various regions in China through KH Coder data mining and hierarchical event coding method and proposes a new protective framework. Findings: (1) Kiln architecture has evolved from built-against-the-mountain to semi-buried, fully-buried, reinforced earth-covered, and independent forms, as functional demands have changed from hazard avoidance to climate adaptability, functional expansion, and energy-saving design; (2) Climate, topography, and soil conditions are key factors driving the emergence of built-against-the-mountain, along-the-valley, sunken courtyard, and independent kiln architecture types; (3) Geological characteristics and material availability significantly shape the vaulted structural features of kiln architecture across different regions. Cultural archaeology and technological advancement have formed the main trajectory of cave dwelling environment development, promoting functional transformation and ecological planning. Meanwhile, political-oriented have acted as a secondary trajectory, advancing the standardization of construction techniques. The results confirm the decisive role of the natural environment in shaping the forms and variations of kiln architecture.

Keywords Ecologicality-architecture-resilience, China kiln architecture, Hierarchical event coding method (HECM), KH coder, Building structure and technology, Protective framework

Background of research

Kiln architecture represents a distinctive form of traditional building and serves as a model for sustainable environmental design. Kiln architecture and cave dwellings both rely on topographical features for construction, yet they have followed distinct evolutionary paths in terms of function and architectural form[1]. As one of the earliest human habitation types, cave dwellings are primarily found in mountainous, hilly, or river valley regions, utilizing natural caves or manually excavated spaces—some of which later evolved into semi-subterranean forms. Kiln architecture can be viewed as a further development of this typology, particularly during the Ming and Qing dynasties, when the stable loess soil of China's Loess Plateau enabled the widespread construction of arched kilns. These structures manifested in various forms—mountain-adjacent, freestanding, and sunken types—each adapted to specific geographical contexts. The integration of modern construction techniques has enhanced the structural safety and residential comfort of kiln architecture, rendering it a representative example of the synthesis between traditional and contemporary architectural practices.

[1]College of Environment and Architectural Arts, Tianjin Academy of Fine Arts, Tianjin 300143, China. [2]School of Architecture and Art, North China University of Technology, Beijing 100144, China. [3]School of Art, Southeast University, Nanjing 211189, China. [4]Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Skudai, 81310 Johor Bahru, Johor, Malaysia. [5]Runze Liu and Xiang Wang contributed equally to this work. ✉email: yuan-lin@ncut.edu.cn

The intensification of ecological pressures and accelerated modernization have exacerbated conflicts between its preservation and ecological development[2]. Existing studies primarily focus on structural durability and cultural heritage transmission but largely overlook the multi-dimensional interactions between ecological adaptation and resilience[3]. This oversight results in conservation strategies that lack regional adaptability. Moreover, the long-term and dynamic aspects of conserving such structures remain underexplored, with few established dynamic collaborative conservation model.

The research on kiln architecture has transitioned through various perspectives: from material conservation to cultural excavation to ecological development[4]. Since the adoption of UNESCO's Convention Concerning the Protection of the World Cultural and Natural Heritage in 1972, the protection of eco-architecture has become a global consensus[5]. Italy's Cultural Heritage and Landscape Law (2004) underscores the need to balance ecological and cultural dimensions in heritage conservation[6]. Similarly, China's Traditional Village Survey Notice (2012) advocates for integrated development principles for kiln architecture[7]. However, the absence of detailed local implementation guidelines and long-term planning undermines policy execution[8].

Several scholars have proposed innovative solutions for the digital preservation of clay buildings[9], reinforcement methods for traditional brick-and-earth construction materials[10], the iteration and biodegradability of log-based construction materials[11], and AI-driven data restoration[12]. These contributions provide theoretical and practical support for the sustainable preservation of earthen architecture, the enhancement of traditional materials, and the innovation of new building materials. However, traditional kiln architectures continue to face several challenges during their preservation, renewal, and development processes[13,14]: (1) Kiln architectural materials, long exposed to natural environments, are prone to aging, and existing restoration technologies struggle to restore their original physical properties, leading to structural instability; (2) The conflict between modern building technologies and traditional craftsmanship makes it difficult to preserve the cultural characteristics of the buildings while meeting modern demands during the restoration process, thus affecting the effectiveness of preservation; (3) Traditional kiln architectures struggle to adapt to contemporary social and cultural contexts, particularly in the face of population migration, changes in land use, and climate change, which threatens their functionality and habitability.

Literature review

This study conducted a search on Google Scholar, identifying 114 articles that include the keywords "kiln building" (107), "kiln architecture" (4), and "kiln dwellings" (3) in their titles. Similarly, this study retrieved relevant literature from the China National Knowledge Infrastructure (CNKI) database. A total of 235 records were identified with the term "窑洞" (kiln dwellings) in the titles, including 105 journal articles, 112 theses, and 18 conference proceedings. Among them, 176 publications fall under the category of "Architecture Science and Engineering," yet only a limited number address the integration of cultural landscapes and ecological technologies. Notably, 55 studies focus on vernacular housing and modernization-oriented design, while only 17 concentrate on construction technologies specific to the Loess Plateau and northern Shaanxi region. This indicates a relative scarcity of research on kiln architecture in northern Shaanxi, underscoring the significance of the present study. Moreover, the annual number of publications has declined from 28 in 2017 to 13 in 2024, reflecting a diminishing academic focus on this architectural typology.

Based on an examination of the titles, these articles can be categorized into the following four primary research themes: (1) Exploring how modern technology can effectively protect the cultural symbols of kiln architecture and ensure its preservation as a traditional cultural heritage; (2) Analyzing the adaptive mechanisms of kiln architecture under different climatic conditions and examining its environmental friendliness within sustainable building practices; (3) Investigating the structural optimization of kiln architecture and the potential for material substitution, with the aim of enhancing its durability and functionality; (4) Analyzing how to modernize the functions of traditional kiln architecture while preserving its heritage to meet contemporary residential and commercial needs.

In natural protection, Manzano-Fernández et al.[15] report that 56% of interventions in earthen architecture demonstrate successful conservation outcomes, particularly those utilizing local materials. Additionally, 75% of cases highlight effective protection of cultural landscapes, and 86% foster sustainable community activities. Mileto et al.[16] show that renovation using natural materials in the renovation of Segesgar kiln architecture reduced environmental impact by 50–80%. Nikolić et al.[17] demonstrate that mortar combining crushed natural brick and ground materials performed effectively in the walls of the Roman Viminacium kiln architecture. Meanwhile, Manzano-Fernández et al.[14] identified 170 earthen heritage sites with varying preservation statuses: 51% were used for cultural or exhibition purposes, 24% were buried or concealed, and 10% faced destruction due to geographical limitations or lack of conservation measures. Wu[18] employed the Post-Occupancy Evaluation (POE) method to develop an assessment framework, identifying limitations in the functionality and cultural engagement of ceramic cultural spaces. The study proposed strategies including spatial optimization, policy support, and community participation to enhance the practical feasibility of heritage conservation. Peng[19], utilizing TF-IDF text analysis and knowledge graph construction, introduced a digital technology-based framework for the systematic organization of heritage information. Through visualization tools, the study aimed to improve the management, dissemination, and commercial potential of Hakka architectural heritage, emphasizing applications in digital preservation and intelligent Q&A systems. Xiang et al.[20], drawing on spatial gene theory, established a spatial gene information chain for Yangjiagou Village, systematically identifying its informational elements, chains, and morphological characteristics. Based on this framework, the authors proposed a preservation and utilization model to advance the understanding of spatial genetic patterns in traditional kiln architecture settlements in northern Shaanxi. Wang and Zhang[21], guided by the concept of human-water symbiosis, examined traditional water management wisdom in northern Shaanxi kiln architecture settlements. Focusing on site selection, residential construction, agricultural production, and ecological governance, they developed a "storage–guidance" water management system. This model, they argue, enhances settlement planning, improves soil and water conservation, optimizes agricultural conditions, and strengthens ecosystem resilience, thereby offering practical guidance for sustainable development in the region.

In artificial development, Yin et al.[9] validated the feasibility of digital clay construction techniques for large-scale production, showcasing the potential of modern methods (e.g., rammed earth technology and drone spraying) in enhancing efficiency and reducing costs. Lehtonen et al.[11] highlighted Finland's increasing use of wood-based architecture in large public projects, emphasizing its dual role in environmental sustainability and carbon storage. Fratini et al.[10] compared the physical properties of two minerals (sasso alberese and sasso porcino) for earthen building restoration, revealing that the former's high calcite content made it ideal for restoration, while the latter suited hydraulic lime production. In the Santa Ana Chapatillo community, González-Sánchez et al.[22] significantly improved the appearance of traditional earthen walls using VOG-mixed materials. Qiu[23], through historical investigation and landscape planning analysis, emphasized the spatial rationality of heritage site layout and proposed a five-zone functional division to balance cultural display, environmental conservation, and recreational use, highlighting the revitalization and adaptive reuse of heritage assets. Zhu and Lai[24] examined the kiln architecture workshop of the Shenxin Spinning Mill in Baoji, integrating traditional architectural forms with industrial plant design. They utilized local materials and low-tech construction methods to optimize structural stability, ventilation, and dust removal systems, thereby improving the production environment and efficiency. While the study reveals the adaptive technologies used in wartime industrial architecture, it prioritizes economic factors while overlooking cultural and ecological dimensions. Li[25] proposed a sustainable renovation model for semi-subterranean kiln dwellings, integrating loess-specific geotechnical characteristics with modern construction techniques such as glass domes, vegetation layering, and rainwater harvesting systems. The approach enhances natural lighting, ventilation, and thermal insulation, improving environmental quality and offering a viable architectural strategy for economically underdeveloped regions. Qin et al.[26], employing field sampling, numerical simulation, and strength reduction methods, investigated the failure mechanisms of subgrade structures underlying kiln architecture. The study established safety standards and proposed six mitigation strategies to support the construction of the Sanxi Expressway. However, the influence of complex joint systems was not considered, and further refinement of stability analysis and protective measures was recommended.

In heritage site management and analysis, scholars have increasingly employed social media data to uncover public perceptions of cultural heritage, identify management challenges, and explore pathways toward sustainable development, thereby providing scientific support for the conservation and revitalization of heritage sites. Guo et al.[27], through semantic analysis and grounded theory, investigated tourist perceptions of both historic and replica ancient towns, emphasizing the critical role of authenticity in cultural heritage. They further suggested that replica towns should rely on modern design and cultural reinterpretation to enhance attractiveness and facilitate the dynamic transmission of heritage values. Özen[28], using textual sentiment analysis, examined visitor reviews of the Cappadocia rock-cut landscape and found that while tourists expressed concern for cultural heritage preservation, they also voiced criticism regarding tourism infrastructure and environmental management, underscoring the urgent need for integrated conservation and sustainable development. In the domain of architectural heritage and cultural transformation, Li et al.[29] applied word frequency statistics and classification methods to analyze the stylistic evolution of ancestral temple murals, revealing their transformation in response to economic development and ritual change, and underscoring the importance of murals as cultural assets requiring active preservation. This aligns with the study by Zhang et al.[30], which employed co-occurrence network analysis combined with cultural geography to examine the spatial restructuring of Lingnan ancestral halls, highlighting the adaptive strategies and preservation challenges faced by architectural heritage under the influence of political, economic, and cultural forces. Mouraz et al.[31] used GIS and data mining to analyze rural architectural clusters in Portugal and Spain, identifying spatial distribution patterns and evolutionary logic through outlier detection. Their findings complement Zhang et al.[30] by further emphasizing the adaptability of cultural heritage within pluralistic social contexts and the necessity of systematic conservation approaches. Additionally, Ma[32], through cognitive map construction and semantic text analysis, proposed innovative perspectives on the holistic protection of Red culture resources by reconstructing their spatial information through data visualization, although the practical effectiveness of such methods remains to be validated.

These studies on kiln architecture underscore its ecological characteristics, heritage conservation, and the role of modernization in balancing preservation and economic benefits. However, they raise two critical issues. How can a balance be achieved between preserving traditional kiln architecture and promoting ecological sustainability? How can a dynamic conservation strategy be constructed to align with regional cultural characteristics? Although some scholars have explored these aspects, their focus on single-dimensional protection often neglects the adaptive interplay between kiln architecture and its ecological environment. A systematic conservation framework remains absent. This is what makes this study so valuable.

Research aim and objectives

This study aims to analyze the ecological technologies, environmental characteristics, and conservation status of kiln architecture. First, the KH Coder data mining algorithm and hierarchical event coding method (HECM) are employed to analyze the cultural origins and development context of China's kiln-built environment. Second, the ecological technologies, functional characteristics, and conservation status of kiln architectures across different regions of China are examined. From the perspective of "ecologicality-architecture-resilience," this study innovatively proposes a conservation strategy framework for such built environments. The study asserts that the natural environment of different regions determines the form and diversity of kiln architecture, while the introduction of modern technology imparts common features. The findings contribute to Goal 15 of the 17

No.	Concept	Methodology
1	Dynamic interactivity: Emphasizes the nonlinear dynamic relationship between ecological and cultural systems, focusing on the long-term interactions between architecture and the natural environment	Contextual analysis: Combines historical articles and field investigations to evaluate the dynamic roles and evolutionary trajectories of kiln architecture within ecological and cultural systems
2	Multidimensional adaptability: Proposes that architectural conservation should address both environmental adaptability and diverse social demands, avoiding single-dimensional design or management approaches	System modeling approach: Utilizes event-relationship coding to analyze overall development trajectories, revealing how environmental changes influence architectural functions and cultural values
3	Resilience and robustness: Enhances the redundancy and resilience of architecture to external disturbances by diversifying its functions and enriching its cultural value	Interdisciplinary integration: Merges methodologies from ecology, architecture, and sociology to comprehensively interpret the ecological adaptability and cultural significance of kiln architecture
4	Environmental embeddedness: Advocates for architectural preservation and development to be contextually integrated within natural and cultural settings, prioritizing the symbiotic relationship between buildings and their surrounding ecosystems	Digital conservation: Introduces digital monitoring tools, such as drone imagery and environmental sensors, to dynamically track the physical condition and ecological changes of kiln architecture
5	Cultural sustainability: Highlights the synergy between technological innovation and cultural heritage preservation, leveraging digital technologies to optimize the functionality and sustainability of traditional architecture	Participatory design: Encourages public engagement and stakeholder collaboration to develop conservation and development strategies that align with regional characteristics and community needs, fostering cultural heritage preservation and community growth

Table 1. Ecologicality-cultural resilience theory, methodology and analytical framework.

