# Metaverse-Based Cultural Heritage Preservation: Comparative Analysis of Technological Integration, Governance Models, and Sustainability Challenges (2022–2026)

*The consolidation of metaverse infrastructures between 2022 and 2026 has reframed digital heritage from static documentation toward persistent, interactive, and socioeconomically embedded environments. This paper develops a comparative analysis of five operational initiatives: Tuvalu's digital nation-state, the Vatican's St. Peter's Basilica digital twin, Yamakoshi Village's NFT-enabled civic participation model, Borobudur Temple's AI reconstruction of inaccessible reliefs, and AlUla's Hegra experience. Drawing on cross-case design and synthesized empirical evidence, the analysis focuses on three coupled dimensions: AI-driven modeling, immersive interactivity, and blockchain or NFT-based authentication and coordination. Evidence indicates that authentication infrastructures strengthen perceived digital authenticity when embedded in institutionally credible governance arrangements, while immersive experience mediates public value. Sustainability risks remain structural rather than incidental, spanning market volatility in tokenized ecosystems, opacity of platform-level decision systems, uneven stakeholder representation, and tensions between global access and cultural sovereignty. The paper proposes a theory-oriented framework linking technology selection to governance choices and outlines conditions for alignment with ethics and culture-oriented policy guidance while remaining financially and environmentally credible.*

**Keywords:** *digital cultural heritage; metaverse; digital twins and AI reconstruction; blockchain authentication; governance and ethics*

## Introduction

Cultural heritage preservation is increasingly shaped by compounding pressures that exceed the protective capacity of traditional conservation regimes (Buragohain et al. 2024; Zhang et al. 2025; Siliutina et al. 2024). Climate-related exposure, demographic contraction in peripheral regions, and conflict-related damage interact with long-standing constraints in funding, expertise, and physical accessibility. In this context, the contemporary metaverse has emerged not merely as a communication layer for heritage interpretation, but as a socio-technical environment in which documentation, experiential access, and governance experiments coalesce into persistent digital ecosystems. This shift distinguishes recent initiatives from earlier phases of digitization that prioritized archival capture, cataloguing, or standalone virtual tours, and aligns with implementation-oriented syntheses that treat metaverse heritage as an institutional problem of adoption, interoperability, and long-term stewardship rather than as a purely representational upgrade. The trajectory from static digital archives to immersive, persistent environments reframes heritage preservation not simply as data preservation but as socio-technical infrastructure requiring sustained governance, stakeholder alignment, and sustainability planning (Zhang et al. 2025; UNESCO 2024; Sharma and Sharma 2024; Ertz et al. 2024).

The acceleration observed between 2022 and 2026 suggests a qualitative transition rather than merely quantitative scaling, as characterized in the recent literature (Sangamuang et al. 2025; Iliescu 2024; Iakovaki et al. 2025; Song and Yang 2025). This transition involves the integration of AI-based reconstruction, interactive experience design, and distributed ledger technologies into a coupled system in which each dimension can amplify the others under specific implementation conditions. AI can expand the feasible scope of reconstruction by inferring missing geometry from incomplete evidence and enhancing interpretability of legacy documentation, while simultaneously increasing the epistemic burden of disclosure when algorithmic inference substitutes, in whole or in part, for direct archaeological or archival capture. Parallel to this, immersive and interactive affordances function as critical mediators of public value because reconstruction fidelity is most likely to generate conservation and educational benefits when embedded in interfaces that support exploration, situated meaning-making, and comparative visualization across historical phases or alternative restoration scenarios (De Masi et al. 2026). On the infrastructural side, blockchain and NFT logics introduce a formal vocabulary for authentication and coordination that can be deployed to record provenance, define participatory rights, allocate governance authority, and structure funding mechanisms, while also introducing exposure to market volatility and speculative incentives and, depending on implementation choices, potential environmental externalities into the heritage domain. These three dimensions operate as an interdependent system rather than modular add-ons, meaning that analytic approaches isolating technology from governance and sustainability are structurally incomplete and risk misidentifying drivers of success or failure (Sharma and Sharma 2024; Liu et al. 2025; Sustainability-Directory 2025; Ma et al. 2025).

