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RESEARCH ARTICLE

Research on the Collaborative Mechanism of Cultural Heritage Conservation from the Perspective of Citizen Science Based on the "Quadruple Helix + Culture" Model

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ABSTRACT

In the contemporary context of constructing "resilient cities," cultural heritage, as a vital component of "cultural resilience," bears an extremely important mission. However, the protection, dissemination, and utilization of cultural heritage have gradually transcended the traditional scope of cultural relics conservation. It no longer relies solely on professionals in cultural heritage protection but increasingly demands the participation of the general public. Citizen science, as an emerging research paradigm, offers new ideas and pathways to break through the constraints of traditional heritage conservation models. Yet, current research and applications of citizen science in the field of cultural heritage conservation remain insufficient both domestically and internationally. In light of this, this paper aims to systematically review and analyze the application cases of citizen science in the United States, with the expectation of providing theoretical and practical support for the innovative development of cultural heritage conservation. Furthermore, based on this analysis, this paper proposes the theoretical model and application pathways of "Citizen Science + Quadruple Helix + Culture" in cultural heritage conservation, with the goal of offering new theoretical support and practical guidance for research and practice in related fields and promoting the development of cultural heritage conservation in a more scientific, democratic, and sustainable direction.

1. INTRODUCTION

The National Cultural Heritage Administration of China, in the Regulations for the Implementation of the Law of the People's Republic of China on the Protection of Cultural Relics, has pointed out that the current involvement of the public in the protection of domestic cultural heritage is largely confined to the construction of theoretical frameworks. Although public

archaeology activities have been carried out in some cities, there is still a lack of necessary and feasible practices. In particular, under the complex contemporary context, it is no longer feasible to rely on traditional methods and modes of thinking to recognize and protect heritage, nor is it possible to continue using the current effective conservation paradigms to further promote the protection and transmission of cultural heritage (Cheng, 2019).

Citizen science refers to open scientific research activities that involve non-professional scientists, science enthusiasts, and volunteers. Its scope encompasses the exploration of scientific questions, the development of new technologies, and the collection, analysis, and interpretation of data. As an emerging research paradigm, citizen science has broken through the constraints of traditional scientific research models by leveraging public participation and collective intelligence to address various challenges and problems in scientific activities, especially those that require extensive public engagement, diverse knowledge backgrounds, and geographically distributed efforts. Although citizen science originated in the natural sciences, it has rapidly developed in recent years across various fields, including ecology (Li, 2016), marine science, botany (Mulhauser & Gaille, 2024), archaeology, astronomy, biomedicine (Wiggins & Wilbanks, 2019), and tourism (Alony et al., 2020; Slavec et al., 2021). To date, numerous large-scale citizen science projects have been successfully implemented in the natural sciences, such as the Cornell Lab of Ornithology at Cornell University, the Galaxy Zoo project, and the Global Learning and Observations to Benefit the Environment (GLOBE) program (Zhang, 2017).

The contemporary idea of citizen science can be traced back to the Cornell Laboratory of Ornithology, jointly established by the National Audubon Society and Cornell University in 1915. This laboratory is recognized as the longest-standing institution for natural history research (Li, 2022). In 1965, the laboratory initiated a nest record project, one of the earliest organized efforts in North America to recruit amateur birdwatchers to collect data. In 1987, it launched the "Feeder Watch" project(He & Hu, 2022), which was one of the largest citizen science data collection efforts at the time.

However, the origin of the term "citizen science" remains a matter of debate in academia. Some scholars argue that the term first appeared in Alan Irwin's 1995 book Citizen Science: A Study of People, Expertise and Sustainable Development (*Citizen Science: A Study of People, Expertise and Sustainable Development*, 1995; He & Hu, 2022). In this book, Irwin, based on reflections on public understanding of science, attempted to promote the democratization of science through "citizen science" to address sustainable development issues. Other scholars suggest that the term originated from Rick Bonney's 1996 article Citizen Science: A Laboratory Tradition (Bonney, 1996), in which he first proposed "citizen science." Strictly speaking, the term should be credited to Irwin in 1995. Although both scholars independently introduced the concept of "citizen science," their focuses were significantly different: Irwin emphasized policy and theoretical reflection, while Bonney focused on scientific practice (He & Hu, 2022).