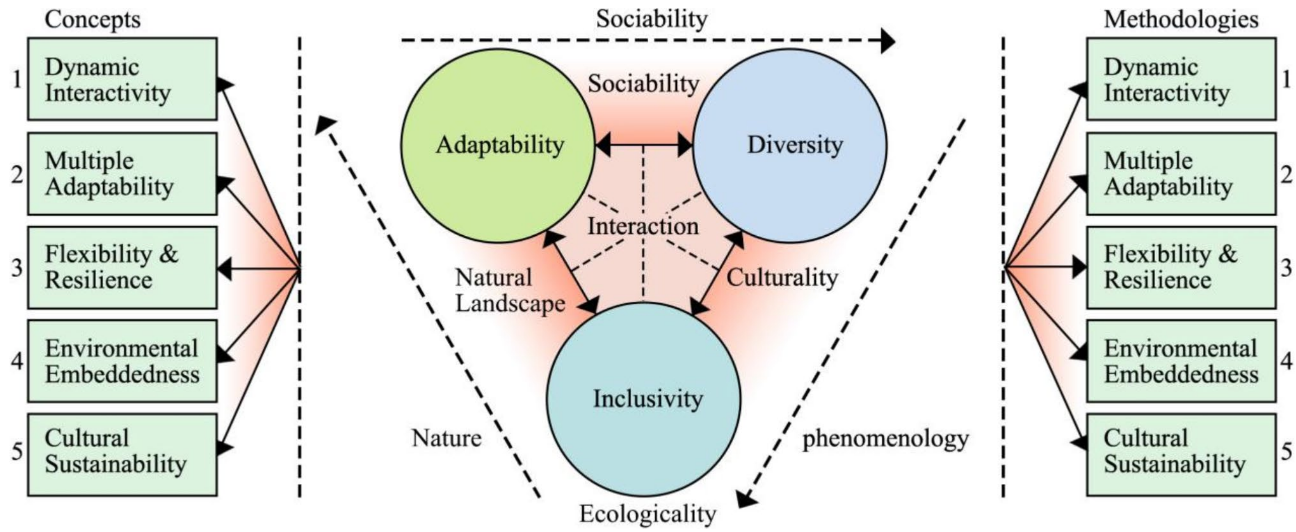


Fig. 1. Ecologicality-cultural resilience theory and methodological framework.

Sustainable Development Goals, which addresses terrestrial ecosystems, providing both theoretical foundations and practical guidance for the conservation of kiln-built environments.

Methodology

Ecologicality-cultural resilience theoretical framework

In, 1906, Kerby and Mallinger[33] first introduced the concept of "ecological resilience," which aimed to describe an ecosystem's ability to recover from external disturbances. Farina[34] expanded this theory to the social domain, proposing "social-ecological resilience" and "cultural resilience," emphasizing adaptability, diversity, and inclusivity as core elements of resilience. According to the World Heritage Convention and its associated frameworks issued by UNESCO[35], the adaptive synergy between cultural landscapes and the natural environment has been emphasized through the proposed coupling of Cultural Heritage and Ecosystem Services (CHES). This conceptual framework provides a theoretical foundation for the protection of historic landscapes and the development of ecological restoration strategies worldwide, while also fostering interdisciplinary integration between cultural ecology and environmental behavior studies. Cumming et al.[36] further introduced the notion of "contextualization," exploring the dynamic interaction between ecological and cultural elements. The work of Saxer and Rosenbloom[37] has driven a shift in the study of social structures towards a dynamic relational paradigm. With regard to kiln architecture and environmental preservation, this study outlines five key concepts and methodologies of this theory (Table 1), while Fig. 1 illustrates the theoretical framework developed in this research.

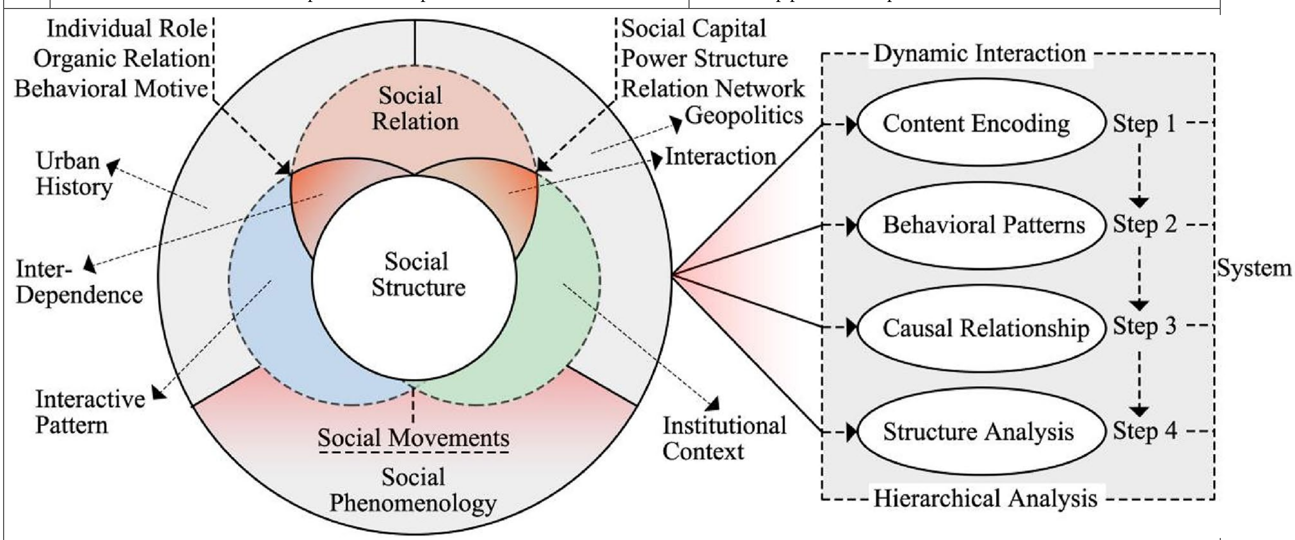
The "New European Bauhaus" initiative emphasizes the synergy between architectural design, ecological harmony, cultural identity revitalization, and social equity. It advocates embedding sustainability into everyday living environments while reshaping cultural diversity. This vision resonates with the theoretical framework proposed in this study—ecologicality-cultural resilience theory—in the following ways: (1) Kiln architecture demonstrates a topographically adaptive construction approach, similar to the "built-against-the-mountain" typologies observed in Santorini and Matmata, achieving high environmental adaptability with minimal technological intervention, aligning with the ecological design ethos of the New Bauhaus; (2) Kiln architecture exhibits notable variations in spatial organization and decorative language across different ethnic groups (e.g., Han communities in the Loess Plateau and Uyghur communities in Xinjiang), reflecting strong cultural inclusivity and the embeddedness of local knowledge systems, which aligns with the principle of diversity; (3) in terms of community participation and place-based construction, several regions continue to maintain traditional kiln dwellings, which have been revitalized through digital platforms and cultural tourism reuse models, thereby reflecting the values of inclusion and participatory development.

Hierarchical event coding method (HECM)

Developed by Kosuke Akaishi's team at Osaka University, KH Coder is a text mining tool based on artificial intelligence algorithms. This study employs KH Coder to conduct qualitative coding and relational analysis of historical events. The logic underlying the event relationship analysis is based on the HECM. The analysis of historical events can be traced back to discussions by Habermas and Gadamer in the late nineteenth century regarding the concept of "historical embeddedness"[38]. They emphasized that the analysis of historical events should focus on their deep integration with social structures. Building on this foundation, Tilly[39] expanded historical research to include the dynamic analysis of social impacts. He introduced the concept of "impact layers," underscoring that historical events are not merely isolated temporal points but also critical drivers shaping social phenomena and structural transformations. According to Tilly, understanding the dynamic processes of social phenomena requires considering three core elements: social ties, interaction patterns, and institutional contexts. Hommel et al.[40] introduced the concept of "coding," proposing a sociological research method based on the coding of historical events. This approach combines quantitative and qualitative analysis, offering a new perspective on examining the developmental logic and social significance of events. Subsequently, Hauser and Featherman[41] advanced this approach by developing the methodology of "stratified coding." This method separates the developmental trajectory of historical events from their impacts on external domains such as society, culture, and economy, allowing for a more nuanced analysis of their relationships and effects.

Although these methodologies have achieved significant progress in sociology and historical research, their application has primarily focused on areas such as social movements, political transitions, and cultural heritage. Systematic exploration of their use in the urban and architectural context remains limited. This study seeks to integrate the HECM into architectural and urban development research, with particular attention to the interplay between architectural events and their socio-cultural impacts. Drawing on the application of this methodology in the field of painting research by Li et al.[42], Table 2 systematically organizes the core principles of this approach and its specific methods for architectural development research.

No.	Concepts	Methodologies
1	The importance of social relationships emphasizes their crucial role in shaping individual behavior and social structure	Content encoding involves analyzing the content of interactions and communication methods to reveal the nature and characteristics of social relationships
2	The dynamics of interaction necessitate attention to how social interactions emerge and change in different contexts	Behavioral patterns refer to studying the behavior patterns and interaction processes of individuals and groups in specific contexts
3	The influence of the institutional context refers to analyzing how social systems and cultural backgrounds shape social relationships and interaction patterns	Causal relationships examine how social relationships influence social phenomena and individual behavior
4	The distribution of power and resources explores how power and resources are allocated within social relationships and their impact on social interactions	Structure analysis uses social network analysis techniques to uncover relationship patterns and power distribution within social structures



HECM application logic (Source from: https://doi.org/10.1186/s40494-024-01456-2)[43]

Table 2. The core concepts and specific analytical methods of HECM.

Research structure

Figure 2 illustrates the methodological steps of this study. Following the literature review and the establishment of the theoretical framework, the experimental design is divided into three components. The first component involves collecting historical data on factors influencing the development of cave dwellings. Using KH Coder, key historical events shaping the evolution of cave architecture and the ecological environment are identified. These events are classified into attribute layers and impact layers, forming the basis for constructing a developmental trajectory model. The second component focuses on analyzing the architectural structures and their geographical distribution. The third component examines the ecological characteristics of architectural types across different regions in China. Finally, the findings are compared with peer studies, leading to the proposal of a preservation framework.

In the first stage, the collection of preliminary data and architectural development events was carried out manually. In the second stage, the data mining tasks (TF statistics and topic co-occurrence networks) based on KH Coder were automated; however, the results of the artificial intelligence analysis depend on the accuracy of the manual classification of the collected data. HECM is a combination of computer-assisted and manual analysis. KH Coder can trace the contextual statements of events by using specific keywords or time indicators from textual data, highlighting the subject, object, action verbs, and social impact of events, thereby assisting in manually coding the nature of different events. The developmental trajectory modeling and the influencing layer model were manually created based on the previous coding analysis. In the third stage, the functional characteristics, ecological technologies, and applied preservation strategies of kiln architecture were manually collected from existing data and further analyzed using various software tools.

From an innovative perspective, HECM offers a more scientifically rigorous approach to social structure analysis compared to traditional literature-based research methods. Traditional methods often struggle to reveal the complex interplay between events and social structures[44]. In contrast, HECM effectively portrays the evolution of historical events and the interaction mechanisms within social structures by categorizing the nature and social impact of events and analyzing the relationships between objects and subjects of events[45]. The innovation of this method lies in its ability to analyze the temporal and spatial dimensions of events, while also uncovering their deeper social, economic, and cultural impacts, thus filling the gaps left by traditional research methods.

In terms of methodological contribution, traditional research on ecological architecture strategies tends to focus on technical aspects, often neglecting the integration with regional cultural significance[46]. This study, however, reveals the interaction between architectural technology and culture. In contrast to Hitchcock's[47] historical perspective on the development of architectural technology, this study analyzes the evolution of kiln architecture forms from the standpoint of cultural adaptability and social structure transformation, broadening the scope of architectural history research. It also examines how technology undergoes functional transformation within specific socio-cultural contexts. This analysis advances the study of the interaction between architectural culture and technological development, expanding the theoretical framework in the interdisciplinary field of architecture and sociology. While Zhang et al.[30] focus on the relationship between architectural function and environmental adaptability, this study explores the adaptability and transformative nature of kiln architecture forms in response to cultural and ecological challenges during historical and social changes. It analyzes how architecture responds to environmental pressures and social demands within a specific historical context, thereby providing new theoretical support for architectural preservation and sustainable development.

