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# Research on the Sustainable Evaluation and Performance Optimization of Silk Cultural Heritage in Digital Museums

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## Article

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**ABSTRACT**

*This study explores the impact of museum digitization on silk cultural heritage. This study compares a high-digitization experimental group with a low-digitization control group and evaluates their outcomes across six dimensions, including relic preservation, audience experience, and cultural dissemination. Results show that digital technology significantly enhances silk heritage conservation and transmission. 3D scanning and intelligent environmental monitoring systems boost the relic preservation rate of museums in the experimental group, the use of VR and interactive projections elevates visitor satisfaction, and multi-platform digital dissemination expands cultural reach. Digital technology also optimizes cost efficiency through diversified revenue models and facilitates academic research and skill inheritance via open databases and virtual workshops. This research confirms that museum digitization effectively promotes the sustainability of silk cultural heritage, thereby offering innovative strategies and practical guidance for cultural heritage conservation and inheritance.*

**KEYWORDS**

*museums, digitization, silk heritage, sustainability, performance optimization*

## INTRODUCTION

Silk cultural heritage encompasses the material and intangible legacies formed during the production, trade, and cultural exchanges of silk, which possess historical, artistic, and scientific value [1]. This heritage includes both tangible items, such as silk fabrics, clothing, and dyeing tools (e.g., Han Dynasty brocades and Tang Dynasty gauze), and intangible elements, such as sericulture techniques, dyeing and weaving processes, and commercial customs [2]. These legacies are rich in historical details and serve as vivid testimonies to the

evolution of human civilization. Since the opening of the ancient Silk Road, silk has become a vital link in the trade and cultural exchanges between the east and west. In the field of art, given its soft texture and gorgeous colors, silk has become a source of inspiration for countless artists. Embroidery, printing, and other decorative arts on silk combine unique artistic styles and folk customs from various places, thus introducing a variety of artistic forms [3]. The silk industry once occupied an important position in the economic development of many countries and regions. In ancient China, silk was an important export commodity, and a large amount of silk was transported to Central Asia, Europe, and other places through the Silk Road, which brought huge trade surplus to the country, promoted domestic economic prosperity, and facilitated the rise and development of cities along the route.

With the rapid development of digital technology, the digitization of museums has become an inevitable trend in the field of cultural heritage protection and inheritance. According to QYResearch (Hengzhou Bozhi) released in August 2024, the global museum digital solutions market reached $1.057 billion in sales in 2023 and is expected to reach $2.22 billion in 2030, with a compound annual growth rate of 10.4% (2024–2030) [4]. Digital technology provides a reliable approach for preserving silk cultural heritage. With the help of virtual reality (VR) and augmented reality (AR), the audience can feel the historical atmosphere of silk culture by walking into an ancient silk workshop and watching the silk production process [5]. The proliferation of social media and digital platforms also facilitates the rapid spread of content related to silk cultural heritage, which help attract young people's attention and expand the influence of such culture [6].

Accordingly, scholars have investigated museum digitalization and silk cultural heritage. In terms of museum digitalization, Clara uses the fuzzy Carnot model to design a digital museum and constructs a specific design from the strategic layer, scope layer, structure layer, frame layer, and performance layer [7]. Dou expounds the relationship among technology, museology, and cultural relics protection and examines the possibility of protecting material and intangible culture through the identity and symbolic significance of such cultural relics and by transforming them into digital objects [8]. Kizhner compares the digitalization scope of museums in Russian Federation with that in Europe and finds that the digitalization depth and scope of Russian museums are not as good as those in Europe—which may be due to legal restrictions—and that many Russian contents are not authorized for digital use [9]. In terms of silk cultural heritage, Farsani takes the Silk Road in Iran as a case to analyze the strategy of developing tourism with the silk cultural heritage handed down from the Silk Road and then identifies product development, group diversification, concentric diversification, joint venture, and market penetration as five important strategies for promoting Iran's Silk Road tourism [10].

From the perspective of world cultural heritage, Xu proposes some suggestions for protecting the Maritime Silk Road site in Haikou by analyzing its historical and geographical background, comparing similar sites at home and abroad, and evaluating the value of cultural heritage [11]. Zhiqi uses brand operation theory to analyze the strategy of cultivating silk cultural heritage into an international cultural brand and making this heritage more diversified and symbolic, thus promoting a cross-border declaration of heritage [12].