In subsequent research, although scholars have different understandings of the term "citizen science," they generally follow the two directions initiated by Irwin and Bonney. Gwen Ottinger has summarized that Bonney pioneered a "scientist-driven citizen science," (Collins & Evans, 2002)while Irwin represented a "social movement-based citizen science". In this study, we primarily adopt Irwin's practice-based "citizen science" as the theoretical foundation.

As the academic community's acceptance of the term citizen science has increased, it has demonstrated strong inclusivity and has become a rich, umbrella concept (Hecker et al., 2018). However, scholars still have different interpretations of the basic question "What is citizen science?" Common interpretations include:

(1) Viewing citizen science as an activity based on the concept of scientific crowdsourcing, focusing on the organizational models of citizen science (Zhao, 2017).

(2) As a pathway to promote social justice, such as the social movement-based citizen science highlighted by Gwen Ottinger, which often aims to address social injustices.

(3) As a research tool and method, such as citizen science projects used for ecological monitoring (Li, 2016; McClure et al., 2020).

(4) As a means of science communication and education, such as considering citizen science as an upgrade of the public understanding of science paradigm or using citizen science to achieve educational goals (Esmaeilian et al., 2018).

This paper primarily adopts the interpretations in (3) and (4).

In numerous domestic and international academic studies, citizen science is also referred to as crowd science, community science, public participation in scientific research, crowdsourcing, networked science, community-based participatory research, citizen sensing, and so on.

Given this context, the purpose of this study is to explore the innovative pathways for cultural heritage conservation from the perspective of citizen science. First, we analyze citizen science projects in the United States, one of the earliest countries to implement such projects, to summarize their characteristics. Based on this analysis, we attempt to preliminarily construct a theoretical pathway for cultural heritage conservation from the perspective of citizen science and propose further considerations and judgments. This study aims to draw implications for current cultural heritage conservation theory and practice in China and around the world, making cultural heritage a vibrant carrier of public engagement and a transmitter of the cultural heritage of humanity.

2. CASE ANALYSIS OF U.S. CITIZEN SCIENCE PROJECTS

The United States places great emphasis on the development of citizen science. In 2015, the White House Office of Science and Technology Policy (OSTP) released a report titled "Addressing Societal and Scientific Issues through Citizen Science and Crowdsourcing." In 2017, the OSTP's Exit Memo specifically identified citizen science as one of the top 20 priority areas for the new U.S. administration and published the first report on citizen science projects, titled Implementation of Federal Prize and Citizen Science Authority: Fiscal Years 2017-18. As one of the earliest countries to implement citizen science projects, the United States provides valuable lessons for exploring the pathways of cultural heritage conservation from the perspective of citizen science in China.

The CitizenScience.gov website, developed in collaboration between the U.S. General Services Administration (GSA) and the Woodrow Wilson International Center for Scholars (Wilson Center), aims to increase public participation in the scientific process to enhance the

transparency and openness of scientific data collection and results. It also provides an open pathway for collaboration between the federal government and the public to advance scientific research. According to the data available on CitizenScience.gov, the website currently lists 503 citizen science projects. The following analysis is based on these projects.

2.1. Early Initiation and Rich Experience

According to the data from CitizenScience.gov, the earliest citizen science project in the United States was in the field of meteorology, dating back to the National Weather Service Cooperative Observer Program of 1890. Initiated by an act of the U.S. Congress in 1890, this program aimed to provide daily weather observations to support weather forecasting and public services. To date, the program has nearly 10,000 volunteers across the country conducting measurements and has become a cornerstone of the most authoritative weather data sources in the United States. Other early projects include the NOAA NWS SKYWARN® Weather Spotter Program (1965), the North American Breeding Bird Survey (1966), and the Midwinter Bald Eagle Survey (1979).

Table 1 lists the top 10 U.S. citizen science projects in chronological order. The table shows that although the term "citizen science" was formally introduced around 1965, the United States had already launched its first citizen science project in 1890. This early start has provided a long history and rich experience in citizen science. However, there was a surge in the number of citizen science projects around 1990, following the First Citizen Science Festival held in San Francisco in 1989 by the American Association for the Advancement of Science (AAAS), which formally integrated citizen science into educational activities.