Results

HECM based on KH coder to analyze the trajectory of kiln dwelling buildings and ecosystems

The references for this study include "Kiln Environment of Baisha Village in Sanyuan County, Shaanxi Province"[48], "Construction Techniques of Chinese Traditional Residential Architecture: Kiln Dwelling Architecture"[49], and "Underground Courtyard in Shan County, Henan"[50], along with additional online data sources. To maintain focus, the analysis in this paper is limited to descriptive information related to the historical development of kiln dwellings. Specific architectural case details, such as images, designers, dates, painting names, and geographical

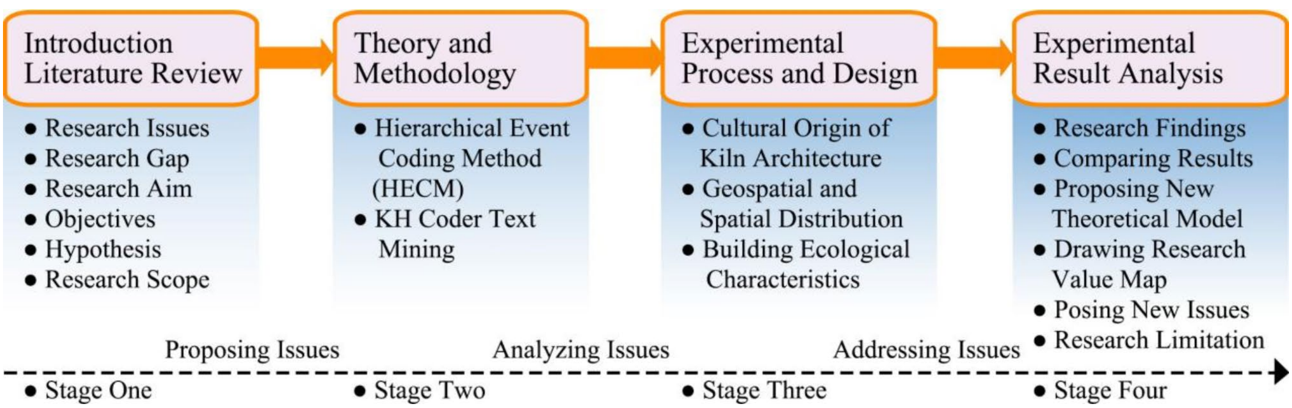


Fig. 2. Kiln architecture and its research framework for ecological conservation.

Force pick up:	窑洞; 窑居; 冶炼; 地区; 器物; 灰坑; 砖拱; 深挖; 胶泥碗; 磨食器; 能耗; 亟需; 竖式窑; 最大; 鹿类; 租界区; 洞穴; 黄土; 塬地; 沟壑; 台塬; 陕北; 河南; 三原; 柏社村; 陕县; 地下空间; 降水量; 稳定性; 地坑院; 四合院; 拱券; 夯土墙; 承重; 砖石; 砌筑; 木构架; 穹顶; 梁架; 洞顶; 采光井; 通风道; 烟道; 开挖; 回填; 夯实; 掏挖; 抹灰; 石材加工; 木构件; 屋架; 土方工程; 湿陷性; 地基; 加固; 侧房; 门楼; 院落; 门洞; 天井; 采光; 排水; 贮藏室; 灶房; 窑口; 围合; 分区; 乡土; 营建; 适应性; 地缘; 风水; 营造法式; 空间序列; 保温层; 阶梯式; 前廊式; 内院式; 并列式; 窑门; 窑顶; 窑壁; 悬挑式
Force ignore:	不; 但; 可; 在; 如; 寺; 唐; 强; 性; 新; 旨; 深; 灾; 界; 窄; 群; 较; 还; 长; 土; 对; 宽; 高; 国; 洞; 的; 了; 是; 和; 也; 与; 或者; 以及; 因为; 所以; 如果; 那么; 这个; 这些; 那些; 只是; 还有; 非常; 可能; 一些; 每个; 任何; 所有; 并且; 然而; 当然; 比较; 似乎; 出; 并; 约; 低; 其实; 其中; 通过; 由于; 于是; 然后; 这样; 因此; 既然; 既是; 之后; 大; 已; 而; 目前; 现在; 以前; 以后; 将来; 曾经; 集; 已经; 正在; 继续; 一直; 依然; 也许; 大约; 甚至; 并不
TAG	雄安新区; 唐冶新城; 猛犸洞穴; 弗兰奇蒂洞穴; 圣罗曼修道院; 埃洛拉石窟; 奥尔塔希萨城堡; 赫兹石灰窑; 世界隧道大会; 国际隧道协会; 城市地下空间联合研究中心; 阪神大地震; 库伯佩地; 大阴洞; 炳灵寺; 屈斗宫; 邓城叶氏庄园; 太平天国; 洋务运动; 汶川地震; 木梁屋架; 陡崖窑; 柏社村; 黄土高原; 关中地区; 华北地区; 中轴对称; 穿堂窑; 冬暖夏凉; 储藏窑; 牲畜窑; 作坊窑; 窑庙; 学堂窑; 防空窑; 祠堂窑

Table 3. Word list of force ignore, force pick up, and TAG.

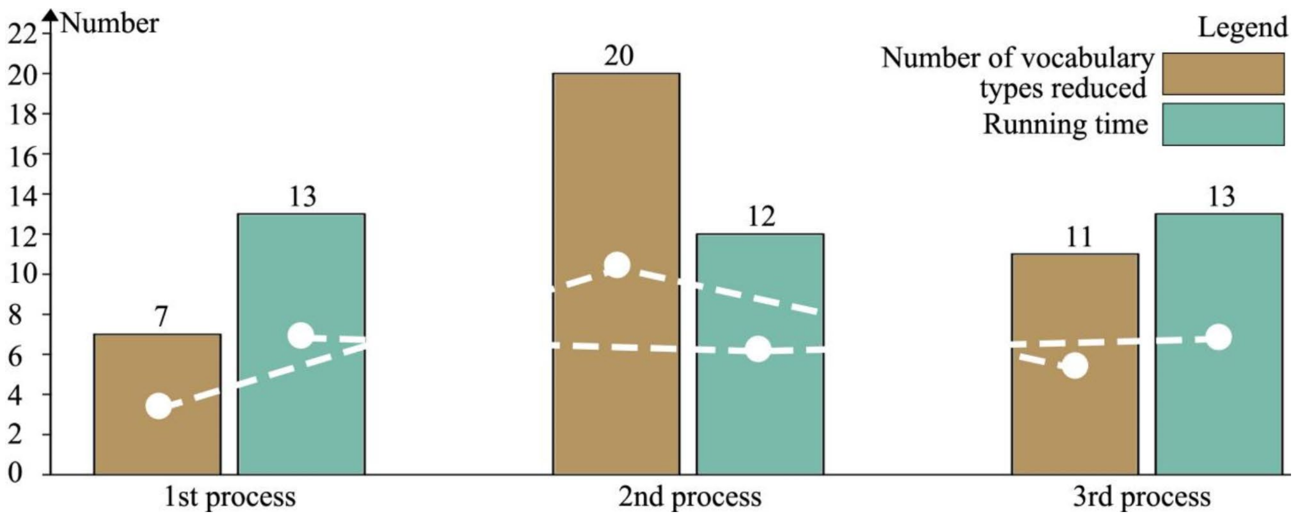


Fig. 3. Comparison of the results of the 3 data processing process.

locations, were excluded during the data mining phase. For subsequent coding analysis, the attributes of historical events (economy, politics, military, archaeology, technology, and religion) were encoded as Group A variables.

Excel data was imported into KH Coder using the Stanford POS Tagger for preprocessing. During this stage, the vocabulary in the frequency list was reviewed and merged where necessary. In the "Select by Parts of Speech" section, check the boxes for noun, propernoun, adj, adv, verb, and TAG words as the main types of words to be counted. Irrelevant words, such as auxiliary verbs, pronouns, and conjunctions, were manually categorized under "Force Ignore," while key lexical items with distinctive semantic relevance were added to the "Force Pick Up" category[29]. After rerunning the process, a refined dataset of descriptive information was obtained. This method involved three iterations of reviewing the frequency list and updating the "Force Ignore" and "Force Pick Up" tables to enhance the validity of the filtered textual data and improve computational accuracy. Compared to the initial preprocessing results, the final step reduced the number of word types by 38. Table 3 shows the word lists for force ignore, force pick up, and set TAG words. Figure 3 illustrates the optimization achieved across the three stages of data processing.

The second step involves calculating Term Frequency (TF) and Document Frequency (DF) to refine content selection, ensuring a focus on core themes and events. TF refers to the frequency of a given term appearing within a document. A high TF value generally indicates a strong correlation between the term and the document's primary theme. DF, on the other hand, measures the number of distinct analytical units (e.g., sentences, paragraphs, or cells) in which a specific term appears. A term appearing in only a few documents may serve as a useful descriptor for those documents' themes. Using Eqs. (1) and (2), TF and DF values are computed, respectively. As illustrated in Fig. 4, approximately 582 terms exhibit TF values below 3. These low-frequency terms are insufficiently representative of the text's key content and are excluded from further analysis. For subsequent analysis, the target range is defined as $4 \le TF \le 17$, referred to as the "Priority" level in this study. Conversely, terms with excessively high TF values ($TF > 17$) are not inherently meaningful, as many of these are common words that lack thematic specificity or representativeness. Consequently, such high-frequency terms are categorized as requiring semantic verification and are designated as the "Inspect" level for further study.

$$TF(i) = \frac{\log_2(\text{Freq}(i, j)) + 1}{\log_2(L)} \tag{1}$$

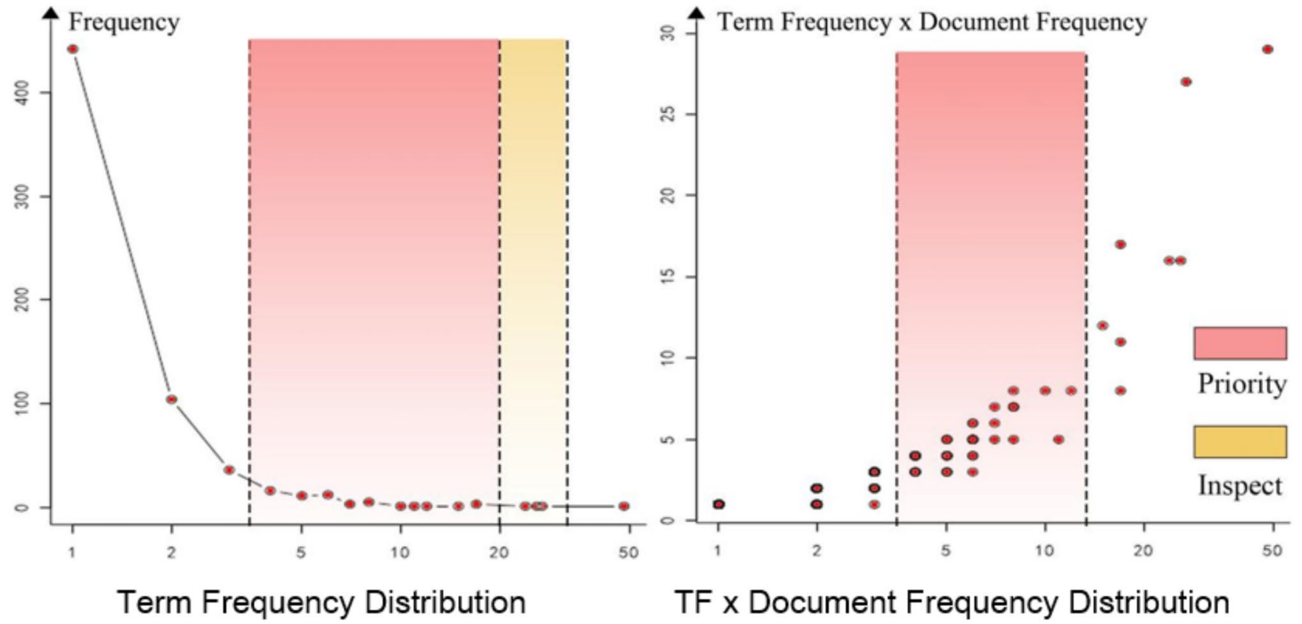


Fig. 4. Calculation results of TF and DF.

$$\mathrm{idf_i} = \log\frac{|D|}{|\{d : d \ni \ t_i\}|} \quad (2)$$

After determining the TF of the core vocabulary, a co-occurrence network consisting of "nodes" and "edges" connecting these nodes was constructed for Variable A. The TF parameter range was set $4 \leq \mathrm{TF} \leq 17$, and the DF parameter range was set $4 \leq \mathrm{DF} \leq 10$. The Types of Edges option was configured as "Words–Variables/Headings", with Variable A Group selected as the target variable. The options "Smaller Nodes" and "Draw the minimum spanning tree only" were both enabled. Finally, a co-occurrence network was generated using a plot size of 1000. Figure 5 illustrates five clustering groups (Clusters 1 to 5). Among these, "archaeology" and "technology" form the central clusters. "Archaeology" is closely connected to Cluster 2 (military) and Cluster 4 (religion), while "technology" is more closely associated with Cluster 5 (politics). Notably, Cluster 6 (economy) is linked to Cluster 4 through the term "culture" but remains largely isolated from the other clusters. This suggests that the heritage-driven economic development of kiln dwelling architecture primarily revolves around cultural revitalization and is closely tied to local religious culture. The terms "function," "resource," and "save" in Cluster 1 indicate that archaeological activities related to kiln dwelling architecture focus on identifying environmental evidence of early human habitation. For instance, the utilization of caves for resource storage and climate adaptation ensured safety (Cluster 2). Additionally, terms such as "ecology," "utilization," and "design" suggest that modern technological advancements have provided a foundation for the ecological conservation and redesign of kiln architecture (Cluster 3). However, the development of construction technology is also associated with the geopolitical tensions of World War II. For example, the construction of underground spaces in many regions was driven by the need to mitigate safety risks during that period.

