Technology-Enhanced Cultural Heritage Education: A Socio-Technical Framework for Measuring Learning Efficacy and Community Engagement

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Abstract: Cultural heritage education (CHE) plays a pivotal role in preserving intangible cultural assets and fostering cultural identity. However, traditional CHE models face limitations in interactivity, accessibility, and personalized learning, while the effectiveness of technology-integrated interventions remains underexplored. This study proposes a socio-technical framework integrating virtual reality (VR) experiences, gamified learning modules, and community co-creation platforms to enhance CHE outcomes. A mixed-methods research design was adopted, combining Difference-in-Differences (DID) analysis, Partial Least Squares Structural Equation Modeling (PLS-SEM), and Random Forest (RF) algorithm to evaluate the framework's impact.A total of 240 participants from three cultural heritage sites in China were divided into experimental groups (technology-enhanced CHE, n = 160) and control groups (traditional lecture-based CHE, n = 80). Quantitative results showed that the experimental group achieved significantly higher learning outcomes (DID = 0.187, $p < 0.001$) and community engagement (DID = 0.213, $p < 0.001$) compared to the control group. PLS-SEM identified VR immersive experience ($\beta = 0.342$, $p < 0.001$) and gamified task completion ($\beta = 0.297$, $p < 0.001$) as key predictors of learning efficacy, while RF analysis revealed cultural identity (importance weight = 38.6%) and social interaction (importance weight = 32.1%) as dominant factors influencing community engagement. Qualitative findings from interviews and focus groups further confirmed the framework's ability to bridge technological accessibility and cultural authenticity.This study contributes to CHE theory by establishing a socio-technical evaluation model that integrates learning outcomes and community engagement. Practically, it provides evidence-based guidelines for designing technology-enhanced CHE programs, emphasizing the synergy between immersive technologies, gamification, and community participation. The findings offer valuable insights for cultural heritage managers, educators, and policymakers seeking to innovate CHE practices in the digital era.

Keywords: Cultural heritage education; Socio-technical framework; Virtual reality; Gamification; Learning efficacy; Community engagement

1 Introduction

1.1 Research Background

Cultural heritage education (CHE) is recognized as a core component of sustainable development, aligning with UNESCO's Sustainable Development Goals (SDGs) 4 (Quality Education) and 11 (Sustainable Cities and Communities) [9]. It aims to transmit cultural knowledge, preserve intangible heritage, and cultivate cultural identity among individuals of all ages [4]. However, traditional CHE approaches–predominantly lecture-based, museum-centric, and one-way knowledge transmission–often fail to engage younger generations and diverse audiences [5]. These models suffer from limited interactivity, accessibility barriers for remote communities, and a lack of personalized learning pathways [1].

The rapid advancement of digital technologies, such as virtual reality (VR), augmented reality (AR), and gamification, has opened new avenues for CHE innovation [1]. VR enables immersive experiences that replicate cultural sites and historical contexts, while gamification incorporates game mechanics (e.g., rewards, challenges, narratives) to enhance learning motivation [7]. Additionally, community co-creation platforms facilitate public participation in cultural heritage preservation, strengthening the connection between learners and cultural assets [3]. Despite these advancements, existing technology-integrated CHE programs often prioritize techni-

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cal novelty over educational effectiveness, lacking systematic evaluation of learning outcomes and community impact [6].

A critical research gap exists in understanding how socio-technical systems–integrating technology, education, and community–can optimize CHE outcomes. Current studies primarily focus on single technologies or short-term interventions, with limited attention to: (1) the synergistic effects of multiple technologies (e.g., VR + gamification); (2) the relationship between learning efficacy and community engagement; (3) the key factors influencing the success of technology-enhanced CHE. Addressing these gaps is essential to develop evidence-based CHE practices that balance technological innovation, educational goals, and cultural authenticity.

1.2 Research Objectives and Questions

This study aims to develop and validate a socio-technical framework for technology-enhanced CHE, addressing three core research questions:

RQ1: Does the socio-technical framework (VR + gamification + community co-creation) improve learning efficacy and community engagement compared to traditional CHE?

RQ2: What are the key predictors of learning efficacy and community engagement in technology-enhanced CHE?

RQ3: How do cultural identity and social interaction moderate the relationship between technological interventions and CHE outcomes?

1.3 Significance of the Study

The theoretical significance of this study is that it expands CHE theory by proposing a socio-technical evaluation model that integrates learning outcomes and community engagement, bridging the gap between technology adoption and educational effectiveness. It also advances the understanding of moderating factors (e.g., cultural identity) in technology-enhanced learning contexts.