Table 1: Top 10 U.S. Citizen Science Projects in Chronological Order

No.	Project Name	Year Initiated	Fields Involved
1	National Weather Service Cooperative Observer Program	1890	Climate and Weather
2	NOAA NWS SKYWARN® Weather Spotter Program	1965	Climate and Weather
3	North American Breeding Bird Survey	1966	Animals, Biology, Birds, Ecology & Environment, Education, Nature & Outdoors
4	Midwinter Bald Eagle Survey	1979	Biology, Chemistry, Ecology & Environment, Nature & Outdoors, Marine/Water & Ocean
5	Elkhorn Slough Volunteer Water Quality Monitoring	1988	Animals, Biology, Ecology & Environment, Health & Medicine, Nature & Outdoors, Marine/Water & Ocean, Science Policy
6	The Delaware Bay Horseshoe Crab Survey	1990	Animals, Biology, Ecology & Environment, Nature & Outdoors, Marine/Water & Ocean
7	Nonindigenous Aquatic Species (NAS) Program	1990	Animals, Birds, Ecology & Environment

8	Rocky Mountain National Park Christmas Bird Count	1990	Biology, Ecology & Environment, Education, Nature & Outdoors, Marine/Water & Ocean
9	Student Watershed Research Project	1991	Computer & Technology, Disaster Response, Geology & Earth Science, Geography
10	The National Map Corps	1994	Biology, Chemistry, Ecology & Environment, Nature & Outdoors, Marine/Water & Ocean

2.2. Diverse Research Fields

An analysis of the fields involved in citizen science projects listed on CitizenScience.gov reveals that these projects cover a wide range of areas, including animals, archaeology, climate and weather, birds, biology, education, and social sciences. A detailed statistical analysis of the project fields is presented in Table 2. It is important to note that the projects listed on CitizenScience.gov are not limited to a single field but often involve multiple areas. For example, the "Rocky Mountain Butterfly Project" encompasses animals, biology, ecology and environment, pollinators/insects, and nature and outdoors.

Overall, citizen science projects in the United States show higher levels of public participation in the natural sciences (such as nature and outdoors, biology, and ecology and environment) and in the field of education. There is also significant public engagement in areas related to animals, oceans, climate, and weather. However, projects related to policy, psychology, social sciences, and archaeology and culture are relatively fewer in number.

Cultural heritage conservation is, to a certain extent, an important component of the fields of archaeology and culture. However, internationally, there is a scarcity of research on citizen science in archaeology and culture, and thus, limited experiences to draw upon. Further research is needed to explore the application of citizen science in archaeology and culture, identify effective models of public participation, and determine how citizen science projects can better promote the protection and transmission of cultural heritage.

Table 2: Distribution of U.S. Citizen Science Projects by Field of Involvement

No.	Field	Number	No.	Field	Number
1	Nature & Outdoors	319	13	Chemistry	36
2	Biology	278	14	Science Policy	33
3	Ecology & Environment	235	15	Geography	32
4	Education	217	16	Astronomy & Space	30
5	Animals	131	17	Disaster Response	29
6	Marine/Water & Ocean	91	18	Social Sciences	25
7	Climate & Weather	89	19	Food	20
8	Computer & Technology	82	20	Archaeology & Culture	19

9	Geology & Earth Science	61	21	Physics	16
10	Birds	57	22	Transportation	9
11	Pollinators/Insects	53	23	Psychology	4
12	Health & Medicine	45	24	Economics & Environment	1

2.3. Diversity of Participating Institutions

The funding required for citizen science projects is a noteworthy issue, as many laboratories have limited budgets and struggle to cover the costs associated with citizen science initiatives. An analysis of the funding sources for the 503 projects listed on the CitizenScience.gov website reveals that the most significant funder is the National Park Service, which has supported 156 projects. The National Science Foundation and the National Oceanic and Atmospheric Administration follow, funding 55 and 48 projects, respectively. The top five funding institutions are detailed in Table 3.

In conjunction with the analysis of the fields of citizen science projects in Section 2, which shows that the fields of nature and outdoors, ecology, and education are among the most prominent, it is evident that the substantial public participation in these areas is largely due to the financial, resource, and policy support provided by relevant government agencies. By analogy, in the field of cultural heritage conservation, how government agencies can provide necessary financial support, policy guidance, and resource allocation to enhance public awareness of heritage protection and thereby promote the in-depth development of citizen science projects in this area remains a topic worthy of further exploration.