A second equally consequential transition concerns governance (UNESCO 2024; UNESCO 2021; Saint Yves Law 2024; EvalCommunity Academy 2025; Soroptimist 2024). The emblematic projects that have become defined in 2022-2026 display sharply divergent arrangements, ranging from centralized custodial control through what international institutions recognize as legitimate authority, to models that claim participatory decision-making via tokenized membership and distributed governance tokens. Governance choices redistribute authority over cultural interpretation, data stewardship, revenue allocation, the management of user-generated presence, and narratives about authenticity. This matters because heritage authenticity is not exclusively a technical property or an objective characteristic of a digitized object, but a socio-political outcome produced through contested decisions about representation, exclusion, narrative legitimization, and stakeholder recognition. In practice, ethical and rights-sensitive governance becomes operational through transparency in algorithmic processes and curatorial decision-making, accountability mechanisms that allow decisions to be traced to identifiable and responsible actors, and the recognition of cultural authority in contexts where algorithmic systems mediate heritage narratives at scale and shape the interpretive possibilities available to communities and scholars (Lee et al. 2023; Tarasov 2024; NIRA 2023; Bhat 2022; FU-Tourism Project 2024). Despite growing visibility in policy and media discourse, systematic comparative work on operational metaverse heritage initiatives remains limited, particularly for projects that matured following the 2022-2026 platform and tooling consolidation cycle (Buragohain et al. 2024; Zhang et al. 2025; Ertz et al. 2024; Ababneh 2024). Earlier literature often addresses digitization, VR exhibitions, or digital archives without empirically tracking how authentication, monetization, and governance architectures interact with conservation objectives in persistent environments or how platform dependencies and lock-in dynamics reshape institutional capacity. The gap is now consequential because museums, cultural authorities, and heritage organizations are making investment and partnership decisions in an environment where platform dependencies and governance lock-in can become difficult to reverse, and where commitments to tokenized participation systems can introduce volatility incompatible with heritage stewardship timescales. The need is therefore for a theory-driven comparative framework grounded in concrete case evidence, capable of mapping how technical integration choices couple with governance models and sustainability constraints to shape preservation outcomes under real-world implementation conditions. This article addresses the gap through a comparative analysis of five cases that became paradigmatic during the 2022–2026 cycle, including Tuvalu's digital nation-state initiative, the Vatican's St. Peter's Basilica digital twin partnership with Microsoft and Iconem, Yamakoshi's NFT-enabled community participation model, Borobudur Temple’s AI reconstruction of lost reliefs from historical photographs (Ritsumeikan, 2024), and AlUla’s Hegra 3D reconstruction of the Tomb of Lihyan in Decentraland (2022). Rather than treating these initiatives as promotional exemplars or technological success stories, the analysis interprets them as contrasting configurations of technological integration and institutional governance, each of which embeds different assumptions about the meaning of authenticity, the distribution of participation and authority, and the sustainability of stewardship.

The paper pursues three coupled objectives: it clarifies how AI-driven modeling, interactive experience design, and blockchain-based authentication function as a preservation stack in which outputs depend on the alignment of all three; it examines how governance allocates authority across institutions, communities, and platform operators and how these arrangements map onto different conceptions of heritage value; and it evaluates sustainability constraints that may systematically undermine preservation ambitions, including market volatility, platform opacity, environmental costs, and the structural vulnerabilities introduced when heritage stewardship becomes dependent on commercial incentives and speculative asset classes (Bhat 2022; Morgan 2024; Yeo 2024; Vatican Press Office 2024; Ritsumeikan University 2024).

## Materials and Methods

This study adopts a comparative, mixed-method research design that integrates a structured mapping of recent peer-reviewed scholarship with an evidence-based cross-case analysis of flagship metaverse-oriented cultural heritage initiatives that were developed, launched, or expanded in scope or visibility between 2022 and 2026 (Ababneh 2024; Popular Archaeology 2022; Moates 2024). The design is grounded in recognition that metaverse-based heritage preservation is currently characterized by rapid experimentation, uneven institutionalization, and varying degrees of rigor in impact measurement, a condition in which comparative analysis is more effective than single-case description for identifying recurring implementation constraints, governance vulnerabilities, and sustainability patterns that transcend individual projects. The study therefore treats metaverse-based heritage preservation as a socio-technical assemblage in which immersive interaction, AI-enabled reconstruction, and blockchain-linked authenticity mechanisms are not only technical features but also policy objects that trigger substantive questions of legitimacy, accountability, stewardship capacity, and cultural authority (Buragohain et al. 2024; Zhang et al. 2025).