Furthermore, this study utilizes the vocabulary tracking function of KH Coder to trace the key events that constitute each cluster group. These events are systematically analyzed from both international and Chinese perspectives. Based on their specific impacts on Kiln architecture and ecological environment development, the study categorizes the events into five distinct impact layers: building functionality, heritage conservation, cultural diffusion, technical specification, and eco-planning.

Tables 4 and 5 outline the development of cave dwelling environments in both international and Chinese contexts, highlighting the progression from environmental adaptation to modification. Before the fourteenth century, cave dwellings were predominantly primitive excavations in hillsides or soil slopes, such as Greece's Franchthi Cave, which leveraged the high thermal capacity of rocks and soil for climate regulation[51]. In northern China during the Han Dynasty, semi-underground dwellings used partially buried structures to regulate indoor temperature based on soil properties[52,53]. Between the fifteenth and eighteenth centuries, surface-covered structures gradually replaced hillside kiln architecture, marking a transition from dependence on natural topography to independent structures. Covered designs retained energy efficiency for insulation while improving lighting and ventilation, as seen in Germany's Hertz Lime Kiln, which optimized energy efficiency through covered soil technology[54]. In Suide County, the Dang Clan Manor integrated courtyards, skylights, and light wells to harmonize ventilation and lighting with nature[55].

During the Industrial Revolution, materials like brick, stone, wood, and early concrete fostered the rise of hybrid kiln architecture. These frame structures combined traditional kiln architecture with modern technologies and advanced subterranean techniques in response to air-raid shelter construction. Montreal's La

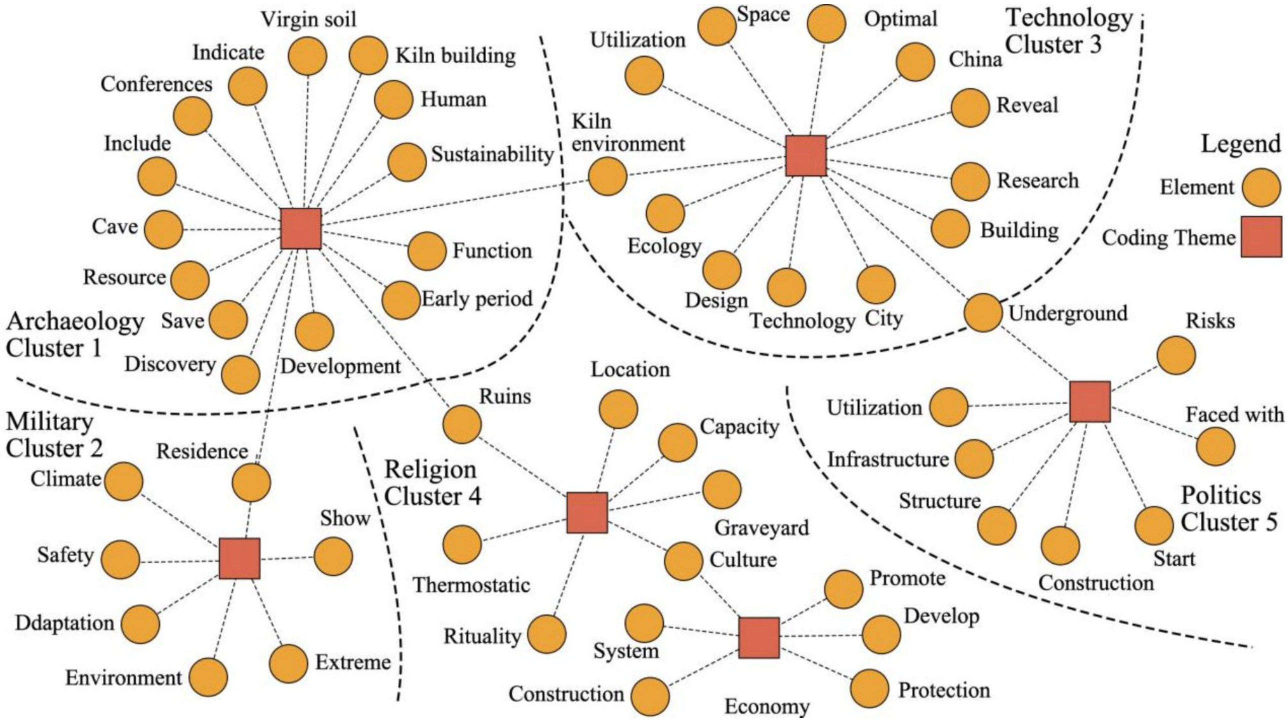


Fig. 5. Thematic co-occurrence networks based on variable A groups.

Ville Souterraine in Quebec demonstrates the potential for underground space utilization[62]. Since the twentieth century, technological innovation has propelled the development of new kiln architecture. For instance, the wave-shaped houses in Reims, France, combine natural slopes, soil covers, and vegetated roofs to enhance sustainability. Meanwhile, the estate-style cave dwellings designed by Vetsch Architektur in Switzerland utilize the ground as a protective layer to shield against harsh environments[71]. A cave-dwelling hotel designed by hyperSity integrates courtyards and interspersed buildings to block northwest winds while ensuring summer lighting[72].

Based on event attributes, the study codes the 39 events in Tables 4 and 5 into six types and five impact layers, reflecting development trends through Figs. 6 and 7. Cultural archaeology and technological innovation form the primary trajectory of cave dwelling environment development, while political guidance (1368–1978) and economic growth (post-twenty-first century) constitute secondary trajectories in the Chinese context. Marking the twentieth century as a pivotal point, functional transformations, heritage conservation, cultural promotion, and ecological practices define the primary trajectories in the early and late phases of kiln architecture development. Additionally, mid-twentieth century military conflicts accelerated the standardization of kiln construction techniques.

Environmental characteristics of kiln dwellings in China and the current status of ecological conservation applications

Based on the research data from Wang[93] and supplemented by the survey data collected by this research team, Table 6 provides an overview of the four types of yaodong (cave dwellings) in China and their geographical distribution. The map was generated using ArcGIS 10.4 and further refined for visual presentation using Adobe InDesign CC 2017 (32-bit). These kiln architectures are characterized as follows: (1) Built-against-the-mountain style kiln architecture leverages the geological conditions of the Loess Plateau by being directly excavated into mountain bodies, utilizing the terrain as the main structural support; (2) Along-the-valley style kiln architecture, distributed in areas with intricate ravines, follows the topography in linear arrangements along valley banks, effectively adapting to the terrain. This type of kiln architecture is primarily found in the regions of Longdong, Yan'an, and Linfen; (3) Sunken courtyard style kiln architecture, centered around sunken courtyards, creates depressions in the ground to form courtyards and digs kilns around the periphery, enhancing thermal performance and resistance to wind and earthquakes. This style is concentrated in Longdong, Yan'an, and parts of Henan; (4) Independent kiln architecture includes two subtypes: brick-and-stone structures and rammed-earth structures, mainly distributed in Shaanxi, Yan'an, Jinzhong, and Linfen. The former uses brick and stone materials to construct barrel vaults or arched coverings, while the latter relies on rammed earth or loess, employing arched structures to disperse loads and improve structural stability.

Li and Chen[48], Wang et al.[49], and Huang[50] categorized kiln architecture into five commonly observed types based on a comprehensive review of their morphological characteristics, typologies, and functional attributes. Figure 8 illustrates these types, corresponding architectural forms, and representative case studies. According to their research, the Cave Houses in Santorini can be classified as Type a1—Built-against-the-mountain Style. This

No	Year	Period	Events	The influence to building development
A	25,000 B.C.	Paleolithic	Early human activities were discovered at Mammoth Cave in Kentucky, USA, including stone preaching platforms, pits, and water holes. To date, more than 225 paths have been identified within the cave[56]	The natural protective function and stable temperature-humidity environment of caves provided survival support for early humans, inspiring the functional optimization of kiln architecture in thermal regulation and humidity control
B	4000 B.C.	Mesolithic	In 1973, early remains were excavated from Franchthi Cave in Greece (approximately 150 m long and 30 m wide), including deer bones, large fish bones, a young male skeleton, and burial sites[51]	Discoveries of animal bones and burial sites suggest that caves served both residential and ceremonial purposes, with their resource storage and temperature-humidity regulation capabilities offering insights into the multifunctionality of terrain-dependent cave dwellings
C	500	Middle age	In 1960, the Abbaye de Saint-Roman was discovered in Garr Province, France. The site includes a church, terrace tombs, and city walls. It was designated a French cultural heritage site in 1991[57]	The cave structures of monasteries illustrate the religious expansion of kiln architecture and its capacity to meet diverse social demands, while rock utilization reduced reliance on external building materials
D	900		The Ellora Caves in Aurangabad, India, constructed around the 9th century, comprise more than 100 intricately carved religious cave structures, representing a significant historical and religious site[58]	Religious carvings and architectural complexes highlight the integration of artistic expression and functionality within kiln architecture
E	1400	Renaissance	During the Ottoman Empire, Ortahisar Castle in Turkey developed into an agricultural and trading town, with caves repurposed as grain storage and temperature-controlled spaces, although some are now abandoned[59]	The adaptation of caves for grain storage and temperature-controlled spaces demonstrates the agricultural value of kiln architecture, with its thermal stability serving as a prototype for modern low-energy buildings
F	1759	Industrial revolution	The Hertz Lime Kiln in Hessen, Germany, is a four-story vertical kiln (10–20 m in height), built with refractory bricks and used for high-temperature calcination in lime production[54]	The high-temperature calcination technology of the Hertz Lime Kiln reveals the industrial potential of underground architecture, with its refractory brick structures and thermal energy utilization offering insights for the energy optimization of kiln architecture
G	1935	World war II	During World War II, Germany enacted the Anti-aircraft Law, funding the construction of shelter buildings, including air raid shelters, underground facilities, and hospitals[60]	The durability and protective functions of air-raid shelters showcase the efficiency of underground spaces in disaster defense, providing references for enhancing the safety and durability of kiln architecture in extreme environments
H	1945	Cold war	During the Cold War, several nations initiated projects such as "Castle of Doom" and "The Ice Worm Project," constructing military facilities, missile silos, and command centers as preventive measures against international warfare[61]	Cold War military underground projects emphasized spatial concealment and functional diversification, offering innovative approaches to improving insulation and ventilation systems in kiln architecture
I	1967	Mid–twentieth century	To address the harsh winter climate of Montreal city in Quebec, authorities developed an underground commercial and residential city based on the concept of a "Cave," which also served as a defense against aerial threats[62]	The underground city of Montreal, Quebec, exemplifies strategies for cold climate adaptation, with its integrated functions offering directions for the urbanization and ecological integration of kiln architecture
J	1970		The global energy crisis highlighted the importance of low-energy ecological architecture, sparking a wave of architectural exploration using natural materials and passive techniques across many regions[63]	The natural ventilation and insulation properties of kiln architecture have regained attention, establishing it as a critical focus in low-energy ecological building research
K	1974	Mid to late twentieth century	The World Tunnel Congress (WTC) was established in Geneva, Switzerland, followed by the founding of the International Tunneling Association (ITA)[64]	The modernization of underground space technologies and kiln architecture theories provides scientific support for the utilization of underground spaces and the standardization of design practices
L	1989		The National Aeronautics and Space Administration (NASA) in the United States conducted underground cave experiments to explore the potential of subterranean spaces for habitation and resource utilization in extraterrestrial environments[65]	The experiment highlights the thermal stability and radiation shielding advantages of underground spaces, offering a scientific basis for applying kiln architecture in extreme climates and resource-efficient utilization
M	1990	End of the twentieth century	The Associated Research Centers for Urban Underground Space (ACUUS) organized academic conferences on "Underground Space and Earthen Architecture," while the Getty Conservation Institute in the USA (GCI) launched academic initiatives on "Preserving Historic Earthen Architecture" to proactively address urban development challenges[66]	The conference discussed the integration of earthen architecture with underground spaces, offering recommendations for the application of kiln architecture in urban sustainable development and heritage conservation policies
N	1995		The Hanshin Earthquake caused severe damage to surface buildings and infrastructure; however, underground lifeline systems, including electricity, communication, gas, and drainage, demonstrated strong disaster resistance and rapid post-quake recovery[67]	The resilience of underground lifeline systems during earthquakes demonstrates exceptional disaster resistance, providing practical references for optimizing seismic design in kiln architecture
O	2003	Twenty-first century	In Coober Pedy, Australia, located in a desert region, authorities began constructing economical underground residences in the early 20th century to mitigate the extreme heat[68]	Cave dwelling residences in desert regions, by adapting to extreme climatic conditions, exhibit excellent thermal stability and energy efficiency
P	2013		ITA[69] proposed a standardized framework for the planning, design, and management of underground spaces in its recently published white paper	The ITA White Paper's planning framework advances the modernization of kiln architecture design and promotes the sustainable development of underground spaces
Q	2016		Inspired by the passive ecological strategies of Chinese kiln architecture, Swiss designer Peter Vetsch created the "Earth House" kiln architecture[70]	This architectural example achieves a balance between aesthetics and ecological functionality, establishing itself as a significant case in modern ecological architecture

Table 4. Relevant events affecting the development of the kiln architecture environment.