Table 3: Top 5 Funding Institutions for U.S. Citizen Science Projects

No.	Institution	Number of Funded Projects	Percentage	Representative Project
1	National Park Service	156	31%	North American Bird Phenology Program
2	National Science Foundation	55	11%	Quake Catcher Network
3	National Oceanic and Atmospheric Administration	48	10%	The Hudson River Eel Project
4	U.S. Environmental Protection Agency	43	9%	IDAH2O Master Water Stewards
5	National Aeronautics and Space Administration	22	4%	The GLOBE Program's Globe Observer App

In conclusion, citizen science projects in the United States are primarily concentrated in the fields of nature and biology, with the majority of these projects funded by federal government

agencies. In most citizen science projects, public participation is often limited to providing the data required for scientific research or experimentation, such as observing and recording wildlife, monitoring weather patterns, or tracking plant growth. While this mode of participation has played a significant role in data collection, it also raises important questions about the role of citizen science: Can public participation extend beyond the role of mere data providers?

3. THEORETICAL MODEL OF CITIZEN SCIENCE IN CULTURAL HERITAGE CONSERVATION

During the development of citizen science, scholars have proposed various models or stages of public participation in scientific research for different application fields. For example, Bonney (Bonney et al., 2009; Lian et al., 2018)divided the implementation of citizen science projects at the Cornell Lab of Ornithology into nine stages: "Selecting a scientific question → Assembling a team of scientists/educators/technologists/evaluators → Developing data forms and related materials → Recruiting participants → Training participants → Editing data → Analyzing data → Disseminating results → Measuring outcomes." Peng et al., (2022) focusing on the mechanisms and roles of public participation in science, proposed a "dual triple helix model" consisting of "industry-academia-government" and "public-academia-government" (see Figure 1). Shirk et al., (2012) categorized the operation process of citizen science projects into five stages based on their organizational patterns: "input-action-output-outcome-impact."Niu et al., (2017) based on the Evolution MegaLab project, summarized the operational mechanism of citizen science projects into three major phases: pre-investment, mid-action, and post-output.

In exploring the application pathways of citizen science in cultural heritage conservation, this study first draws on the "quadruple helix model" of knowledge production dynamics and, based on the unique characteristics of cultural heritage conservation, proposes the "quadruple helix model + culture" theoretical framework from the perspective of citizen science. Subsequently, application pathways are developed based on this framework.

The "quadruple helix model" of knowledge production dynamics evolved from the "triple helix model" initially proposed by Etzkowitz & Leydesdorff (1995) to explain the dynamic interactions among academia, industry, and government in promoting entrepreneurship, innovation, and economic growth in a knowledge-based economy. Later, Carayannis and Campbell (E. Carayannis & Campbell, 2009)added public or civil society as the fourth helix, transforming it into the "quadruple helix model."

Although Carayannis and Campbell later introduced a fifth helix—natural environment—into the quadruple helix model (E. G. Carayannis & Campbell, 2012), the quintuple helix model addresses the socio-ecological transformation of society and economy in the twenty-first century and brings an ecologically sensitive perspective to discussions on innovation and knowledge production, it is not considered in this study. Given the unique nature of cultural heritage conservation, this paper has incorporated the broader concept of "culture" into the theoretical framework and therefore does not draw on the fifth helix at present.

From the perspective of citizen science, the field of cultural heritage conservation has proposed the "quadruple helix model + culture" theoretical framework. The "four" in this model represents the four key participants: academia, industry, government, and civil society. Against

the backdrop of citizen science, these four sectors collaborate closely and share knowledge to jointly enhance the efficiency and optimize the outcomes of cultural heritage conservation. This cross-sector synergy not only integrates resources from various parties but also promotes communication and understanding among different stakeholders, thereby forming a collective force for cultural heritage conservation.