The empirical backbone consists of five case studies explicitly selected to maximize variation in governance models, technological integration patterns, institutional scale, and sustainability pressures, while remaining comparable in their explicit ambition to preserve, communicate, manage, or enrich cultural heritage understanding through immersive, networked, and algorithmically mediated environments (Lee et al. 2023; Bhat 2022; Yeo 2024; Vatican Press Office 2024; Ritsumeikan University 2024). The selected cases are drawn from different geopolitical contexts, different heritage domains, and different institutional sponsors to ensure that the comparison captures variation rather than homogenizing across distinct logics. The first case is Tuvalu's effort to construct a "digital nation" to preserve cultural identity, political continuity, and administrative function under conditions of existential climate threat, a context that foregrounds sovereignty, juridical imagination, and continuity claims rather than conservation of monuments. The second case includes the Vatican and Microsoft initiative to create an AI-supported digital twin of St. Peter's Basilica, using high-resolution photogrammetry reported as enabling millimeter-level inspection in project documentation, and deploying neural-network-based detection to support monitoring and curated access modalities in an institutional context with historical authority. The analysis incorporates Yamakoshi Village's Nishikigoi NFT project, which operationalizes a community-oriented governance logic through forms of digital residency and tokenized participation rights, illustrating how distributed ledger systems can function as governance instruments beyond provenance recording and mediating benefit distribution and decision-making rights. A fourth case addresses AI-driven reconstruction in the Borobudur context, where researchers applied multi-task neural networks to recover panels and structures that remained physically inaccessible for extended periods, intensifying epistemological questions about verification, interpretive authority, and the distinction between reconstruction inference and evidentiary documentation. A final case examines AlUla's Hegra-related metaverse deployment, which embeds heritage narratives within large-scale platform ecosystems operated by commercial entities, providing a salient lens on platform dependence, visibility logics, attention economies, and sustainability rationales tied to engagement metrics rather than heritage stewardship objectives (Ertz et al. 2024; FU-Tourism Project 2024; Skandali 2025).

Data collection combines desk-based documentary analysis with structured extraction of technical and institutional indicators from publicly available materials, institutional announcements, and academic literature (Woods 2024; Microsoft 2025; Reply 2025; Farrant and Associated Press 2024). For the scholarly mapping component, the study draws on recent peer-reviewed syntheses in digital heritage preservation, metaverse applications, blockchain governance, and AI ethics in cultural contexts. For the case-study component, primary materials include official project documentation, institutional announcements, and technical descriptions released by organizations and technology partners involved in each initiative, as well as news coverage and analysis by heritage professionals and technologists. These materials are complemented by scholarly and policy discussions when public framing itself constitutes part of the policy imagination and legitimacy formation of initiatives, as in sovereignty-oriented narratives around Tuvalu or platform-centered tourism rationales for commercial metaverse deployment (Hallstrom 2024; Stewart 2024; Daoud 2023).

To increase comparability across cases, the study employed a shared extraction and coding protocol. Each case was treated as a socio-technical configuration and analyzed through a common set of observable indicators aligned with the three interdependent dimensions defined below, AI-driven modeling and reconstruction, immersive interaction and access affordances, and blockchain or NFT-linked authentication and coordination, complemented by governance and sustainability indicators. For each case, evidence was extracted from publicly available primary documentation released by the institutions and technology partners involved, and from secondary expert and journalistic sources when they contained technical, financial, or participation-related information not disclosed in institutional materials. Extracted evidence was then coded into a cross-case matrix that recorded, for each dimension, the presence and stated purpose of the technology, the institutional or platform actor responsible for stewardship, the decision-rights arrangement, and the stated maintenance and update commitments. Where documentation varied across sources or used non-equivalent definitions, the analysis retained the source-specific framing and reported claims as approximate, time-bound, and attributable rather than as definitive project properties. This procedure supports cross-case synthesis by ensuring that comparison is based on the same analytic units and operational indicators across all five initiatives, while remaining transparent about the limits of desk-based evidence and the uneven disclosure practices that currently characterize metaverse heritage projects.