Previous research in the fields of museum digitalization and silk cultural heritage has achieved certain results. Studies on museum digitalization focus on design frameworks, interdisciplinary theories, and international comparisons, while studies on silk cultural heritage delve into tourism development, conservation planning, and brand operations. However, some significant shortcomings remain in the literature. For instance, research on museum digitalization lacks detailed technical implementation and cultural depth, while research on silk cultural heritage falls short in cross-regional collaboration, digital integration, and sustainable development. This study aims to fill these gaps, enhance regional collaboration and international cooperation along the Silk Road, propose sustainable approaches to cultural heritage protection and development, explore the ethical challenges involved in digital technology applications, and contribute theoretical and practical advancements in related fields.

## EXPERIMENTAL

### Materials and Methods

*Materials*

Choosing museums of different scales and regions with various collections of silk cultural heritage as research objects can fully reflect the digitalization of silk cultural heritage in different environments [13]. Museums with collections of silk cultural heritage serve as important areas for inheriting and studying silk culture, and their level of digital practice is representative. Different types of silk cultural relics, including silk clothing, brocade, and silk reeling, should be chosen as samples of silk cultural heritage as they directly reflect the artistic style and production technology of silk culture, thus highlighting the technology, theory and development history of such culture. Meanwhile, technical samples, including traditional silk production technology and pattern design, are the core content of silk culture inheritance and can represent the main aspects of silk cultural heritage, cover different historical periods, regions, and styles of silk cultural heritage,

and capture various forms of digital presentation, such as digital collections, virtual exhibitions, and multimedia materials.

Digital materials from museums, such as digital collections and virtual exhibition resources, can serve as an important basis for evaluating the digital effect. The digital collection library in these museums contains a large number of high-precision digital models and information related to silk cultural relics, while their virtual exhibition resources provide an immersive experience for the audience through VR, AR, and other technologies and enhance the effect of cultural communication [14].

*Methods*

The level of digitalization, technology application, and data and online platforms of museums were rated as either high or low. Specifically, a level of digitalization of > 80% (using 3D scanning, etc.) was classified as high, while a level of < 30% (traditional imaging) was considered low. Similarly, using VR/AR or digital twins represented high technology application, while using basic multimedia represented low technology application. Data and online platforms were rated as high if they are equipped with big data systems and receive more than a million visits but were rated as low if they do not integrate such systems and attract less than a hundred thousand visits.

Museums were also divided into several groups. Museums in the experimental group have a high degree of digitalization, utilize advanced technology and equipment for the digital collection, storage, and display of cultural relics, have a wealth of digital resources, and heavily rely on digital applications in their daily operations and management. Sample resources include high-resolution digital scanning equipment, VR display systems, and online education platforms, which are utilized by these museums to organize cultural activities and educational projects. Meanwhile, museums in the control group have a low degree of digitalization, a limited application of digital technology, and have scarce digital resources (limited to displaying a few simple digital pictures without any interactive and innovative digital experience). Each of these groups includes 5 museums and 30 samples of silk cultural heritage that cover various periods, types of textiles (e.g., Han Dynasty brocades, Tang Dynasty silks, and Song Dynasty kesi), and types of clothing, curtains, and mounting materials for paintings and calligraphy.

Environmental factors were also taken into account during the selection of silk cultural heritage samples. These samples were collected from dry and cold desert sites in the northwest, humid and rainy Jiangnan water towns, warm coastal port city museums, and highland mountain border sites to ensure

representativeness. Stratified random sampling was adopted in grouping these samples. Specifically, a 3D stratification framework was established based on era (e.g., Han, Tang, or Song), type (e.g., clothing or curtains), and environmental factors (e.g., climate zone and geographical location). The collected samples were labeled with multi-dimensional attribute tags. Using a random number generator, samples were randomly selected from each stratified unit to ensure that the experimental and control groups were balanced in terms of the span of eras (i.e., the proportion of samples taken from each dynasty is consistent), type distribution (i.e., clothing types all accounting for 40% of the entire sample), and environmental variables (i.e., three samples taken from arid regions for each group). The differences in the sample attributes between these groups were statistically insignificant ($P > 0.05$) after chi-square testing, thus ensuring the comparability of the experimental data.