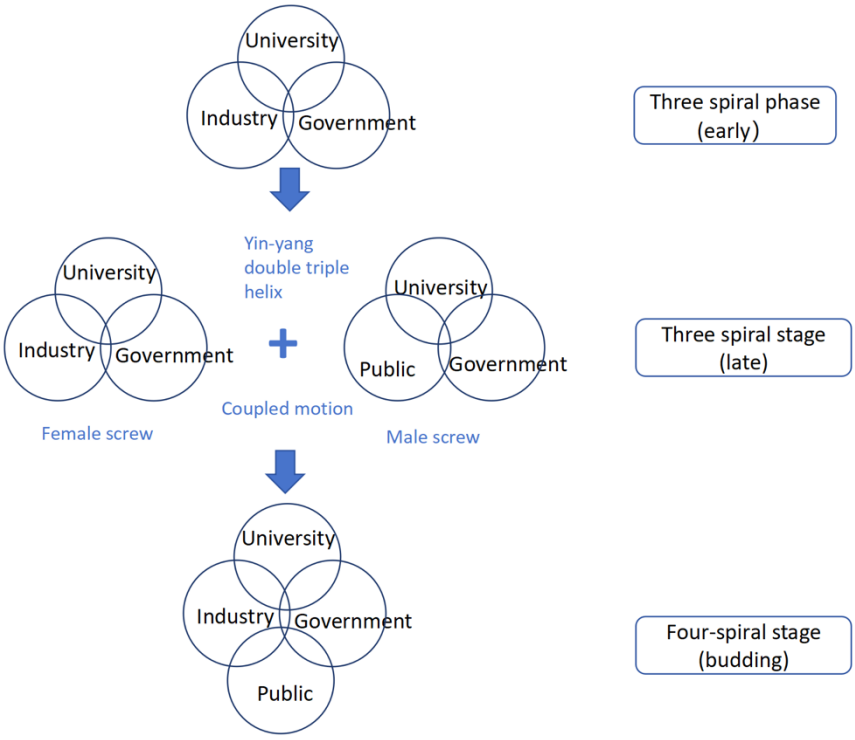

Figure 1: Evolution of the Triple Helix to Quadruple Helix Model Structure (Adapted from (Huang & Wang, 2018))

The term "helix" reveals the dynamic interplay among these four sectors. Each sector promotes and develops together in the process of cultural heritage conservation, presenting a spiral upward trend. This spiral development model emphasizes the dynamism and continuity of cultural heritage conservation, implying that conservation is not a one-time task but a long-term process that needs to continuously adapt to changes in society, economy, and technology. Through this dynamic spiral mechanism, cultural heritage conservation can continuously absorb new concepts and technologies to achieve sustainable development.

"Culture" is the core element of this theoretical model, originating from the unique nature of cultural heritage conservation. Cultural heritage conservation involves not only the tangible protection of the "intrinsic value" of heritage but also the intangible protection of the "symbolic value" embedded in the social environment and cultural connotations. This "symbolic value" reflects the profound significance of cultural heritage at the social, historical, and cultural levels and is at the heart of cultural heritage conservation. Therefore, "culture" permeates the entire process of cultural heritage conservation from the perspective of citizen science, emphasizing the comprehensiveness and depth of conservation work.

In the context of citizen science, public participation in the field of cultural heritage

conservation should not be limited to the role of data providers. As users and beneficiaries of cultural heritage, the public should be granted broader participation rights and responsibilities to play a more active role in the protection and dissemination of cultural heritage. Deepening public participation not only helps enhance public awareness and identification with cultural heritage conservation but also promotes the widespread dissemination of conservation concepts at the societal level. As reflected in the paradigm shift in the field of cultural heritage conservation, from the traditional "fabric-focused approach" to the "values-led approach," the application of citizen science provides new impetus and pathways for this transformation.

Under the "values-led" paradigm, cultural heritage conservation no longer focuses solely on the maintenance of physical forms but places greater emphasis on the cultural values, social significance, and historical memories embodied in cultural heritage. The involvement of citizen science offers new perspectives and methods for this paradigm shift, enabling cultural heritage conservation to better align with social needs and public preferences and to achieve the living transmission and sustainable development of cultural heritage. Through the practice of citizen science, cultural heritage conservation can further expand its connotations and extensions, transforming from mere conservation work to the transmission and innovation of cultural heritage, thereby laying a solid foundation for the future development of cultural heritage.

Based on this, the "quadruple helix model + culture" theoretical framework for cultural heritage conservation is shown in Figure 2 below.