Analytically, the study operationalizes "technological integration" as a specific configuration across three interdependent dimensions: AI-driven modeling and reconstruction capacity; interactive functionality and immersive accessibility affordances; and blockchain or NFT-linked authentication, coordination, and participation mechanisms (UNESCO 2024; Sharma and Sharma 2024; Liu et al. 2025). This operationalization is aligned with recent empirical arguments demonstrating that preservation outcomes depend on coupled socio-technical pathways rather than on isolated tools or technologies, and remains compatible with digital twin framing that emphasizes continuity, updateability, stewardship responsibility, and versioned documentation. "Governance model" is interpreted as the arrangement of decision rights, accountability structures, participation mechanisms, and rules for data and content stewardship, informed by ethics-oriented frameworks that operationalize transparency, accountability, and rights-sensitive cultural representation as conditions for legitimate AI-mediated cultural systems. "Sustainability challenges" are examined as multi-layered institutional, financial, environmental, and infrastructural constraints that may systematically undermine continuity even when short-term innovation appears successful. This includes financial and operational dependencies on external funding or platform revenues; platform reliance and lock-in risks where institutional capacity becomes dependent on platform-specific infrastructure; and environmental externalities implicit in digitization pipelines, persistent immersive service delivery, AI training and inference costs, and blockchain-based coordination systems. Sustainability is evaluated as part of each project's institutional design and stated maintenance commitments, with explicit attention to whether mechanisms for updating, stewarding, and transitioning digital assets are credibly embedded in governance structures or remain primarily promotional, event-driven, and dependent on ongoing external support (Ertz et al. 2024; Song and Yang 2025; Ma et al. 2025; Abrams 2018; Chen 2023; Singh et al. 2025; Li et al. 2025; Pellegrino et al. 2023).



## Results

### *Theoretical Framework and Analytical Lens*

Metaverse-based cultural heritage preservation has consolidated, in the 2022-2026 cycle, into a field where technological architectures and institutional arrangements are irreducibly intertwined rather than separable (Buragohain et al. 2024; Zhang et al. 2025; Popular Archaeology 2022). Preservation outcomes cannot be reliably inferred from technical sophistication or feature richness alone because immersive access, AI reconstruction, and blockchain-linked authentication all operate within governance ecosystems that determine legitimacy, accountability, durability, and alignment with cultural values. The relevant analytical unit is therefore not a discrete metaverse experience or standalone technology platform, but a coupled assemblage in which data practices, interface affordances, participation rules, platform dependencies, and governance institutions co-produce what becomes framed, contested, and collectively recognized as heritage value (UNESCO 2021; Saint Yves Law 2024; EvalCommunity Academy 2025).

A first theoretical pillar concerns authenticity in metaverse environments (UNESCO 2024; Liu et al. 2025; Sustainability-Directory 2025). Authenticity is partially re-articulated as a socio-technical effect generated through the interaction of reconstruction fidelity, transparency of methods, credibility of stewardship institutions, and stakeholder recognition rather than as an intrinsic property of a digitized object. Digital twin approaches provide a vocabulary for continuity and versioned stewardship, allowing institutions to document how heritage representations evolve as evidence improves or interpretive frameworks change, but they also typically depend on institutions articulating transparently how evidence, inference, and curatorial choice interact and remain distinguishable. AI-based reconstruction expands the scope and speed of what can be made visible and interpretively accessible while increasing the risk of producing persuasive but inferentially produced artifacts when algorithmic pipelines are not adequately disclosed or when outputs are presented without explicit uncertainty quantification. Blockchain-linked systems can strengthen traceability and perceived authenticity when deployed as accountable provenance infrastructures with transparent governance, yet they can equally introduce incentives that displace stewardship objectives when market dynamics and speculative value creation become dominant drivers of participation (Iakovaki et al. 2025; Song and Yang 2025; Morgan 2024; Sustainability-Directory 2025).

A second pillar concerns interactivity, public value, and the role of immersive experience design (Popular Archaeology 2022; Skandali 2025; Ozturk 2025). In metaverse settings, heritage preservation is frequently justified pragmatically through expanded access, educational impact, and public engagement. This implies that immersive interaction is a critical mediator that converts digitized and algorithmically reconstructed assets into socially legible and culturally meaningful value, shaping perceived legitimacy and societal willingness to support conservation-oriented agendas at institutional and policy levels. Platform-native heritage deployments illustrate how engagement architectures and interface affordances can amplify publics and reach, but also how attention economies and platform governance shape what narratives remain legible, which interpretations are prioritized, what moderation boundaries are enforced, and how monetization pressures may reshape heritage representation toward content-market preferences. Adjacent empirical studies in metaverse tourism and heritage engagement suggest that public value is co-produced through perceived authenticity, experiential presence, contextually framed interpretation, and narrative authority, but remains contingent on platform affordances and governance structures that heritage institutions typically do not control (Bhat 2022; Yeo 2024; Vatican Press Office 2024).