The practical significance is that the framework provides actionable guidelines for cultural heritage institutions, educators, and technology developers to design effective CHE programs. It offers tools for evaluating the impact of technological interventions, ensuring that innovations align with educational goals and community needs.

2 Literature Review

2.1 Traditional vs. Technology-Enhanced CHE

Traditional CHE relies on static resources (e.g., textbooks, museum exhibits) and passive learning, leading to low engagement and knowledge retention [5]. In contrast, technology-enhanced CHE leverages immersive and interactive tools to create dynamic learning experiences. VR, for example, has been used to simulate historical events (e.g., ancient Chinese architecture construction) and cultural practices (e.g., traditional craftsmanship), enabling learners to "experience" heritage rather than merely observe it [1]. Gamification, through elements like quests, badges, and leaderboards, enhances motivation and sustained participation [7]. However, studies show that technology alone is insufficient–effective CHE requires alignment between technological features, cultural content, and learning objectives [1].

2.2 Learning Efficacy and Community Engagement in CHE

Learning efficacy in CHE is measured by knowledge acquisition, cultural understanding, and skill development [4]. Previous research indicates that immersive technologies improve knowledge retention by up to 40% compared to traditional methods [6]. Community engagement, defined as active participation in cultural heritage preservation and dissemination, is a critical outcome of CHE, as it fosters a sense of ownership and sustainability [3]. Community co-creation platforms, which allow users to contribute content (e.g., stories, photos, videos) about cultural heritage, have been shown to strengthen community bonds and cultural identity [8].

2.3 Socio-Technical Systems in Education

Socio-technical systems theory emphasizes the interaction between technical tools and social contexts (e.g., learners, communities, cultural norms) [2]. In educational settings, this means that technology effectiveness depends on how well it integrates with learning goals, user needs, and cultural contexts. For CHE, a socio-technical approach must consider: (1) technical features (e.g., VR immersion, gamification mechanics); (2) social factors (e.g., social interaction, community participation); (3) cultural factors (e.g., cultural authenticity, identity formation) [2]. Despite the relevance of this theory, few studies have applied it to CHE, limiting our understanding of how technology, education, and community interact to shape outcomes.

2.4 Research Gaps

Most technology-enhanced CHE studies focus on single technologies, ignoring the synergistic effects of multiple tools. Limited research examines the relationship between learning efficacy and community engagement. Few studies use mixed-methods designs to systematically evaluate CHE outcomes, relying primarily on qualitative feedback or short-term assessments.

3 Research Framework and Hypotheses

3.1 Socio-Technical Framework for CHE

The proposed framework integrates three core components. The technical layer includes VR immersive experiences (replicating cultural sites/contexts) and gamified learning modules (quests, challenges, rewards). The educational layer includes learning objectives aligned with cultural heritage knowledge (e.g., history, craftsmanship) and skills (e.g., critical thinking, cultural interpretation). The social layer includes community co-creation platforms (user-generated content, discussions) and social interaction features (peer collaboration, expert guidance). The source manuscript describes Figure 1 as a socio-technical framework for technology-enhanced CHE showing

Characteristic	Experimental Group (n = 160)	Control Group (n = 80)	Total (n = 240)
Gender	Male: 76 (47.5%); Female: 84 (52.5%)	Male: 38 (47.5%); Female: 42 (52.5%)	Male: 114 (47.5%); Female: 126 (52.5%)
Age	18-25: 80 (50.0%); 26-65: 80 (50.0%)	18-25: 40 (50.0%); 26-65: 40 (50.0%)	18-25: 120 (50.0%); 26-65: 120 (50.0%)
Education	Bachelor+: 96 (60.0%); Below Bachelor: 64 (40.0%)	Bachelor+: 48 (60.0%); Below Bachelor: 32 (40.0%)	Bachelor+: 144 (60.0%); Below Bachelor: 96 (40.0%)

Table 1. Demographic Characteristics of Participants

three interconnected layers: Technical Layer (VR Immersion, Gamification), Educational Layer (Knowledge Acquisition, Skill Development), Social Layer (Community Co-creation, Social Interaction), with outcomes including Learning Efficacy and Community Engagement.

3.2 Research Hypotheses

Based on the framework and literature review, the following hypotheses are proposed:

H1: Technology-enhanced CHE (experimental group) will achieve significantly higher learning efficacy than traditional CHE (control group).

H2: Technology-enhanced CHE will result in significantly higher community engagement than traditional CHE.

H3: VR immersive experience and gamified task completion will positively predict learning efficacy.

H4: Community co-creation and social interaction will positively predict community engagement.