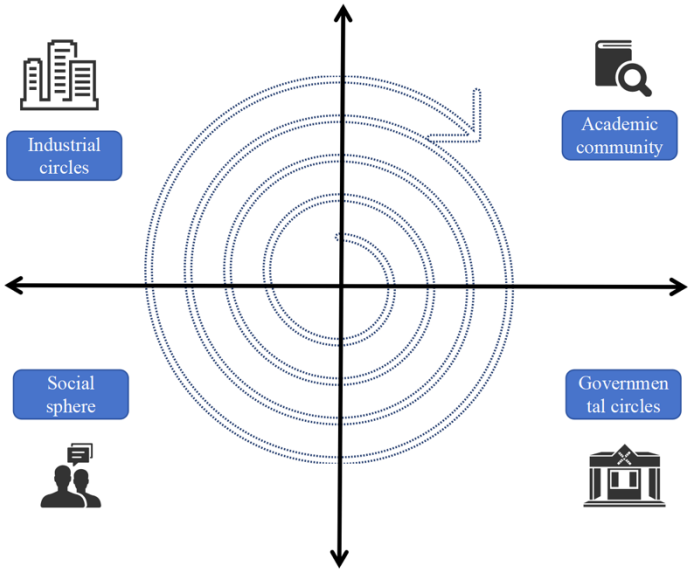

Figure 2: The "Quadruple Helix Model + Culture" Theoretical Framework for Cultural Heritage Conservation

4. APPLICATION PATHWAYS OF CITIZEN SCIENCE IN CULTURAL HERITAGE CONSERVATION

4.1. Application Pathways

Based on the "quadruple helix model + culture" theoretical framework, the macro-level

pathways for applying citizen science in cultural heritage conservation can be systematically constructed from project design to dissemination of outcomes, as detailed below.

4.1.1. Project Design and Planning: Goal-Oriented and Resource Integration

At the inception of a citizen science project in cultural heritage conservation, clarifying project goals is essential. The project should center on the protection and transmission of cultural heritage while enhancing public awareness and participation. Project planning must encompass a detailed timeline, budget allocation, resource requirements, and expected outcomes to ensure systematic and feasible implementation. Additionally, project design should consider diverse public participation methods, such as site surveys, data collection, and environmental monitoring, to ensure deep engagement in cultural heritage conservation activities.

4.1.2. Team Formation and Role Clarification: Interdisciplinary Collaboration and Knowledge Sharing

The formation of the project team is critical to its success. Building an interdisciplinary team is essential, comprising archaeologists, historians, education experts, project managers, and representatives from industry and government sectors. Through collaborative efforts, the team can integrate professional knowledge and resources from various fields to form a cohesive force for cultural heritage conservation. Clear roles and responsibilities for each team member are necessary to facilitate efficient communication and collaboration, driving knowledge sharing and collaborative innovation.

4.1.3. Public Recruitment and Training: Diverse Participation and Capacity Building

To ensure smooth project implementation, it is necessary to widely recruit members of the public who are interested in cultural heritage conservation, with an emphasis on diversity, including participants of different ages, occupations, and social backgrounds. Volunteers should receive systematic training before participating in the project, covering basic knowledge of cultural heritage conservation, data collection methods, understanding of cultural connotations, and communication skills. Through training, the scientific literacy and conservation awareness of the public can be enhanced, enabling them to better engage in cultural heritage conservation activities.

4.1.4. Project Implementation and Data Collection: Cultural Connotation Protection and Knowledge Sharing

During the implementation phase, the project must strictly follow the planned schedule to ensure the effectiveness and safety of public participation. Emphasis should be placed on the protection and dissemination of the cultural connotations of cultural heritage, highlighting its social value and symbolic significance. If data collection is involved, the public should operate under professional guidance to ensure data accuracy and reliability. The collected data should be scientifically analyzed to support decision-making in cultural heritage conservation and promote interaction and collaboration among academia, industry, government, and civil society through knowledge-sharing mechanisms.

4.1.5. Project Acceptance and Evaluation: Outcome Verification and Continuous Improvement

After the project concludes, a comprehensive assessment of the project outcomes is necessary to ensure that the expected goals have been achieved. The evaluation should cover multiple dimensions, including public participation levels, the impact of project outcomes, and the efficiency of collaboration. Through a scientific evaluation system, the experiences and shortcomings of the project can be summarized to provide recommendations for future citizen science projects in cultural heritage conservation, driving continuous optimization of conservation efforts.