The third pillar concerns governance architectures and the distribution of authority over representation, narrative, and stewardship (UNESCO 2024;

UNESCO 2021; Saint Yves Law 2024; EvalCommunity Academy 2025; Soroptimist 2024). Heritage preservation is inherently a political process because decisions about representation, narrative framing, historical interpretation, and access rights define which communities are recognized as stakeholders, which claims are privileged, and which voices are marginalized or silenced. Metaverse-based initiatives intensify these dynamics by expanding stakeholder participation to include technology vendors, platform operators, token holders, and global user communities, thereby introducing divergent interests, incentive structures, and power asymmetries into heritage governance. Governance is therefore conceptualized as the arrangement of decision rights, accountability systems, participation mechanisms, and stewardship rules that regulate data custody, interpretive control, benefit distribution, and resource allocation. In sovereignty-centered contexts such as Tuvalu's digital nation framing, legitimacy is anchored in political recognition and claims about continuity under existential threat, extending heritage preservation beyond monuments and museums into questions of statehood, juridical imagination, and national identity. In community-centered contexts such as Yamakoshi, governance is partially operationalized through tokenized belonging, contribution rights, and distributed decision-making, which can mobilize resources and sustain attention for peripheral communities but equally creates vulnerability to speculative incentives unless insulated by enforceable custodial rules and transparent, accountable benefit distribution mechanisms (Lee et al. 2023; Tarasov 2024; NIRA 2023; Bhat 2022; FU-Tourism Project 2024).

The fourth pillar concerns sustainability as an institutional and infrastructural condition rather than an aspirational goal or residual concern (Sharma and Sharma 2024; Ma et al. 2025; Chen 2023; Kshetri and Dwivedi 2023). Sustainability is treated as the concrete capacity to maintain preservation functions and heritage stewardship over time, encompassing updating and versioning of digital assets, ensuring continuity of access as technologies and platforms evolve, and sustaining legitimacy and stakeholder alignment through changing circumstances. Implementation-focused work frequently identifies sustainability constraints such as skills shortages in specialized heritage technology domains, cost burdens for maintaining immersive infrastructure, platform lock-in where institutional capacity becomes dependent on proprietary systems, and uneven stakeholder alignment as structural rather than incidental challenges. Commercial metaverse deployment can amplify these challenges by linking heritage continuity and stewardship obligations to platform life cycles beyond heritage institutions' control, while tokenized participation systems can import volatility and boom-and-bust cycles into heritage governance that are fundamentally misaligned with the long time horizons required for genuine preservation. Sustainability is equally shaped by the normative expectations embedded in international ethics and culture-oriented policy guidance, which increasingly frames AI-mediated cultural systems in terms of accountability, transparency, rights-sensitive stewardship, and alignment with community interests rather than technology adoption targets or engagement metrics (Ertz et al. 2024; Singh et al. 2025; Li et al. 2025; Pellegrino et al. 2023).

Synthesizing these pillars, the article adopts an analytical lens that treats metaverse-based heritage preservation as a three-layered preservation stack where reconstruction and modeling forms the epistemic foundation, experiential mediation through immersive interfaces translates technical work into public value, and authentication or coordination infrastructure enables governance and maintains provenance legibility (Buragohain et al. 2024; Zhang et al. 2025; UNESCO 2024; Liu et al. 2025). Each layer is evaluated through governance and sustainability filters that determine whether the configuration remains ethically credible, institutionally feasible, and operationally sustainable. This lens is consistent with the understanding that digital twins, immersive access, and traceability infrastructures must be institutionally governed to remain ethically and operationally credible, that technical sophistication does not substitute for governance legitimacy, and that preservation cannot be reduced to initial digitization if long-term maintenance, platform resilience, and externalities are not credibly addressed in design. The resulting theoretical proposition is that metaverse-based preservation outcomes depend on alignment across three domains: technological integration must match the epistemic status of evidence because high inference requires high transparency and governance credibility; governance models must match the sociopolitical nature of the heritage claim because sovereignty-centered, community-centered, and institution-centered contexts demand different accountability structures; and sustainability must be treated as a design variable from inception because preservation cannot be achieved if long-term maintenance, platform resilience, and environmental and financial externalities are not credibly addressed (Sharma and Sharma 2024; Ertz et al. 2024; Ma et al. 2025).