architectural form typically involves excavation into mountainous terrain, utilizing the landform for structural support and thermal regulation. While the form exhibits regional variation shaped by local environmental and cultural conditions, in China, this type is predominantly found in the Loess Plateau regions such as Shaanxi and Shanxi, where it is commonly referred to as "Cliffside Kiln Architecture." In Greece, similar structures are known as "Cave Houses"[94] or "Troglodyte Dwellings"[95]. Furthermore, this type shares spatial characteristics with the Tower House, as both employ vertical expansion to adapt to terrain variation and maximize space efficiency[96]. By contrast, sunken kiln architecture makes use of subterranean space to enhance insulation and concealment[50], reflecting distinct approaches to climate adaptation and land utilization. The similarities and divergences among

No	Year	Period	Events	The influence to building development
1	15,000 B.C.	Paleolithic	In 2014, stone axes, grinding tools, clay bowls, and animal remains were unearthed at the Ningxia rock cave site, providing evidence of early human habitation[73]	Early humans utilized caves for shelter and resource storage, demonstrating an adaptive response to environmental challenges
2	3000 B.C.	Mesolithic	In 2017, over ten thousand carbonized rice grains were discovered in Cave 4 of the Nanshan site, indicating that cave dwellers had developed farming techniques[74]	Archaeological research indicates that early cave dwellers mastered farming techniques, integrating residential and grain storage functions into kiln architecture, exemplifying a functional synergy
3	1000 B.C.	Neolithic	In 2017, the Dayin Cave site in Yunnan, covering approximately 1500 m^2 with a height of 40 m and a width of 20 m, revealed ash pits, ceramic axes, and 17 well-organized burials, showcasing the multifunctional use of early caves[75]	The multifunctionality of cave architecture fulfilled residential needs while also serving religious rituals and resource storage, reflecting its cultural and practical versatility
4	220	Han dynasty	In 2006, the Tangye New Town site in Jinan revealed a 10 m^2 semi-subterranean structure with pillar hole traces, suggesting the use of wooden structural supports[52,53]	The design of narrow and elongated doorways optimized heat-driven ventilation, enhancing fire pit combustion efficiency, showcasing the energy-saving and insulation innovations of kiln architecture
5	618	Tang dynasty	The Tang Dynasty caves at Bingling Temple in Gansu, featuring over 130 grottoes and a colossal cliff-carved Buddha, are masterpieces of Tang religious art[76]	The temperature-stabilizing properties of kiln architecture provided a controlled ecological environment conducive to the long-term preservation of cultural heritage
6	1368	Ming dynasty	In 1953, the Dehua Kiln site in Fujian uncovered 20 Ming Dynasty kilns, integrating industrial, commercial, and residential functions, including workshops, firing rooms, and protective walls[77]	Kiln architecture constructed within loess layers leveraged the material's plasticity and stability, integrating natural topography to form complex internal structures
7	1421		During the Ming Dynasty, the capital was relocated to Beijing, marked by the construction of the Forbidden City and the large-scale building of the Great Wall[78]	Urbanization facilitated the adoption of brick-arch structures in underground drainage systems, driving innovation in subterranean architecture such as earth-covered buildings, fortifications, and tunnels for military applications[62]
8	1814	Qing dynasty	The Dang Clan Manor in Suide County represents the largest cluster of kiln architecture in northern Shaanxi today, featuring 17 large gates and courtyards with five interconnected cave dwellings[55]	Courtyards in cave dwellings demonstrated efficient spatial organization within high-density residential settings while integrating energy conservation with ecological adaptation
9	1851		During the Taiping Rebellion, underground tunnel spaces were utilized by civilians to resist Qing forces[80]	The use of underground passages highlighted the defensive functions and ecological adaptability of kiln architecture during times of conflict and unrest
10	1900		Following the Self-Strengthening Movement, advanced Western underground construction techniques were introduced, with concession zones leading the application of these technologies in urban modernization[81]	The underground drainage system of Shanghai's Bund employed advanced reinforced concrete structures of the era, exemplifying the technological progress in urban subterranean engineering
11	1937	Republic of China	During World War II, Chinese civilians effectively utilized tunnels and traps to resist air raids and invasions, showcasing the defensive functionality of underground spaces[82]	By leveraging the concealment and safety of underground spaces, tunnels provide practical evidence for the protective functionality and spatial optimization of kiln architecture in extreme environments
12	1950	People's Republic of China	In response to international tensions, authorities promoted the strategic philosophy of "dig deep tunnels, store ample grain, and avoid seeking hegemony" and issued the telegram titled "On the Issue of Preparing Civil Defense Work"[83]	Underground air-raid shelters constructed in heavy industrial bases integrate functions such as refuge, transportation, and production, driving multifunctional development and utilization of underground spaces
13	1976		Traditional kiln architecture demonstrated strong seismic resistance, providing safe shelter for residents during the Tangshan Earthquake[84]	Post-disaster reinforcement and retrofitting of traditional kiln architecture, including the development of seismic-resistant brick arches and concrete kiln structures, have enhanced their safety and adaptability
14	1980	Reform and opening up	Ren Zhenying founded the "Kiln and Raw Earth Architecture Research Society" and organized its inaugural symposium in Yan'an in 1981[85]	The conference introduced for the first time the sustainable development pathway for kiln architecture and earthen buildings, establishing a theoretical foundation for ecological studies of kiln architecture
15	1990		Human-induced soil erosion has negatively impacted the ecological environment surrounding kiln architecture, highlighting the urgent need for strengthened environmental protection measures[86]	China explores integrated approaches to ecological protection and economic development of kiln architecture
16	1999		The "8th International Academic Conference on Underground Spaces" was held in Xi'an, focusing on the sustainable development of eco-friendly raw earth architecture, kiln architecture, and cave dwelling villages [87]	The conference provided an in-depth discussion on the sustainable development of kiln architecture and earthen buildings, offering a global perspective on modern renovations
Continued				

No	Year	Period	Events	The influence to building development
17	2008	Twenty-first century	Retrofitted kiln architecture exhibited high seismic resilience during the 2008 Wenchuan Earthquake, providing empirical evidence for further safety research on kiln structures[88]	Advances in seismic technology for kiln architecture have facilitated improvements in building codes, promoting its evolution toward safer, more environmentally friendly, and more comfortable designs
18	2011		In Shaanxi Province, the municipal government of Yan'an initiated a conservation and restoration project targeting traditional kiln architecture, focusing on the repair or reconstruction of aging structures with potential collapse risks[89]	The project employed techniques such as shotcrete wall reinforcement and steel mesh stabilization to ensure structural safety. The restored buildings were repurposed with contemporary functions, including Red Culture exhibition centers and eco-tourism guesthouses, thereby promoting both local tourism and ecological preservation
19	2014		China published its first comprehensive research findings on the development of urban underground spaces[90]	The research findings offer scientific support for the ecological adaptability and functional expansion of kiln architecture in urban underground space planning
20	2016		In Mengzhou City, the "Beautiful Countryside" initiative was launched to repurpose clusters of abandoned kiln architecture from the Ming and Qing dynasties into a public library. Guided by the principle of "restoration to original appearance," the project preserved the architectural form to the greatest extent possible while integrating modern structural reinforcement techniques to enhance safety and durability[91]	This adaptive reuse project has become a representative case of converting traditional dwellings into public cultural spaces. It offers practical insights for the protection and reuse of kiln architecture, while also fostering cultural heritage conservation and the development of rural tourism economies
21	2018		The development of characteristic towns and beautiful countryside projects has presented new opportunities for the preservation and tourism development of kiln architecture, a traditional northern dwelling style[86]	Kiln architecture has been redefined as a cultural and tourism resource within new urbanization and rural revitalization efforts, with its ecological adaptability and cultural value driving its inheritance and innovation in modern society
22	2020		The city of Yan'an issued the "Regulations on the Protection of Old Revolutionary Sites in Shaanxi Province"[92], supporting the growth of red cultural tourism industries	Regulations emphasize the protection of earthen kiln architecture, historic buildings, and revolutionary sites while promoting their organic integration with public service facilities

Table 5. China kiln architecture and the developmental origins of ecology.

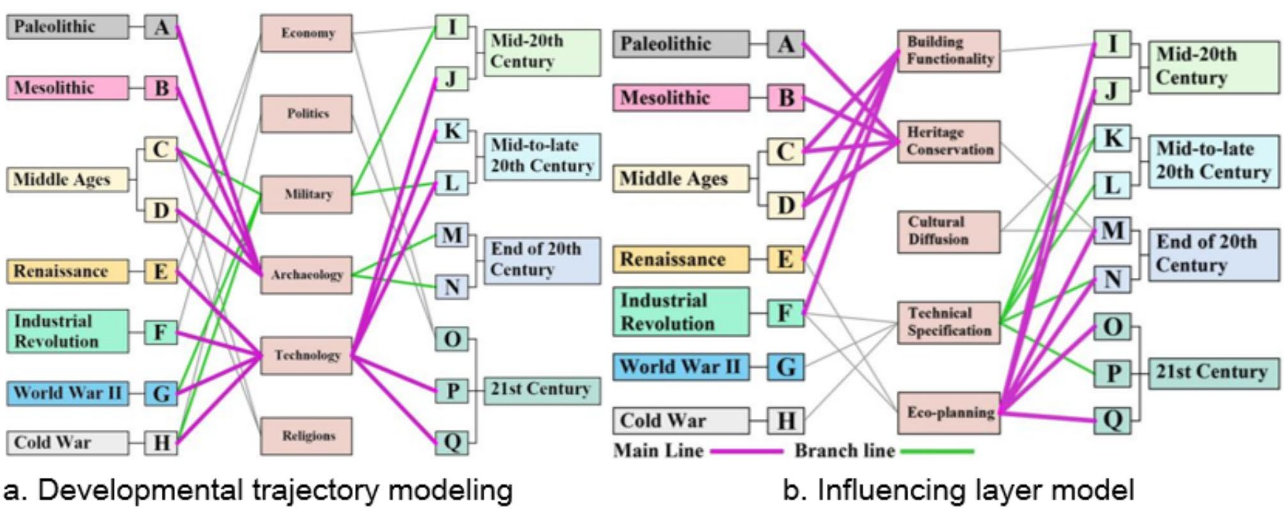


Fig. 6. The cave dwelling environment development model constructed based on the events of Table 4.

these typologies not only underscore the influence of regional environments on architectural forms but also reveal culturally specific strategies in response to ecological and material constraints.

Table 7 outlines the vault structures and construction techniques of kiln architecture in different regions; (1) Jinzhong primarily employs multi-layered brick-and-stone arches to enhance seismic resistance and stability; (2) Longdong uses rammed earth as the dominant material, reinforced with stone or wooden frames to adapt to the collapsible geology of the Loess Plateau; (3) Western Henan combines brick-and-stone with rammed-earth techniques, with exterior brickwork enhancing waterproofing and aesthetics, while internal rammed earth provides insulation and energy efficiency; (4) Northern Shaanxi is renowned for "hanging kiln architecture," where vault structures integrate wooden beams and rammed earth to improve wind resistance and adapt to varied terrain elevations; (5) Northern Hebei adopts thick walls and double-arched structures, using stone and clay to highlight cold resistance, addressing harsh winters and strong winds; (6) Inner Mongolia widely employs wooden arches, with some areas using stone for stable vault structures to withstand arid and sandy environments.

Research team conducted field investigations of seven cases of kiln architecture in China, accompanied by photographic documentation, and identified two additional cases from Europe through online sources for comparative analysis. Table 8 presents the common ecological technology features observed in these 9 kiln architectures: (1) Reliance on the natural insulation properties of loess to maintain stable indoor temperature and humidity; (2) Promotion of air circulation and natural lighting through entrance orientation and internal structural design; (3) Use of renewable earthen materials to reduce carbon footprints, supporting low-carbon

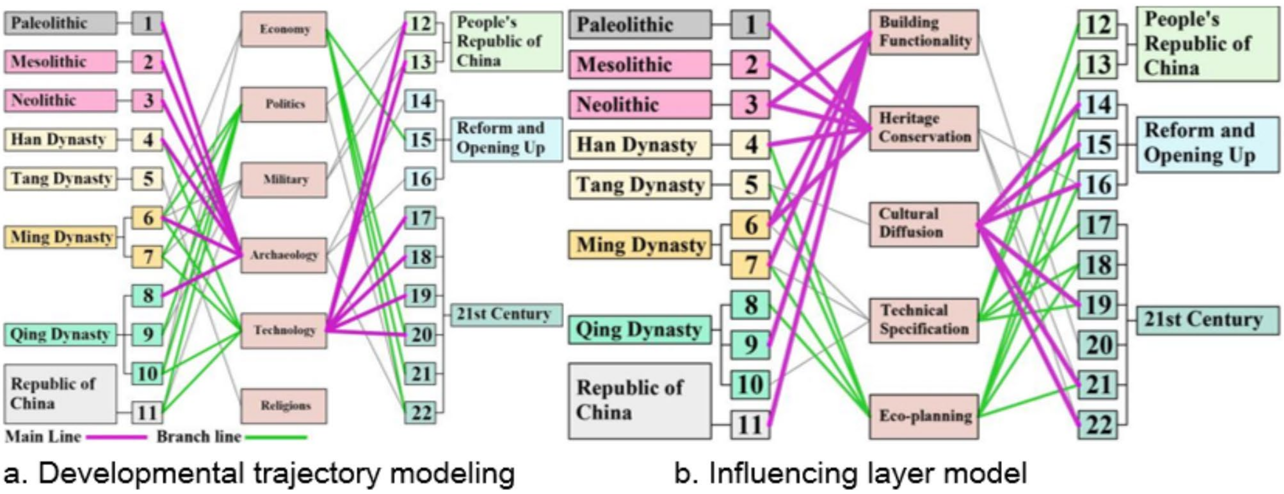


Fig. 7. The cave dwelling environment development model constructed based on the events of Table 5.

construction; (4) Incorporation of underground structures for rainwater collection and storage to establish recycling systems; (5) Integration of storage, agricultural, and cultural functions to enhance spatial efficiency. However, these architectural forms face challenges in protection and modernization: (1) The lack of adaptive ecological strategies to address climate change and modern needs; (2) Outdated technical standards and norms, with no unified design guidelines or evaluation systems; (3) Conflicts between heritage conservation and economic development, where urbanization and commercialization have eroded the original ecological value of kiln architecture; (4) Insufficient community participation, as local residents lack proactive involvement in heritage conservation, making protective measures unsustainable; (5) A disconnect between research and practice, with inadequate translation of existing ecological technology theories into field applications.