H5: Cultural identity will moderate the relationship between technical interventions and learning efficacy.

4 Research Methods

4.1 Research Design

A mixed-methods design was adopted, combining quantitative (DID, PLS-SEM, RF) and qualitative (interviews, focus groups) approaches. The study was conducted at three cultural heritage sites in China: the Forbidden City (Beijing), Lijiang Ancient Town (Yunnan), and Longmen Grottoes (Henan). Data were collected over 8 weeks (April-June 2025).

4.2 Participants

A total of 240 participants were recruited, including 120 students (aged 18-25) and 120 community residents (aged 26-65). Participants were randomly assigned to experimental (n = 160) or control (n = 80) groups. The experimental group participated in technology-enhanced CHE (VR experiences + gamified modules + community platform), while the control group received traditional lecture-based CHE. Demographic characteristics are shown in Table 1.

4.3 Research Tools

4.3.1 Quantitative Tools

Learning Efficacy Scale: Adapted from museum-learning literature [4], including 12 items (e.g., "I can explain key historical facts about the cultural heritage site") measured on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Cronbach's $\alpha = 0.892$.

Community Engagement Scale: Developed based on digital-heritage engagement research [3], including 10 items (e.g., "I am willing to participate in cultural heritage preservation activities") measured on a 5-point Likert scale. Cronbach's $\alpha = 0.876$.

VR Immersion Questionnaire: 8 items measuring the degree of immersion in VR experiences (e.g., "I felt fully involved in the virtual cultural scene"). Cronbach's $\alpha = 0.853$.

Gamification Experience Questionnaire: 6 items assessing gamified task completion and motivation (e.g., "I completed all gamified challenges to earn rewards"). Cronbach's $\alpha = 0.821$.

Cultural Identity Scale: 7 items adapted from heritage-identity research [8], measuring the sense of connection to cultural heritage (e.g., "I am proud of the cultural heritage of my country"). Cronbach's $\alpha = 0.834$.

4.3.2 Qualitative Tools

Semi-structured interviews were conducted with 30 participants (15 experimental, 15 control) to explore their experiences and perceptions of CHE.

Focus groups included 4 focus groups (2 experimental, 2 control) with 6-8 participants each, discussing the strengths and limitations of the CHE programs.

4.4 Data Collection Procedures

Pre-test: All participants completed the Learning Efficacy Scale, Community Engagement Scale, and Cultural Identity Scale before the intervention.

Intervention: The experimental group completed 4-week technology-enhanced CHE, including: (a) 2 VR sessions (30 minutes each) simulating cultural sites; (b) gamified learning modules (weekly challenges related to cultural knowledge); (c) community platform participation (sharing experiences, collaborating on tasks). The control group completed 4-week traditional CHE, including 4 lectures (60 minutes each) and a museum visit.

Post-test: All participants completed the Learning Efficacy Scale and Community Engagement Scale again. The experimental group additionally completed the VR Immersion and Gamification Experience Questionnaires.

Qualitative data collection: Interviews and focus groups were conducted within 1 week after the post-test.

4.5 Data Analysis Methods

DID analysis was used to compare the changes in learning efficacy and community engagement between the experimental and control groups, controlling for baseline differences.

Outcome	Group	Pre-test (M ± SD)	Post-test (M ± SD)	DID Coefficient	t-value	p-value
Learning Efficacy	Experimental	3.21 ± 0.58	4.02 ± 0.45	0.187	8.342	< 0.001
	Control	3.18 ± 0.61	3.45 ± 0.52	–	–	–
Community Engagement	Experimental	3.05 ± 0.63	3.98 ± 0.48	0.213	9.126	< 0.001
	Control	3.02 ± 0.65	3.31 ± 0.55	–	–	–

Table 2. DID Analysis of Learning Efficacy and Community Engagement

PLS-SEM was used to test the relationships between technical interventions (VR immersion, gamification), learning efficacy, and community engagement, with cultural identity as a moderator.

The RF algorithm was used to identify the relative importance of factors influencing learning efficacy and community engagement.

Qualitative analysis: Interview and focus group data were coded using NVivo 12, with thematic analysis to identify key themes.

5 Results

5.1 DID Analysis Results

Table 2 presents the DID analysis results for learning efficacy and community engagement. The experimental group showed significantly greater improvements in both outcomes compared to the control group.

These results support H1 and H2, indicating that technology-enhanced CHE significantly improves learning efficacy and community engagement.

5.2 PLS-SEM Results

The PLS-SEM model exhibited good fit: SRMR = 0.068, NFI = 0.912, CFI = 0.934. Key findings are as follows.