4.1.6. Project Dissemination and Education: Outcome Sharing and Public Advocacy

The outcomes of the project should be widely disseminated through various channels, such as academic seminars, research reports, and social media, to enhance public understanding and awareness of cultural heritage conservation. Emphasis should be placed on the symbolic and socio-cultural significance of cultural heritage during dissemination. Educational and advocacy activities should be used to inspire greater public engagement in cultural heritage conservation. Additionally, project outcomes can serve as educational resources for school curricula and community outreach, further expanding the influence of citizen science in the field of cultural heritage conservation.

Through the systematic design and implementation of the above macro-level pathways, the application of citizen science in cultural heritage conservation can not only enhance the efficiency of conservation efforts but also promote the widespread dissemination and social acceptance of conservation concepts. This approach supports the paradigm shift from a "fabric-focused" to a "values-led" approach in cultural heritage conservation, achieving sustainable development in the field.

4.2. Key Elements

In addition to the pathways discussed above, the application of citizen science in cultural heritage conservation under the "quadruple helix model + culture" framework must fully consider the following key elements to ensure its scientific rigor, systematic approach, and sustainability.

4.2.1. Multi-Domain Collaboration: Building an Ecosystem for Cultural Heritage Conservation

The macro-level pathways of citizen science in cultural heritage conservation first manifest in the collaborative efforts among academia, industry, government, and civil society. This multi-domain cooperation integrates resources from various sectors to form an ecosystem for cultural heritage conservation, promoting comprehensive and systematic development in this field.

Academia: As the primary producer of knowledge, academia is responsible for providing scientific and technical guidance. By researching conservation techniques, cultural value assessments, and public participation models, academia lays a solid theoretical foundation for cultural heritage conservation. Moreover, academia should deeply engage with citizen science projects through popular science and educational activities to enhance public scientific literacy and conservation awareness.

Industry: Industry supports cultural heritage conservation through financial contributions,

technological tools, and innovative solutions. For example, companies can develop digital platforms and virtual reality tools for cultural heritage, facilitating public participation. Such investments not only improve conservation efficiency but also bring social and economic benefits to the industry.

Government: The government plays a crucial role in policy guidance and financial support. By enacting laws and regulations, establishing special funds, and promoting citizen science projects, the government provides institutional and resource support for cultural heritage conservation. Policy support from the government is one of the key factors for the sustainable development of cultural heritage conservation.

Civil Society: Civil society, including the public, non-governmental organizations, and communities, is the core participant in citizen science. Through citizen science projects, civil society can directly engage in cultural heritage conservation by providing data, participating in monitoring, and disseminating cultural values. Widespread public participation not only strengthens the social foundation of cultural heritage conservation but also enhances public identification with and sense of belonging to cultural heritage.

4.2.2. Expanding the Depth and Breadth of Public Participation

The macro-level pathways of citizen science in cultural heritage conservation also involve expanding the depth and breadth of public participation. The public should not merely be data providers but active contributors and disseminators of cultural heritage conservation.

Depth of Participation: The public can engage in the entire process of cultural heritage conservation, including project design, data collection and analysis, and the formulation of conservation strategies. For example, through citizen science projects, the public can participate in the digital recording, historical research, and testing of conservation techniques for cultural heritage. This deep involvement not only enhances public scientific literacy but also strengthens their sense of responsibility for cultural heritage conservation.

Breadth of Participation: Citizen science projects should encourage broader social groups, including students, volunteers, and community residents, to participate. Through education and training, public awareness of cultural heritage conservation can be enhanced, leading to active engagement in its protection and dissemination. This broad participation expands the social base for cultural heritage conservation, creating a positive scenario of collective involvement.

4.2.3. Dissemination and Education of Cultural Values

The macro-level pathways of citizen science in cultural heritage conservation also involve the dissemination and education of cultural values. Cultural heritage conservation is not only about protecting material heritage but also about transmitting and disseminating its cultural connotations.

Education and Training: Through citizen science projects, educational activities targeting different groups can be conducted to enhance public awareness of cultural heritage conservation and scientific literacy. For example, schools can offer courses on cultural heritage conservation, and communities can organize lectures and activities. These educational activities not only

improve public knowledge levels but also strengthen their identification with cultural heritage conservation.