The architectural structure of Dazhan Fortress Town is similar to that of a city wall, typically constructed using rammed earth. The shapes are often round or square, and they are strategically built on elevated points at the edge of mountain villages, offering the advantage of being easily defensible and difficult to attack[106]. According to records in the Qing Historical Manuscripts[107], in order to resist the White Lotus Rebellion in Sichuan, Hunan, Shaanxi, and Gansu, earthen fortifications were reinforced in the Shaanxi-Gansu region beginning in the Jiaqing period. The walls of these earthen fortresses were constructed using loess, with the base thickness reaching one to two zhang (a traditional Chinese unit of length), the top width varying from five or six feet to one zhang, and the height ranging from two to three zhang. Every 20–30 m, corner buttresses were built to enhance stability and provide lateral defense. Surrounding the fortress, there was a moat that was two zhang wide and deep, used to house livestock and serve as a defense mechanism in times of banditry. In Shaanxi, earthen fortresses were generally square or rectangular, constructed with four rammed earth walls. These walls were built layer by layer using wooden supports and manual labor, with a height of about 4–5 m. The base was wide, gradually narrowing toward the top, where the wall thickness was typically 1.6 m. The structure featured double walls, with a passageway of approximately 1.5 m in the middle, allowing pedestrian access. The fortresses had internal staircases to prevent conflicts when two people crossed paths, creating a closed-loop route leading to lookout holes at the top. Inside, there was a single entrance, typically accommodating four to five households, or around thirty people. Larger fortresses could house six to seven households, or fifty to sixty people. The fortress was surrounded by a moat that was 3–4 m wide, and an underground tunnel was also built to address emergencies.

Pit Kilns were constructed by excavating square or rectangular pits about 6–7 m deep on level ground, with kiln caves carved into the four walls, creating a layout similar to that of a traditional courtyard, providing the benefits of warmth in winter and coolness in summer. The height of the kiln caves was approximately 4 m, with a width of about 3 m. The size of the courtyard and the number of kilns depended on economic, labor, and residential needs, typically ranging from 6 to 10 kilns, and up to 16 kilns in larger complexes[108]. Each courtyard generally accommodated one household, with two kiln caves on the east, south, and west sides, and one on the north side. Two to three kilns were used for living, two for livestock, one for a kitchen, and the remaining kilns for storage. The layout was influenced by factors such as terrain, ventilation, and lighting, with entrances usually located at the corners of the courtyard, and ramps leading to the ground. A 1-m-high surrounding wall was built around the courtyard to prevent people or livestock from falling in and to prevent rainwater from seeping in. The kiln roofs were compressed with stone rollers to prevent water seepage and to facilitate drainage, and they could also be used for grinding and drying grain. Rainwater was collected by dry wells inside the courtyard and allowed to percolate underground, while side kilns were used for well drilling or rainwater collection for drinking[109]. The sunken pit kilns utilized the stability of loess slopes by digging the kilns into the courtyard, with the ramp designed in a straight or zigzag pattern depending on the terrain. This architectural style is simple and economical, making full use of underground heat energy and soil insulation characteristics, maintaining warmth in winter and coolness in summer.

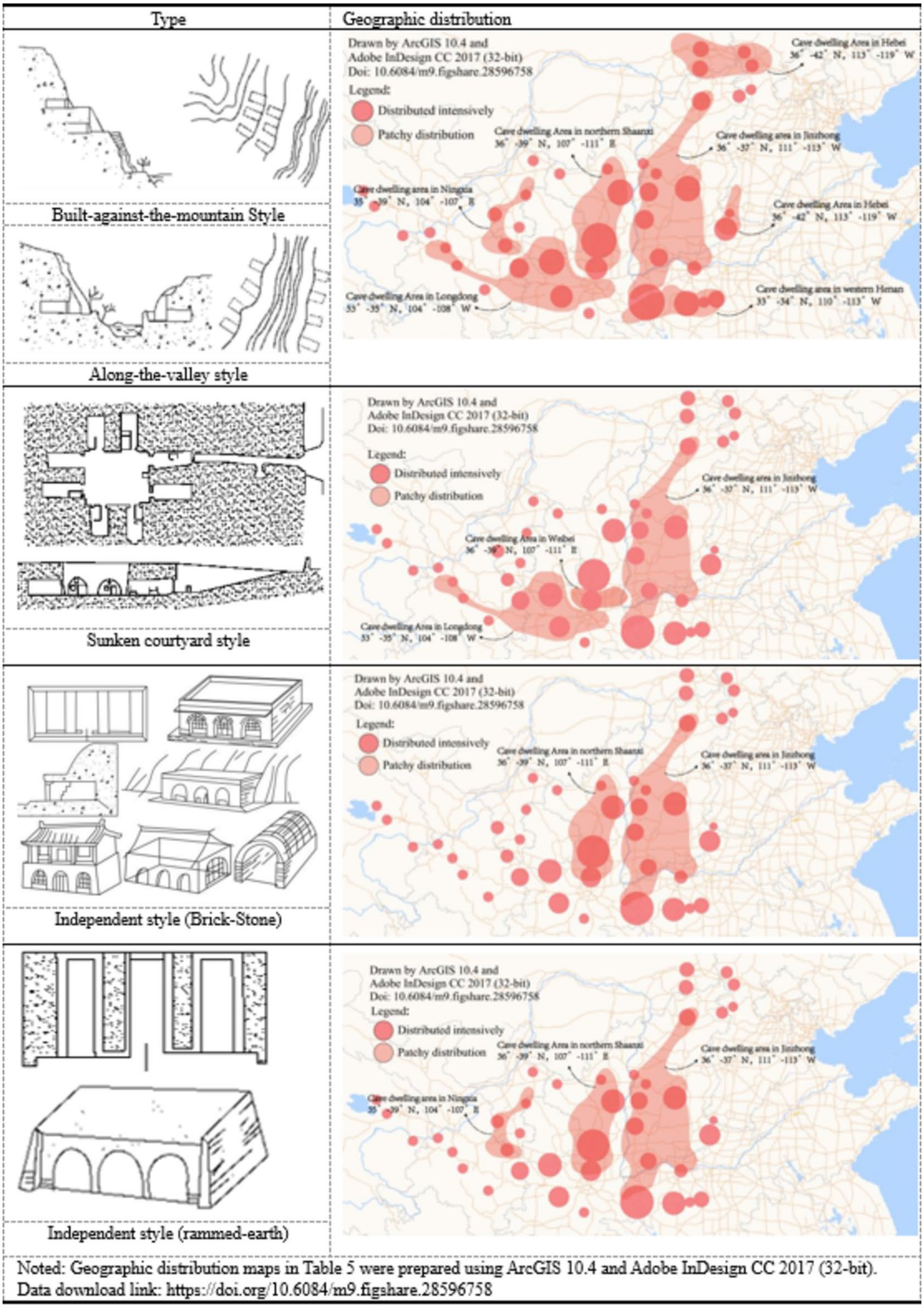


Table 6. Four types, characteristics and geographic distribution of kiln architecture in China.

The kiln dwellings of the Berber people are located in the Matmata Highlands of southern Tunisia and were excavated to adapt to the region's extreme desert climate[104]. A typical dwelling is organized around a central courtyard with a diameter of 7–15 m and a depth of 5–10 m, surrounded by bedrooms, kitchens, and storage rooms. These functional spaces are interconnected through a network of tunnels, forming a complex subterranean structure. The courtyard provides both natural lighting and ventilation, while the thick earthen walls help maintain an indoor temperature of approximately 20 °C throughout the year, offering effective thermal regulation for both summer and winter conditions[110]. Interior surfaces, including walls and ceilings,

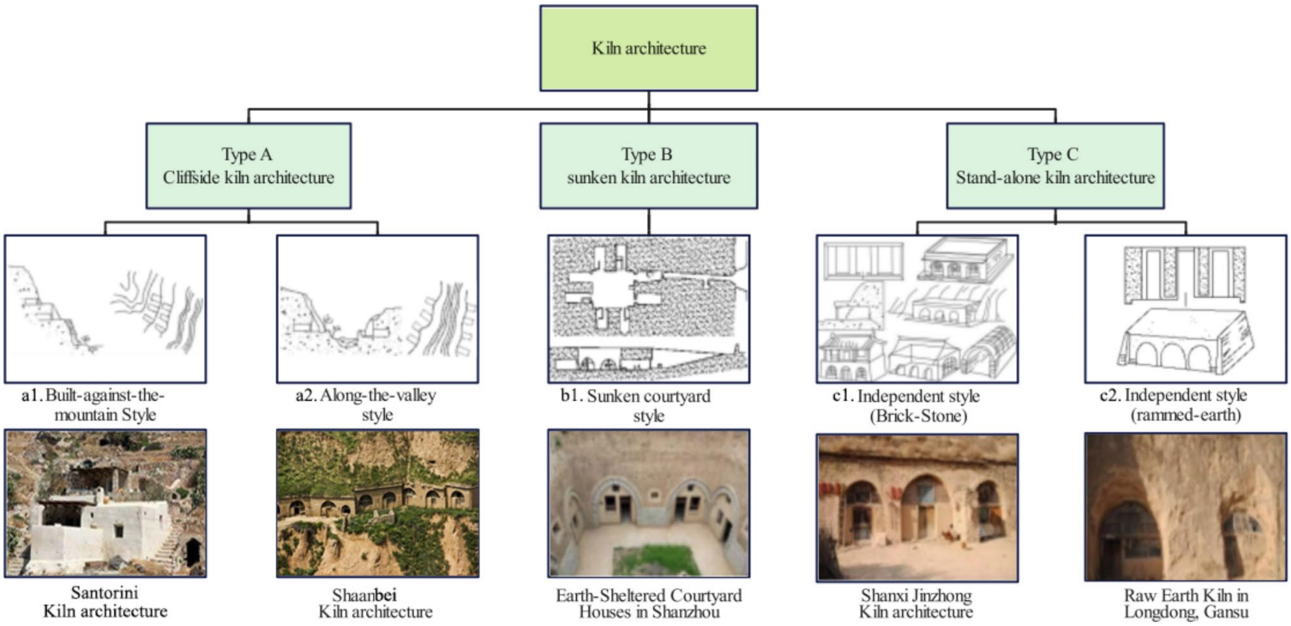


Fig. 8. Typological diagram of kiln architecture (Type a1 is adapted from the work of Ovalı and Tachir[94], while Type a2 is based on the study by Li and Wang[97]. The figures of Types a1 and a2 are cited from publications licensed under CC-BY 4.0 and therefore do not involve any copyright concerns. The figures representing Types b1, c1, and c2 were photographed by the authors).

are often decorated with carved patterns, reflecting the artistic heritage of Berber culture. However, with the advancement of modernization, many residents have relocated to the surface settlement of Nouvelle Matmata, leading to the abandonment of some traditional dwellings. In recent years, the rise of tourism has contributed to local economic revitalization but has also raised concerns regarding the conservation and management of this architectural heritage.

The cave dwellings of Cappadocia, located in central Turkey, are renowned for their distinctive "fairy chimney" landforms and historical rock-cut architecture[105]. Dating back to the fourth century CE, these dwellings were originally carved into soft volcanic rock and served as homes, churches, and monasteries. Over time, they evolved into underground cities featuring storage rooms, wine cellars, and ventilation shafts[111]. Their compact spatial organization also provides favorable climatic adaptability. Today, many of these cave dwellings have been converted into boutique hotels, restaurants, and museums, forming an essential part of the region's cultural tourism economy. Nonetheless, the rapid growth of tourism and increasing visitor numbers pose a threat to the fragile geological structures, potentially accelerating erosion and jeopardizing the long-term preservation of these heritage sites.

Discussions

Since the Middle Ages, cultural archaeology and technological advancements have laid the foundation for the diversification of kiln architecture in form and function, contributing to the early conceptualization of heritage conservation and ecological planning. During the Ming and Qing Dynasties, sociopolitical changes in China accelerated technological innovations, while the Republican period extended and adapted the application of cave dwellings. In the twenty-first century, economic growth and modernization have facilitated the integration of cultural heritage and technological innovation, resulting in functional and structural updates to traditional cave dwellings. Evolving from primitive cave systems to earth-covered structures and, eventually, independent brick or stone designs, kiln architecture embodies a continuous pursuit of comfort and functionality. From natural disaster protection to climate-adaptive design, these structures have diversified to meet economic, religious, defensive, and environmental demands. Natural conditions such as climate, terrain, and soil composition remain critical determinants of cave dwelling typologies, while socioeconomic factors and technological advancements have significantly influenced their morphological evolution. These structures are concentrated in Baoji, Yan'an, and Linfen while exhibiting fragmented distributions across Ningxia, Shaanxi, Henan, and Hebei. Regional geological and material characteristics have fostered distinct architectural styles, with the application of vaulted structures often constrained by material availability and technological expertise.