A five-point Likert-type scale was adopted for the questionnaire survey, and the environment and cultural relics preserved in museums were observed on the spot during exhibition visits. A literature search was also conducted wherein the annual reports published by the selected museums over the past five years were collected to retrieve data regarding their investments in digital-related projects and the citation frequency of their digital resources.

Six evaluation indexes were established as detailed in Table 1. A combination of mean filling and deletion strategies was adopted in case of missing values for these indexes, and the mean of all valid datapoints was used for those indicators with a missing ratio of below 5% to ensure sample integrity and minimize data bias. If a sample has more than two missing indicators or if the missing ratio of any single indicator exceeds 10%, then this sample was directly removed to prevent abnormal data from affecting the overall analysis and to ensure the reliability and validity of the data analysis results.

Table 1. Selected evaluation indicators and the corresponding scoring criteria

| Name of index | Index meaning | Data acquisition method | Scoring criteria |
|---|---|---|---|
| Preservation rate of cultural relics | This index reflects the influence of digital technology (e.g., 3D scanning and environmental | Professional cultural relic protection personnel used the Leica DM6M metallographic microscope (with an amplification range of 100×–1000×) to observe microscopic changes in silk fibers, such as fiber fractures and wear. | Percentages（The missing values are filled with the mean value of this group of data to maintain the overall distribution |

| | | | |
|---|---|---|---|
| | monitoring systems) on the physical preservation state of silk cultural relics and evaluates the effect of preventive protection. | They also used the X-Rite MA98 multi-angle colorimeter (measuring wavelengths from 400 nm–700 nm, with repeatability ΔE*ab 0.04) to measure the degree of fading. They referred to the "Textile Colorfastness Test" (GB/T 250-2019) and the "Trial Specifications for the Preservation Environment of Cultural Relics" (WW/T 0001-2007) to evaluate various indicators. Additionally, they used a 3D laser scanner (FARO Focus S70, with a scanning accuracy of ±2 mm) to regularly digitize cultural relics. These data were used in this study to compare and analyze the integrity change rate of the experimental and control groups over five years. The study ensured the scientific and standardized nature of the monitoring results by meticulously recording and statistically analyzing data on damage and fading. | characteristics of the data) |
| Visitor satisfaction | This index measures the effect of digital displays (e.g., VR experience and interactive projection) on improving visitors' experience and pays attention to these visitors' emotional cognition and educational gains. | Paper questionnaires were distributed onsite (500 copies for each group, with a recovery rate of more than 90%), and a Likert-type scale was adopted to quantify the subjective evaluation of the respondents on silk cultural heritage. This scale also has a simple structure that conforms to the research conventions in the field and facilitates a comparative analysis of the results with those of similar studies. | A maximum score of 100 points. |

| | | | |
|---|---|---|---|
| Influence of silk cultural heritage | This index evaluates the ability of digital means (e.g., social media and virtual exhibitions) to expand the dissemination area of silk culture. | Virtual exhibition visits and social media topic readings were counted. | Number of annual visits |
| Digital technology input–output ratio | This index reflects the cost effectiveness of museum digitalization projects and measures the efficiency of resource allocation. | The selected museums' total investments in digitalization projects (including equipment procurement, personnel training, and content development) over the past three years were counted, and then the direct (e.g., paid access to virtual exhibitions and sales of derivatives) and indirect economic benefits of such investments were calculated (e.g., brand value enhancement). [15] | Input–output ratio of the two groups of museums |
| Frequency of utilizing digital resources in the literature | This index measures the frequency by which the digital resources of museums (e.g., high-definition image libraries and 3D models) were used to support academic research on silk culture. | The number of times that museum digitalization resources were cited in statistical academic papers was counted. | Annual citation rate of digital resources |
| Inheritance and participation of silk culture skills | This index reflects the role of digital means (e.g., online courses and virtual workshops) in promoting the | The number of students participating in the digital inheritance project was counted. | Average number of participants in a statistical year |