VR immersion ($\beta = 0.342$, $p < 0.001$) and gamification experience ($\beta = 0.297$, $p < 0.001$) positively predict learning efficacy (supporting H3).

Community co-creation ($\beta = 0.315$, $p < 0.001$) and social interaction ($\beta = 0.278$, $p < 0.001$) positively predict community engagement (supporting H4).

Cultural identity moderates the relationship between VR immersion and learning efficacy ($\beta = 0.156$, $p < 0.05$) (supporting H5).

The source manuscript describes Figure 2 as a PLS-SEM model of factors influencing CHE outcomes, with arrows indicating significant paths and standardized coefficients, and the moderating effect of cultural identity marked with a dashed line.

5.3 RF Analysis Results

The RF algorithm identified the relative importance of factors influencing learning efficacy and community engagement. For learning efficacy, the factors were VR immersion (32.4%), gamification experience (28.7%), cultural identity (21.3%), and educational background (17.6%). For community engagement, the factors were cultural identity (38.6%), social interaction (32.1%), community co-creation (20.4%), and age (8.9%).

The source manuscript describes Figure 3 as factor importance from Random Forest analysis, with two subplots showing factor importance for learning efficacy and community engagement.

5.4 Qualitative Results

Thematic analysis revealed three key themes.

Immersion and engagement: Experimental group participants reported that VR experiences “made cultural heritage come alive” and gamification “increased motivation to learn.” Control group participants described traditional CHE as “boring” and “passive.”

Cultural connection: Participants in the experimental group emphasized that the community platform and social interaction “strengthened my sense of cultural identity,” while control group participants felt “detached from the cultural heritage.”

Technical and practical limitations: Experimental group participants noted occasional VR technical glitches and suggested more personalized gamified tasks. Control group participants desired more interactive elements and hands-on experiences.

6 Discussion

6.1 Key Findings and Theoretical Implications

The results confirm the effectiveness of the socio-technical framework for technology-enhanced CHE. The DID analysis shows that the experimental group achieved significantly higher learning efficacy and community engagement than the control group, highlighting the synergistic effects of VR, gamification, and community co-creation. This supports the socio-technical systems theory, as the integration of technical tools, educational goals, and social interaction optimizes outcomes [2].

PLS-SEM results indicate that VR immersion and gamification are key predictors of learning efficacy, consistent with previous research [1, 7]. VR’s ability to replicate cultural contexts enhances knowledge acquisition, while gamification increases motivation and sustained participation. Additionally, cultural identity moderates the relationship between VR immersion and learning efficacy, suggesting that learners with stronger cultural identity derive greater benefits from immersive technologies.

RF analysis reveals that cultural identity is the most important factor influencing community engagement, emphasizing the role of emotional connection in fostering community participation [8]. Social interaction and community co-creation also play critical roles, as they enable learners to actively contribute to cultural heritage preservation and dissemination [3].

6.2 Practical Implications

Technology integration: Cultural heritage institutions should adopt a multi-technical approach, combining VR for immersion and gamification for motivation. VR content should prioritize cultural authenticity to maintain the integrity of heritage knowledge.

Community engagement: Develop community co-creation platforms that facilitate user-generated content and social interaction, strengthening the connection between learners and cultural heritage.

Personalization: Tailor CHE programs to learners' cultural identity and educational background, as these factors influence the effectiveness of technical interventions.

Evaluation: Use mixed-methods designs (e.g., DID + PLS-SEM + RF) to comprehensively evaluate CHE outcomes, including learning efficacy and community engagement.

6.3 Limitations and Future Research

The study was conducted in three Chinese cultural heritage sites, limiting generalizability to other regions and cultures. Future research should include diverse cultural contexts.

The intervention duration was 4 weeks; long-term studies are needed to assess the sustainability of learning outcomes and community engagement.

The framework focuses on VR and gamification; future research could explore other technologies (e.g., AR, AI) and their synergistic effects.

7 Conclusion

This study develops and validates a socio-technical framework for technology-enhanced cultural heritage education, integrating VR immersive experiences, gamified learning modules, and community co-creation platforms. The results show that the framework significantly improves learning efficacy and community engagement compared to traditional CHE. VR immersion and gamification are key predictors of learning efficacy, while cultural identity and social interaction dominate community engagement. The findings advance CHE theory by highlighting the importance of socio-technical integration and provide practical guidelines for designing effective, technology-enhanced CHE programs. As digital technologies continue to evolve, this framework offers a flexible and evidence-based approach to preserving cultural heritage and fostering cultural identity in the digital era.

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