The results of this study suggest that balancing the cultural heritage preservation of kiln architecture with contemporary usage demands through energy optimization strategies, such as passive lighting and ventilation systems. Besides, integrating community participation mechanisms to ensure the feasibility and sustainability of cave dwelling environment adaptations. Kiln architecture forms are significantly constrained by natural environments. However, regional disparities and technological challenges continue to pose obstacles to conservation and adaptation strategies.

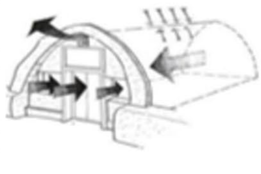
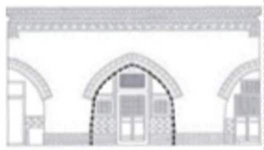
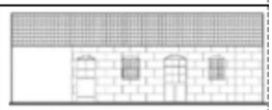
Regions	Range	Architrave technology	Technological structure	Architectural style
Jizhong (晋中)	The central region of Shanxi Province, located on the western side of the Yaihang Mountain.	The entrances of kiln architecture often feature semicircular or pointed arch designs, with misaligned inner and outer arch structures that enhance aesthetic appeal and structural harmony [61].	Flat-roofed kiln architecture features parapets and drainage outlets or sloped eaves, while sunken courtyards are formed by excavating multiple kiln architecture units around a central courtyard, connected by sloped paths.	
Longdong (陇东)	The eastern region of Gansu Province, situated on the western edge of the Loess Plateau	The pointed arch structure transmits weight directly to the walls, ensuring stability and visual appeal. The design of taller, wider front arches and shorter, narrower rear arches improves lighting and ventilation in deeper sections [62].	The central part of the cave entrance serves as the main door, with square windows on the left. Fire kangs are installed near the windows, creating a well-lit and warm south-facing primary activity area.	
Yuxi (豫西)	The western part of Henan Province, within the middle and lower reaches of the Yellow River	Kiln architecture entrances commonly utilize circular brick arches with windows incorporated into the arch, without additional window designs, emphasizing simplicity and functionality [63].	The entrance to kiln architecture is reinforced with a brick retaining wall and an eave, known locally as "brick facing," to prevent collapse. Central infiltration wells in sunken courtyards distinguish their design from similar structures in Longdong's pit dwellings.	
Shanbei (陕北)	The northern area of Shanxi Province, forming part of the core region of the Loess Plateau.	The edges and tops of arches are reinforced with stone masonry, providing solidity and precision. The semicircular arch openings are spacious and elegant, and decorative lattice windows enhance aesthetic appeal while significantly increasing lighting efficiency [64].	Earthen kiln interiors, characterized by soil walls, are well-lit, warm in winter, and cool in summer, making them highly popular. Stone kilns, constructed with stone blocks, are sturdier but colder and are typically used for public facilities such as offices or schools.	
Chaibei (察北)	Zhangjiakou City and its surrounding areas in Hebei Province.	Barrel-vault kiln architecture features roofs directly excavated into a curved arch shape, forming a natural arch structure [65].	Fully earthen kilns, which lack brick or stone reinforcements, have smaller windows, centrally positioned door frames, and fire kangs near the entrance with extended depth. These are often used as storage facilities.	
Inner Mongolia (内蒙古)	The Inner Mongolia region.	Kiln architecture often incorporates fixed wooden frames and adobe blocks to construct arch caves. Interior spaces include earth stoves, fireplaces, wall niches, and raised earthen platforms, with large decorative lattice windows adorning the entrance and vaulted roofs completing the structure [66].	Kiln architecture is constructed using wooden molds to support adobe arches. After drying, the molds are removed, and the topsoil layer is compacted. The neatly trimmed edges of the cave entrance highlight the distinct features of kiln architecture, with certain variants considered derivative forms of the original style.	

Table 7. Structural characteristics of kiln architecture in 6 regions of China.

Manzano-Fernández et al.[15] highlighted an 86% support rate for earthen architecture's ecological development due to landscape conservation and technological application, corroborating the findings of this study. Mileto et al.[16] and Nikolić et al.[17] emphasized the benefits of natural material renovation and hybrid mortar technologies in reducing environmental impact and enhancing wall performance, consistent with this research's investigation into technological transformations in kiln architecture from the fourteenth to early twentieth centuries. Yin et al.[9] explored the potential of modern construction techniques for traditional architecture, paralleling this study's focus on intelligent construction as a means of overcoming environmental constraints in kiln architecture.

	Case 1: Dazhan Fortress Town (大会战堡子城)
Chaoyanggou Village, Beidong Township, Quwo County (曲沃北董乡朝阳沟村)	
Function:	The architecture, primarily constructed with loess, integrates hillside terrain with a defensive system combining above-ground watchtowers and underground tunnels, including traps, ambush pits, and observation holes, demonstrating a high degree of environmental and functional integration.
Condition:	Despite the architectural form largely retaining its original appearance and undergoing preliminary reinforcement by the local government, structural damage persists, with long-term protection planning and ecological restoration strategies still lacking, and its cultural value remaining underexplored.
	Case 2: Pengzhen Former Residence (彭真故居)
Dieshang Village, Houma City, Linfen (临汾侯马市垤上村)	
Function:	Kiln architecture, characterized by practicality, reflects the traditional loess architectural style, with rational layouts and interiors that are warm in winter and cool in summer, effectively adapting to the local climate.
Condition:	As a designated protected site, the structure remains intact and functions as an educational base, yet agricultural modernization and infrastructure construction have disrupted the surrounding natural landscape, leading to ecosystem degradation.
	Case 3: Laoniuwan Village Oil Painting Base (老牛湾油画写生基地)
Laoniuwan Fort Village, Pianguan County, Xinzhou (忻州偏关老牛湾堡村)	
Function:	The site preserves traditional arched roofs and loess walls, and following modernization, it is equipped with essential infrastructure, making it suitable for artistic creation and habitation.
Condition:	The adaptive reuse of the site has enhanced the economic and social value of kiln architecture, but modifications to its original ecological features have sparked debates over cultural authenticity, while increasing resource pressures on the surrounding environment. Improved ecological protection mechanisms are urgently needed.
	Case 4: Laoniuwan Village Scenic Area (老牛湾景区)

Table 8. Current status of 7 kiln architecture and environmental use in China and 2 European cases.

Fratini et al.[10] provided mineralogical insights that complement this research's analysis of vaulted structures under varying geological conditions. Similarly, Lehtonen et al.[11] underscored the environmental benefits and carbon storage capacity of timber-based structures, resonating with this study's findings on the functional shift of kiln architecture toward energy-efficient design. By analyzing the geology, soil quality and climate, the structural and spatial distribution analysis of the different types of kiln architecture in this study forms a mutual support with the conclusions of Manzano-Fernández et al.[15] on the impact of geographic constraints on the preservation of earthen architecture.

Wanjiazhai Town, Pianguan County, Xinzhou (忻州偏关万家寨镇)	
Function:	Kiln architecture built with stone, featuring arched roofs and semi-subterranean structures, adapts to the slopes along the Yellow River. The interiors are simple yet functional, providing a warm winter and cool summer environment that reflects the ecological adaptability of traditional dwelling modes.
Condition:	By integrating kiln architecture with natural landscapes, the scenic area has formed an eco-cultural tourism complex. While initial conservation efforts have been successful, environmental pressures from tourism development remain significant, necessitating further ecological carrying capacity assessments and cultural landscape management.
	Case 5: Pit Kiln Demonstration Base (地坑窑示范基地)
Dongpingtou Village, Pinglu County, Yuncheng (运城平陆县东坪头村)	
Function:	Featuring a sunken courtyard style, the underground kiln is embedded in the ground, with loess walls and a compact layout. The design is highly adaptive to local climatic conditions, providing a warm winter and cool summer environment.
Condition:	The sunken courtyard kiln demonstration base has optimized temperature and humidity regulation through modern technologies, enabling functional reuse. However, local policies on integrating the surrounding ecological environment remain insufficient, highlighting the need for enhanced resource protection and ecological corridor construction.
	Case 6: Jinbu Room (Revolutionary Period Architectural Site)
Kenanpo Village, Jixian County, Linfen City (临汾市吉县克难坡村)	
Function:	The "Jinbu Room" kiln architecture in K'nanpo Village, built on traditional loess structures, remains well-preserved, showcasing the arduous living and working conditions during the revolutionary period, with significant historical and educational value.
Condition:	As a revolutionary site, the "Jinbu Room" kiln architecture is well-protected, but weak infrastructure and poor accessibility limit the potential for eco-tourism. Ongoing vegetation restoration efforts require sustained investment to achieve comprehensive ecological improvement.
	Case 7: Kiln Architecture Temperature and Humidity Laboratory

Figure 8. (continued)

This study develops a theoretical model to elucidate the complex mechanisms underlying the formation of cave dwelling environments. The model incorporates five core concepts and methodologies (Table 9). Figure 9 illustrates the following interactive mechanisms. Cave dwellings and ecologicality form a bidirectional relationship, wherein cave dwellings rely on natural conditions for ecological adaptation and achieve low-carbon objectives through optimized resource utilization. Ecologicality is enhanced through the use of sustainable materials and green design. Cave dwellings and adaptability establish a dynamic coupling, with the latter enhancing structural stability and functional flexibility to better respond to environmental and societal demands. Ecologicality and

Gaoyang Village, Gaoxian Town, Quwo County (曲沃高显镇高阳村)	
Function:	The kiln architecture laboratory, through long-term temperature and humidity monitoring, provides critical data for adaptive technological modifications, serving as a demonstration model for scientific research.
Condition:	The laboratory's research focus remains limited to technical functionality, failing to encompass the broader conservation and ecological restoration of surrounding kiln architecture. Expanding the research scope is essential to develop integrated conservation strategies.
	Case 8: Berber people's kiln architecture
The Matmata Highlands in southern Tunisia	
Function:	The central courtyard typically features a circular or elliptical configuration, measuring approximately 7–15 meters in diameter and 5–10 meters in depth. Residential spaces—such as bedrooms, kitchens, and storage rooms—are excavated along the surrounding walls and connected via narrow passageways, forming a secure, enclosed, and functionally coherent living system.
Condition:	Some of these spaces have gradually fallen into disuse due to the absence of modern infrastructure, while others have been repurposed for storage or tourism-related exhibitions. These dwellings now face the dual challenge of insufficient revitalization and cultural discontinuity.
	Case 9: The cave dwellings of Cappadocia
The cave dwellings of Cappadocia, Turkey	
Function:	The cave dwellings in Cappadocia were carved into the region's soft volcanic rock and have served residential, religious, and storage functions for centuries. Today, these structures have been repurposed as cultural heritage sites, tourist accommodations, and historical landmarks.
Condition:	However, rapid tourism expansion and urbanization have contributed to the degradation of some cave structures. In addition, excessive development and natural erosion continue to threaten their structural integrity. Accordingly, comprehensive conservation strategies are urgently needed to balance heritage preservation with contemporary use.
Noted: The images of Cases 1–7 in the Table were photographed by the author. The figures for Case 8 are sourced from [104] (https://doi.org/10.35788/uab.v2i1.95), and those for Case 9 are sourced from [105] (https://doi.org/10.2495/DN060061). Both sets of figures for Cases 8 and 9 are derived from publications under the CC BY 4.0 license, and therefore do not involve any copyright infringement.	

Figure 8. (continued)

adaptability coexist symbiotically, with ecological system stability supporting long-term adaptability of the cave dwelling environment, while dynamic adjustments in cave dwellings bolster ecological resilience. Cultural resilience reinforces heritage value by preserving historical memory and fostering identity, while economic resilience invigorates economic vitality through optimized resource allocation and industrial transformation.

The concept of HECM is derived from the social relationship and event coding logic proposed by Tilly[39], Hommel et al.[40], and Hauser and Featherman[41]. Following further refinement by Li et al.[112], Zhang et al.[30], and Liu et al.[45] in terms of event coding classification, organizational relationships, and weighting methods, this

Concept	Methodology
Ecological coupling: The structural stability and functional adaptability of kiln architecture in response to environmental changes, disaster impacts, and socio-economic transitions	Field investigation: Collecting multidimensional data on cave dwelling environments through on-site surveys and interviews to analyze local ecological and cultural characteristics comprehensively
Architectural resilience: The capacity of kiln architecture to maintain structural stability and functional adaptability amidst environmental shifts, disaster impacts, and socio-economic transformations	Value assessment: Constructing evaluation scales to quantify the ecological, cultural, and social value of kiln architecture, providing a scientific basis for prioritization in heritage conservation decision-making
Cultural resilience: The continuity and dynamic adaptability of cave dwelling environments in cultural heritage preservation, social cohesion, and local identity	Participatory decision-making: Engaging multiple stakeholders, including government, community, and expert teams, to enhance the scientific validity and social acceptance of collaborative planning and decision-making processes
Heritage economy: The potential of kiln architecture as a cultural heritage resource for transformation into tourism, cultural innovation, and green economic development	Event encoding: Applying event analysis methods to code significant historical milestones, uncovering the driving forces and architectural impacts of varying historical contexts on cave dwelling environments
Cultural empowerment: Promoting the modernization and sustainable dissemination of cave dwelling culture through technological innovation, educational outreach, and policy support	Multi-source data integration: Combining GIS, remote sensing data, and archival records to conduct longitudinal and cross-comparative analyses of case studies, validating the universality and practical feasibility of theoretical models

Table 9. The core concept and methodology of "ecologicality-architecture-resilience" in kiln architecture.