| | |
|---|---|
| | inheritance of traditional silk culture skills. |

## RESULTS AND DISCUSSION

### Integrity Rate of Cultural Relics Preservation

Figure 1 shows the statistical silk cultural heritage data of the two groups of museums over the past five years. The silk cultural heritage of museums in the experimental group demonstrated a higher preservation rate due to the use of advanced 3D scanning technology and environmental monitoring systems, such as intelligent control equipment with constant temperature and humidity, to reduce the physical contact frequency of cultural relics by non-contact digital means. By contrast, museums in the control group remained dependent on traditional preservation methods due to their lack of technical investments, thus resulting in the particularly obvious influence of temperature and humidity fluctuations and light oxidation on their cultural relics. Museums in the experimental group were also able to build a risk model of cultural relics protection and achieve preventive maintenance (e.g., repairing fragile fibers in advance), while those in the control group only repaired their relics passively [16]. Museums in the experimental group were also able to monitor and track data on the preservation state of their cultural relics in real time by using a digital system, while museums in the control group demonstrated low manual inspection frequency and fragmented data records.

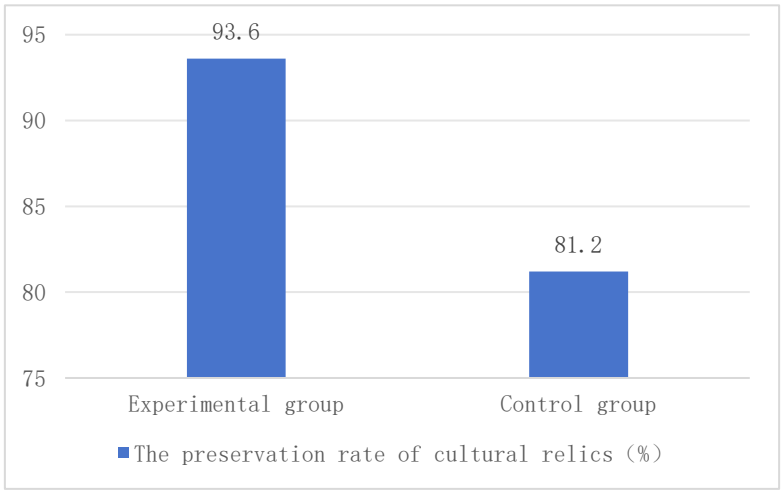


Figure 1. Preservation rate of silk cultural heritage in two groups of museums with different degrees of digitalization

**Audience Satisfaction**

Figure 2 shows the satisfaction scores of visitors visiting the two groups of museums. In general, these visitors expressed higher satisfaction for those museums with higher digitalization levels. Museums in the experimental group used VR silk clothing, interactive projection restoration weaving technology, and other immersive technologies to encourage audience participation. By contrast, museums in the control group only offered their audience with static exhibition without any dynamic experience [17]. In addition, museums in the experimental group were equipped with a relatively perfect data system and can provide their audience with personalized knowledge interpretation services through a digital navigation system (e.g., AR voice explanation), while museums in the control group only offered fixed explanation content that could not easily adapt to their audience's multiple cognitive levels. Museums in the experimental group were also able to use digital streaming technology (e.g., online booking and virtual queuing) to reduce onsite congestion and optimize their visitors' visit routes, while those in the control group were limited by their physical space and were prone to experience congestion.