Cultural Dissemination: Citizen science projects can use digital platforms and social media to disseminate the value of cultural heritage to a broader audience. For example, through virtual reality technology, the public can remotely visit cultural heritage sites and learn about their historical and cultural backgrounds. This mode of dissemination not only expands the influence of cultural heritage but also promotes its living transmission.

4.2.4. Dynamic Spiral Development Model

The macro-level pathways of citizen science in cultural heritage conservation also involve a dynamic spiral development model. This model emphasizes the continuity and dynamism of cultural heritage conservation, achieving a spiral upward trend through interactions and cooperation among various parties.

Knowledge Sharing and Feedback Mechanisms: By establishing knowledge-sharing platforms and feedback mechanisms, academia, industry, government, and civil society can exchange information in real-time, share research outcomes, and practical experiences. This dynamic interaction promotes innovation in cultural heritage conservation techniques and optimization of conservation strategies. For example, through regular seminars and workshops, all parties can share the latest research findings and practical experiences, driving continuous development in cultural heritage conservation.

Iteration and Upgrading of Citizen Science Projects: Citizen science projects should continuously iterate and upgrade based on the actual needs of cultural heritage conservation and social feedback. For example, by introducing artificial intelligence and big data technologies, citizen science projects can more efficiently collect and analyze data related to cultural heritage, improving conservation efficiency. This iterative upgrading not only enhances the scientific validity and effectiveness of the projects but also improves the public's participation experience.

4.2.5. Paradigm Shift from "Fabric-Centered" to "Value-Led" Approaches

The macro-level pathways of citizen science in cultural heritage conservation also involve promoting a paradigm shift in the field. Moving from the traditional "fabric-centered" approach to a "value-led" approach, citizen science projects can better reflect the "symbolic value" of cultural heritage.

Value Assessment and Conservation: Citizen science projects can involve the public in comprehensive assessments of the cultural, social, and historical values of cultural heritage, thereby formulating more targeted conservation strategies. This value-led conservation strategy focuses not only on the physical form of cultural heritage but also on its cultural connotations and social significance.

Active Public Participation: Citizen science projects encourage the public to shift from passive participants to active conservators and disseminators. Through active public involvement, cultural heritage conservation can better integrate into social life, achieving the living transmission of cultural heritage. This public participation not only strengthens the social

foundation of cultural heritage conservation but also enhances public identification with and sense of belonging to cultural heritage.

5. CONCLUSION

The protection of cultural heritage is now inextricably linked to the public. The theoretical and practical significance of "protection" extends beyond the preservation and restoration of existing physical forms to include the spiritual transmission carried by intangible elements. In contemporary discussions on heritage conservation, public participation is no longer a peripheral issue but a central concern. The necessity of researching, understanding, and clarifying public participation in cultural heritage conservation has become increasingly evident, emerging as a crucial topic that the international heritage conservation community must confront.

Given this context, this study introduces citizen science into the process of cultural heritage conservation, pioneering a new model that transcends the traditional framework dominated by professionals. By mobilizing broader social forces and promoting knowledge sharing and public engagement, this approach aims to enhance the scientific, democratic, and sustainable development of heritage conservation.

Firstly, through a systematic review and in-depth analysis of the development of citizen science and relevant case studies in the United States, this study has validated the feasibility and effectiveness of citizen science in cultural heritage conservation. These case studies not only provide valuable experience for heritage conservation efforts but also offer empirical support for the construction of theoretical models and the formulation of practical pathways. Based on these analyses, the "quadruple helix model + culture" theoretical framework was proposed, emphasizing collaborative efforts among government, academia, industry, and the public. Through the interaction and cooperation of multiple stakeholders, this model aims to advance the scientific, democratic, and sustainable development of heritage conservation.

Furthermore, this study explores the application pathways of citizen science in cultural heritage conservation. Overall, this research makes a significant contribution to the theoretical and practical aspects of heritage conservation. By proposing pathways for citizen science in cultural heritage conservation, this study offers important theoretical innovations and practical value. Looking to the future, as citizen science continues to evolve and be applied more broadly, cultural heritage conservation is expected to achieve greater progress in terms of scientific rigor, public participation, and sustainability. This will contribute significantly to building more resilient cities.

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CONFLICT STATEMENT

The authors declare no conflict of interest.

COOPERATION STATEMENT

All authors contributed equally to this work and approved the final manuscript.

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