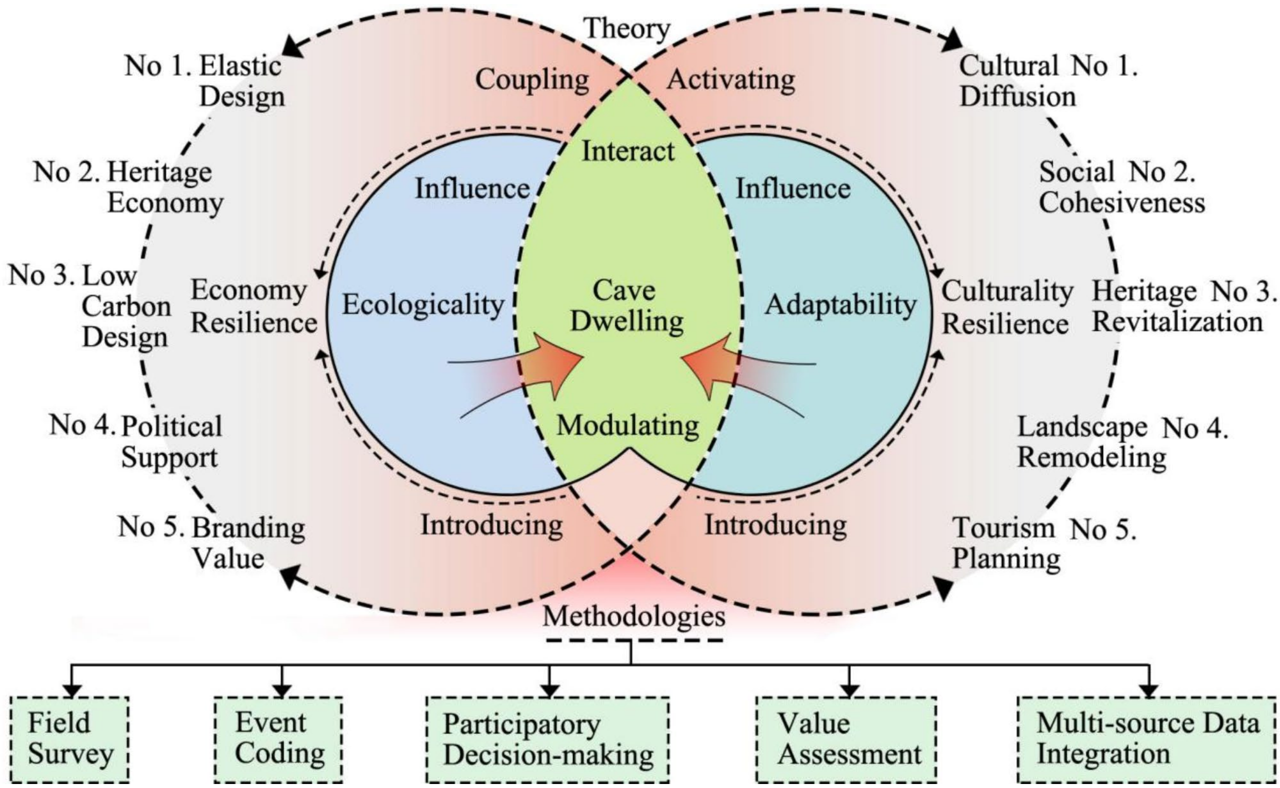


Fig. 9. Ecological protection strategy framework for the kiln built environment from the perspective of "ecologicality-architecture-resilience".

approach has been extended to thematic studies in fields such as cultural geography, material heritage, mural art, and decorative arts. Despite variations in the description of the method by these scholars, the fundamental logic remains similar. Therefore, the stratified event coding method exhibits both reproducibility and generalizability. This study provides a detailed explanation of the application steps of this method. For instance, it can be combined with the morphological quantitative typology proposed by Ao et al.[113,114], blending both quantitative and qualitative approaches to analyze the evolution of ceramic forms and social factors from different periods. Additionally, the method can integrate the relational sociology framework proposed by Li et al.[43], incorporating social capital variables into the contemporary application of art heritage transmission. Furthermore, by combining iconographic analysis methods such as "classification of character identity, decorative elements, character attire, and composition"[115,116], HECM can serve as a factor analysis tool, offering a fresh perspective on the stylistic formation of exported painting commodity art.

Research on kiln architecture reveals the applicability of traditional ecological knowledge to contemporary regional architectural practices. Environmental adaptability theory and vernacular architecture theory emphasize enhancing resilience through optimized spatial layout and material selection, while passive design focuses on thermal regulation and natural ventilation for improved indoor comfort. Zheng et al.[117] proposed a morphology-climate adaptation model highlighting the impact of architectural form and microclimate modulation on regional energy performance. Rawes[118], through his space-society interaction theory, underscored how the built environment shapes community behaviors and residential adaptability to foster environmentally responsive design. Building on these perspectives, this study develops an integrated ecological-cultural resilience framework that models the dynamic interrelations between ecological adaptation, cultural continuity, and functional evolution in kiln architecture. Methodologically, the research employs data mining, HECM, and multi-case studies to analyze the ecological and functional characteristics of kiln architecture, addressing gaps in understanding the environment-architecture-society nexus. Spatial organization and functional adaptability are shown to be influenced by both environmental factors (e.g., climate, topography, vegetation) and socio-cultural dynamics (e.g., residential patterns, community interaction, cultural identity). Huang et al.[119] proposed an architecture-environment coupling model, asserting that architectural forms must align with local ecosystem characteristics to ensure energy efficiency and thermal comfort. Accordingly, this study introduces an "ecologicality-architecture-resilience" framework to formulate conservation strategies for kiln architecture, revealing the interdependence between built form, climatic responsiveness, and cultural context, thereby contributing to heritage conservation and sustainable design. Alnaim and Noaime[120] further emphasized, through their theory of socio-spatial dynamics, that the revitalization of historic buildings must satisfy evolving cultural interaction needs to ensure sustainable heritage activation. This research reinforces the importance of spatial-cultural adaptation mechanisms and systematically categorizes different types, construction techniques, and ecological-cultural compatibility of kiln architecture, offering theoretical guidance for heritage protection, modernization, and management.

Since Plato[121], Western philosophy has centered on the metaphysical dichotomy of time and eternity. Heidegger's Being and Time[122] deconstructed this binary, uncovering the ontological significance and generative nature of time. This philosophical shift transformed how temporality is conceptualized in architecture. Giedion[123], drawing on the notion of the fourth dimension, argued that architecture is not merely a static object but a dynamic intersection of space, time, and social practice. He advocated for breaking away from linear conceptions of time in favor of fluidity and historical continuity. In a similar vein, Frampton[124], within the framework of critical regionalism, treated temporality as a bridge between architecture and place identity. He posited that architecture should respond to localized experiences rather than globalized technological imperatives, making time a foundational dimension in the interaction between built form and environment.

Philosophical methodologies in architecture transcend spatial perception and human-centered experience, profoundly influencing formal expression, material articulation, and environmental symbiosis. Hermeneutics, structuralism, and ecophenomenology have progressively permeated architectural discourse, especially in ecological and sustainable design. Their contributions include: (1) revealing how environmental factors shape spatial cognition and advancing ecological adaptability in design theory; (2) deconstructing architectural contexts to explore the cultural and symbolic significance of form; (3) emphasizing dynamic adaptation of buildings to natural environments, uncovering co-evolutionary relationships among architecture, ecosystems, and sociocultural systems; (4) providing a temporal continuity framework for heritage resilience research that integrates historical development, environmental change, and cultural adaptation.

The "Ecologicality-Architecture-Resilience" framework proposed in this study integrates the architectural practices of Wang Shu at the China Academy of Art's Xiangshan campus[125], Rafael Aranda at the Bell-Lloc Winery[126], Francis Kéré at the Gando Village design[127], and Berlanda's[128] approach, further developed based on the ecological characteristics of kiln-built environments. Theoretically, HECM provides an applied case for architectural heritage research. However, the linear analysis inherent in this method still falls short of fully revealing the complex relationships between ecology, architecture, and cultural resilience. The application of this framework in the conservation design of kiln architecture requires further exploration. Manzano-Fernández et al.[15] highlight the impact of cultural background differences on architectural conservation strategies, which raises the following key issues. How can the "Ecological-Architecture-Cultural Resilience" framework be adjusted to meet the specific needs of different cultural and ecological contexts? How can the new model reflect the non-linear interactions between ecology, architecture, culture, and social structures? How can the balance between traditional architectural conservation and modern ecological needs be achieved in different social contexts?

In response to these emerging issues, this study suggests integrating GIS and environmental simulation technologies to enhance the framework's adaptability to diverse ecological conditions, enabling it to accurately reflect regional characteristics and ecological changes. Additionally, the geographic scope of the research should be expanded, particularly to regions such as the Middle East, North Africa, and the Mediterranean, to validate the framework's generalizability and enhance its global applicability. Finally, it is essential to promote social participation in decision-making and uncover the deep-seated issues between kiln architecture, ecological protection, and neighborhood relations, thereby improving the sustainability and appropriateness of architectural preservation strategies.

One of the limitations of this study is the lack of a global comparison of kiln-built environments, due to practical constraints. Future research plans include a comparative study focusing on China, Japan, Southeast Asia, and other Asian regions as the first phase, followed by an analysis based on continental regions and climate in the second phase to further develop and refine the proposed theoretical framework. Against the backdrop of increasing globalization and environmental changes, the deterioration of ecological environments and the challenges in cultural heritage preservation have sparked profound reflection. Reevaluating the limitations of traditional architectural conservation methods requires achieving a balance across social, cultural, and ecological dimensions. The traditional "restorationist" concept is gradually being replaced by the more comprehensive "resilience-based conservation" approach, which focuses not only on the physical restoration of buildings but also on the holistic restoration of their historical, cultural, and ecological systems. This shift indicates that architectural heritage conservation in the new era is no longer merely about replication; instead, it aims to create an "ecologicality-architecture-resilience" framework that aligns with modern demands, thus expanding the depth and breadth of architectural heritage conservation. This new paradigm not only enhances the value of architectural heritage but also provides new pathways for sustainable conservation.

Conclusions

Findings: (1) marking the Middle Ages as a turning point, cultural archaeology and technological advancements shaped the primary trajectory of early kiln architecture development, driving functional transformation, heritage conservation, and ecological planning; (2) From the Ming Dynasty to the Republic of China era, political directives and technological innovations established alternative trajectories for China's kiln architecture, while economic development in the twenty-first century has notably supported cultural dissemination, improved technical standards, and facilitated ecological practices; (3) In terms of construction forms, the evolution of cave dwelling environments transitioned from hillside excavation to semi-subterranean forms, flat-ground covered structures, reinforced concrete-covered structures, and eventually freestanding forms; (4) Functionally, kiln architecture evolved from hazard avoidance to climate adaptation, followed by expanded applications (economic, religious, and defensive purposes), and finally energy-efficient design to meet practical needs; (5) Climate, topography, and soil quality were critical factors in shaping four main types of kiln architecture: the built-against-the-mountain style, the along-the-valley style, the sunken courtyard style, and the freestanding type. These architectures are primarily concentrated in Baoji, Yan'an, and Linfen, with fragmented distributions in Ningxia, Shaanxi, Henan, and Hebei; (6) Geological characteristics and material availability largely influenced the arched structures and construction methods of kiln architecture in six regions: Jinzhong, Longdong, Yuxi, Northern Shaanxi, Northern Chahar, and Inner Mongolia; (7) Balancing urban renewal, economic development, and heritage conservation remains a core challenge for the development of cave dwelling environments, with current issues including insufficient adaptive planning, lack of dynamic development, and limited stakeholder participation requiring greater attention.

Based on the HECM function of KH Coder, this study examines the developmental trajectory of cave dwellings and their relationship with the ecological environment. Through a comparative analysis of multiple cases, the research investigates the characteristics, ecological technologies, and conservation status of cave dwellings across different regions in China. Building on these findings, the study proposes an ecological conservation framework to address the challenges faced by these traditional architectural forms. The findings confirm the decisive role of natural conditions in shaping the forms and regional variations of kiln architecture, while the influence of modern technologies on shared characteristics across regions warrants further exploration. Through HECM, this study integrated fragmented research on the development of China's cave dwelling environments and reconstructed an analytical framework for the coupling relationship between ecological technologies and cultural adaptation, providing a foundational reference for design practice. The research findings align with the United Nations Sustainable Development Goal (SDG 15), which advocates for the protection, restoration, and sustainable use of terrestrial ecosystems.

Data availability

The data used to support the findings of this study are included within the article. The figures for Types a1–a2 in Fig. 8 and cases 8–9 in Table 7 are reproduced from publications licensed under CC-BY 4.0. The figures for Types b1, c1, and c2 in Fig. 8 and cases 1–7 in Table 8 were taken by the authors, and therefore do not involve any copyright issues. The geographic distribution maps presented in Table 5 were generated using ArcGIS 10.4 and Adobe InDesign CC 2017 (32-bit). Data download link: https://doi.org/10.6084/m9.figshare.28596758.

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Author contributions

Y.G., Y.Z., M.Y. and W.L. were responsible for preliminary research and data collection.R.L., X.W. and L.Y. provided conceptual design and wrote the first draft. R.L. and X.W. performed data analysis. R.L., L.Y. and W.L. reviewed and revised the manuscript. R.L. provided the research and project funding.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to L.Y.