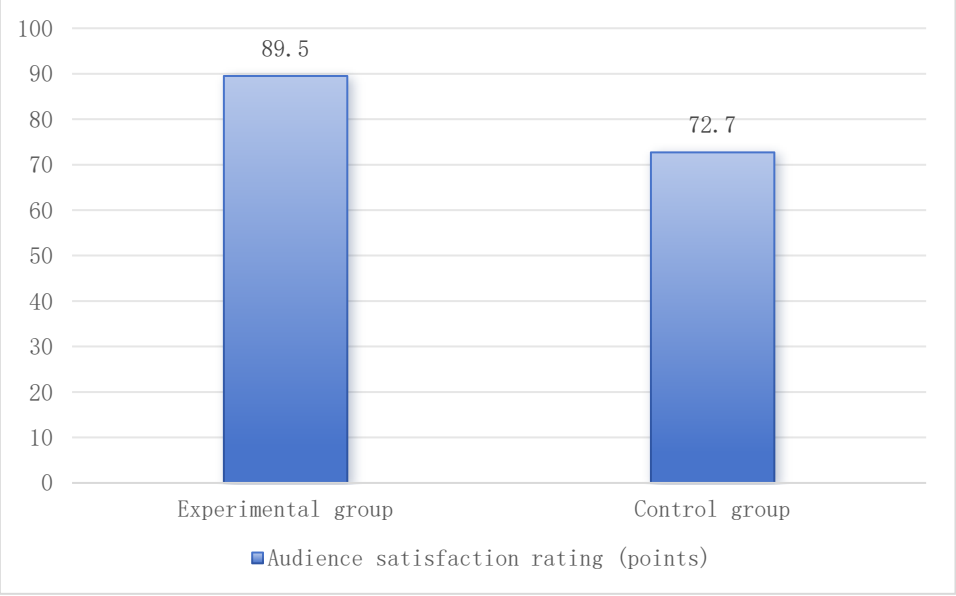


Figure 2. Audience satisfaction for silk cultural heritage in museums with different levels of digitalization

**Influence Coverage of Silk Cultural Heritage**

Figure 3 shows the coverage of silk cultural heritage in the two groups of museums. By offering virtual exhibition visits and social media topic readings, the museums in the experimental group significantly outperformed those in the control group in terms of number of visitations. The former also used short video

platforms (e.g., TikTok), international social media (e.g., Facebook), and virtual exhibition halls to create a multi-channel communication matrix, while the latter only relied on their official websites or local media, which had a limited communication radius [18]. The museums in the experimental group could also use digital technology to identify the differentiated needs of their audiences and to offer tailored content (e.g., silk story animations specifically catered to teenagers), while those in the control group offered homogeneous content that could only attract a specific niche of visitors [19].

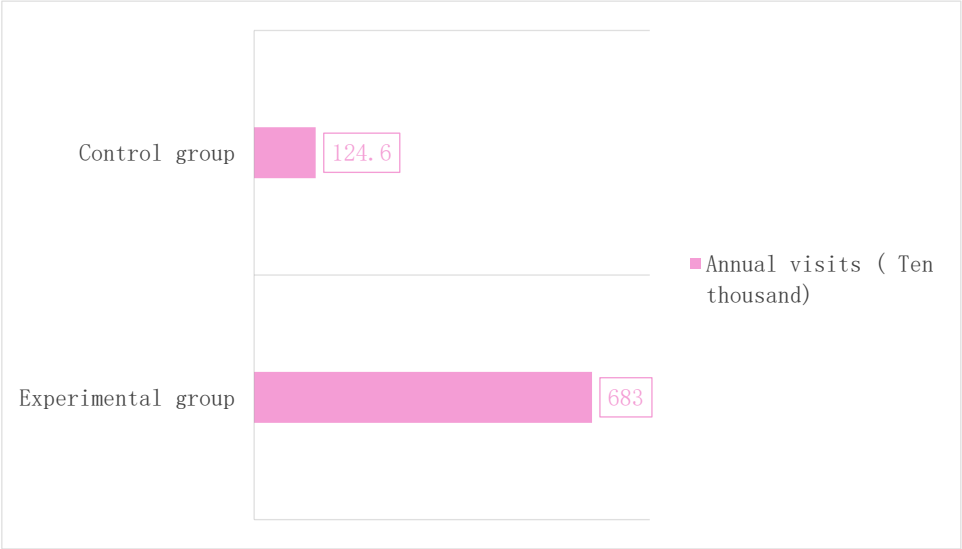


Figure 3. Coverage of the influence of silk culture in museums with different levels of digitalization

**Input–Output Ratio of Digital Technology**

Figure 4 shows the input–output ratio of digital technology in the two groups of museums. Museums with higher degrees of digitalization had significantly higher input–output ratios. Museums in the experimental group cold use modular technology to purchase (e.g., renting a cloud server instead of building their own computer room) and share the cost of digital resources (e.g., developing a common platform with other museums), while those in the control group frequently experienced problems such as repeated procurement and idle hardware. In addition, museums in the experimental group could offer their audiences with virtual exhibition subscriptions and digital derivatives (e.g., silk pattern NFTs) and cooperate with technology enterprises to continuously upgrade their technology (e.g., updating their AI cultural relics restoration algorithms) to improve their resource reuse rate [20]. Meanwhile, museums in the control group only relied on offline ticket sharing for their revenues, their digital indirect income (e.g., brand premium) could not be

quantified, and their technology platform was generally old and unable to support their commercial operations.

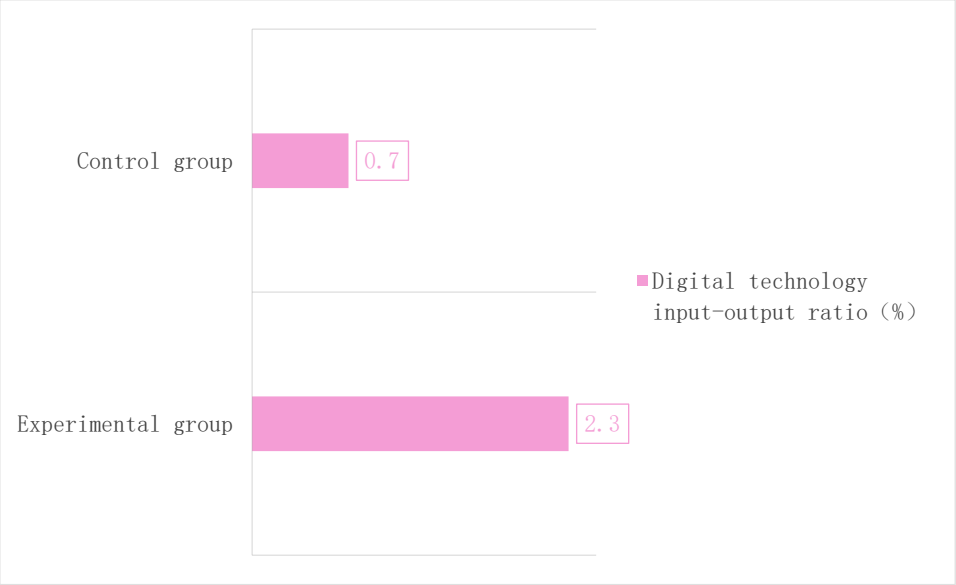


Figure 4. Input–output ratio of digitalization technology investment in two groups of museums with different levels of digitalization

**Frequency of Digital Resources Utilization in the Literature**

Figure 5 shows the utilization frequency of the digital resources offered by the two groups of museums. The digital resources offered by the museums in the experimental group had a higher utilization rate among researchers compared with those offered by the museums in the control group. The museums in the experimental group may build an open and shared high-definition image database and a 3D model database (supporting API interface to connect with academic platforms), introduce digital tools for labeling and comparative analysis, invite researchers to participate in digital tool trainings (e.g., 3D model data extraction methods), and establish an inter-agency research community [21]. Meanwhile, the digital resources offered by the museums in the control group were only available internally and had incompatible formats, thereby introducing challenges to researchers. In addition, these museums could only provide researchers with basic picture browsing features, which cannot meet their deeper research needs.

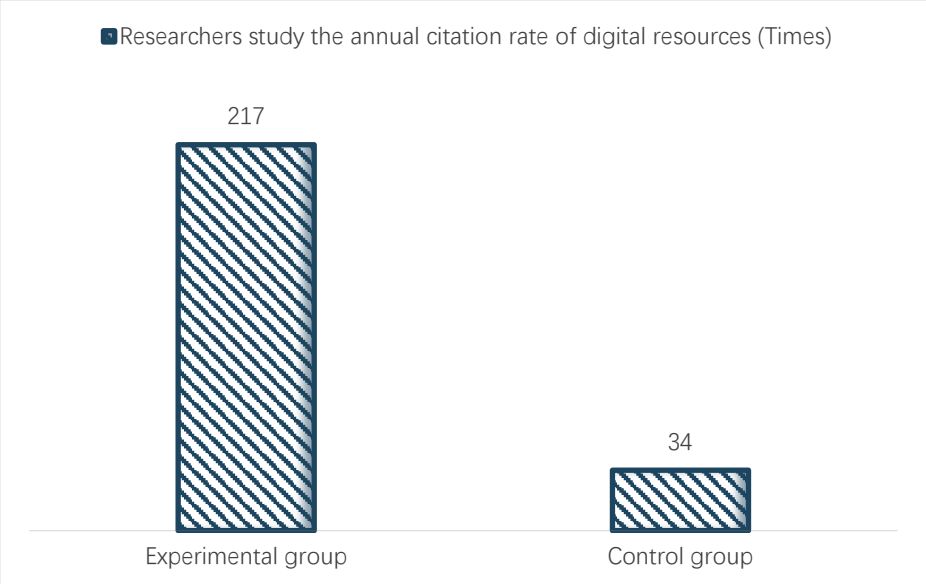


Figure 5. Utilization of digital resources offered by the two groups of museums with different levels of digitalization

**Inheritance and Participation of Silk Culture Skills**

Figure 6 shows the average number of people participating in the programs organized by the two groups of museums for the inheritance of silk culture and skills. The museums in the experimental group attracted a significantly higher audience participation than those in the control group. The museums in the experimental group may break the limitations of time and space by organizing online virtual workshops (e.g., real-time live streaming of silk reeling techniques) and introducing mobile interactive courses (e.g., DIY tie-dye games). They may also invite intangible cultural heritage bearers to use their VR technology to recreate the entire process of silk weaving or set up an online platform that showcases their students' works, thus promoting their sense of achievement. These museums may also link digital courses with professional certification (e.g., obtaining a silk skill level certificate through online assessments) [22]. Meanwhile, museums in the control group largely relied on offline short-term training classes, adopted a monolithic educational model, lacked channels for visualizing students' outcomes, and had no authoritative certification system that could attract young people to participate in their programs.

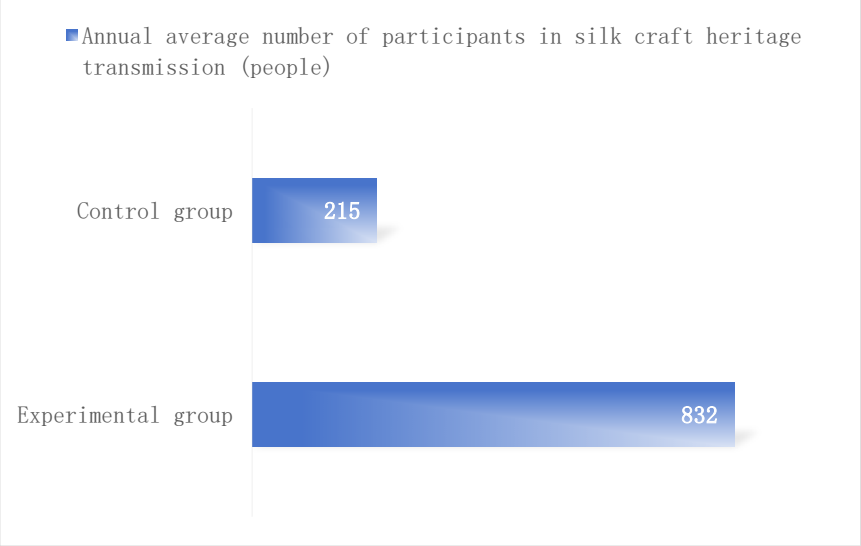


Figure 6. Annual participation in the inheritance of silk culture skills in the two groups of museums with different degrees of digitalization

## CONCLUSION

By comparing museums in experimental and control groups, this study demonstrates the significant impact of museum digitalization on the preservation and inheritance of silk cultural heritage. Digital technology reduces physical wear and tear in cultural relics, VR/AR technology expands the reach of museum exhibitions and information dissemination, and digitalization facilitates academic research and the transmission of silk culture skills. The differences in museum size result in uneven levels of digitalization, which affects the balance of cultural heritage protection and inheritance. The Silk Road, once a vital trade and cultural link between the east and west, carries the historical memory of silk trade, technological exchange, and cultural interaction. Today, digital transformation has become a key pathway for the sustainable development of silk cultural heritage. Unlike grottoes and ancient buildings, the digitalization of silk cultural heritage not only leverages technologies such as 3D reconstruction but also emphasizes the restoration of color and texture due to the fragility of the material.

While national and local plans provide support for silk cultural heritage, the intensity of such support varies across regions, thereby necessitating a balance between policy and market forces to guide social capital investment. Although the initial costs of digitalization are high, in the long run, such investment can reduce the wear and tear of cultural relics through virtual exhibitions and digital cultural products while enhancing the economic and social benefits of cultural resources, thereby achieving a balance between cost and benefit.

The digitalization of silk cultural heritage not only continues the historical lineage but also promotes the international dissemination of the Silk Road spirit through innovative methods, thus fostering modern dialogue and integration among civilizations.

While previous research has achieved some success, several limitations remain. Firstly, these studies have considered a relatively limited sample size, with only a few silk cultural heritage samples and museums selected as research subjects, thereby limiting the scope of their works to a certain range of silk cultural heritage types, regions, and periods and to museums of specific sizes and operational models, thus ultimately affecting the generalizability of their conclusions. Secondly, these studies lack long-term tracking for evaluating the effects of certain policies, and the interaction between policies and digital technology applications has not been adequately considered. To address these gaps, future studies should consider expanding their scope of sample collection to include silk cultural heritage from other countries along the Silk Road, different climate and geographical environments, and digital cases of museums of various sizes. They may also establish a long-term dynamic monitoring mechanism to track the specific outcomes of museum digital transformation after policy implementation and introduce interdisciplinary research methods to deeply analyze the synergistic effects of policies, technologies, and economic factors, thereby improving the extant theoretical and practical systems for the digital protection and inheritance of silk cultural heritage.

To better leverage the role of museum digitalization in protecting silk cultural heritage, several improvements should be made. In terms of policy, the government can draw on the successful digitalization experiences of the Gansu Provincial Museum and the Chuxiong Prefecture Museum. Specifically, the “Digital Gansu Museum” management service platform developed by the Gansu Provincial Museum integrates valuable cultural relics, thus enhancing the protection, research, utilization, and public service capabilities of cultural relics. Meanwhile, the Chuxiong Prefecture Museum has set an example for the digital transformation of small and medium-sized museums by using digital technologies such as the “Magic Wall,” naked-eye 3D displays, and panoramic projections [23]. Technically, artificial intelligence algorithms can automatically identify damage to silk artifacts, while blockchain encryption technology ensures data security. Similar to how Bitcoin uses the SHA-256 hash algorithm and elliptic curve encryption, blockchain uses hash functions and asymmetric encryption to generate public and private key pairs for transaction signatures and verifications, thereby ensuring secure data transmission and storage and preventing data tampering. Future studies may also introduce a cultural audit mechanism to regularly review the use and dissemination of digital cultural

resources, thereby ensuring that their utilization complies with relevant laws and ethical standards [24]. Museums may consider developing innovative products such as silk pattern NFTs and digital collection blind boxes and generate stable revenue through virtual exhibition membership subscriptions. They may also explore potential collaborations with fashion brands for launching digital silk products. By analyzing audience behavior, these museums can optimize their exhibition content and information dissemination strategies, such as tailoring localized silk cultural stories based on their visitors' regional preferences. In terms of inheritance, museums may collaborate with intangible cultural heritage bearers to launch livestreaming courses that use slow-motion replays and 360° views to showcase the intricate details of silk weaving. A hybrid inheritance model that combines online learning with offline workshops may also be established, and silk-culture-themed puzzle games that incorporate pattern recognition and weaving processes may be organized to attract young people to participate in cultural heritage preservation. In terms of cooperation, museums may form a digital alliance to share resources and encourage joint efforts to build laboratories and cultivate professional talent. They can establish a digital alliance for silk cultural heritage where they can share 3D model libraries, academic research results, and other resources, thus avoiding redundant construction. Museums, universities, and tech companies may also collaborate in constructing laboratories, digitally restoring silk artifacts, and training interdisciplinary professionals [25].

*Author Contributions*

Yue Man and Md Gapar Md Johar designed the study; all authors conducted the study; Yue Man, Md Gapar Md Johar and Rusyda Binti Ramly collected and analyzed the data. Rusyda Binti Ramly and Yue Man participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

*Conflict of Interest*

The authors declare no conflict of interest.

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*Availability of Data and Materials*

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

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Not applicable.

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