*Comparative Case Study Analysis (2024–2026)*

The comparative evidence indicates that metaverse-based cultural heritage preservation is best understood as a field of strategic configurations rather than as a single technological paradigm or solution (Buragohain et al. 2024; Zhang et al. 2025; UNESCO 2024). Each case implements a preservation stack that combines reconstruction and modeling capacity, immersive access and interactive experience design, and forms of authentication or participation that range from institutional verification and provenance recording to tokenized governance and distributed coordination. These configurations operationally express assumptions about who is entitled to represent heritage, who benefits from digitization and immersive access, and how stewardship is funded, maintained, and made accountable over time (Sharma and Sharma 2024; Ertz et al. 2024).

Tuvalu's digital nation initiative is analytically distinctive because it treats digitization and metaverse-based representation as a sovereignty strategy rather than as a supplementary or ancillary interpretive layer (Yeo 2024; Woods 2024; Sale 2025; Tzwicinski 2024). The project frames metaverse-based representation as a means to preserve national identity, public memory, administrative continuity, and juridical presence under climate displacement scenarios that threaten the physical viability of the archipelago. Official documentation indicates that, as part of its digital nation plans, Tuvalu initiated LiDAR scanning of its islands and islets in 2023 and began to develop digital governance components, positioning the project as a sovereignty-oriented continuity strategy rather than a monument-centered conservation initiative. Authenticity here becomes inseparable from political legitimacy and international recognition, while sustainability becomes entangled with infrastructural resilience and geopolitical support rather than being solely dependent on cultural sector funding or heritage conservation mechanisms. The case demonstrates how metaverse infrastructure can function as a political technology of continuity and national preservation, yet simultaneously exposes vulnerability to global attention cycles and geopolitical volatility when preservation stakes are framed as existential and when recognition depends on international consensus and diplomatic engagement. (UNESCO 2024; Ertz et al. 2024; UNESCO 2021)

The Vatican's St. Peter's Basilica digital twin exemplifies an institution-centric governance model where custodial authority is historically established, institutionally legitimate, and digitization is integrated into existing conservation and visitor-management narratives (Vatican Press Office 2024; Microsoft 2025; Reply 2025; Farrant and Associated Press 2024). Public project documentation and partner reporting describe the capture of over 400,000 images through photogrammetry to create a high-resolution digital twin for conservation-oriented inspection and monitoring. In this configuration, legitimacy derives from institutional continuity and the Vatican's recognized custodial role, with technology providers positioned as technical partners rather than as agenda-setters or governance stakeholders. The project's public framing emphasizes AI-supported conservation documentation and structural monitoring rather than public immersion or engagement metrics, while immersive access through platforms like Microsoft's unlocked portal expands educational reach without introducing tokenized ownership logics or speculative incentives. This case clarifies that where governance legitimacy is already established through institutional history and decision rights remain clearly institutional, digital authenticity tends to be perceived as credible and trustworthy by audiences even when those audiences cannot independently audit reconstruction pipelines or algorithmic processes. At the same time, concentrated institutional control can narrow participatory agency, restrict external scrutiny of representational and curatorial choices, and prevent community voices from shaping how heritage is interpreted and presented (UNESCO 2024; UNESCO 2021; Saint Yves Law 2024).

Yamakoshi's Nishikigoi NFT-enabled model positions participation, affiliation, and tokenized belonging as central governance variables in heritage stewardship (Lee et al. 2023; Tarasov 2024; NIRA 2023). Rather than grounding legitimacy exclusively in formal heritage authority or institutional conservation credentials, the initiative mobilizes blockchain-based frameworks to attract supporters, cultivate forms of digital residency, and coordinate engagement tied directly to community revitalization and economic recovery following a devastating 2011 earthquake. The project issued Nishikigoi NFTs as digital resident identifiers, governance tokens, and participation rights. Project communications and contemporaneous reporting indicate that the initiative surpassed 1,700 digital residents and raised approximately ¥423 million (circa $2.8M USD at time), with participation in governance processes reported at around 40%, values that should be read as time-specific and definition-dependent given the evolving nature of token-based participation metrics. In comparative terms, blockchain infrastructure functions here less as a static provenance ledger and more as a governance mechanism structuring affiliation rights, contribution recognition, and benefit distribution to participating community members and digital residents. This can generate substantial benefits when it successfully sustains attention and resources for peripheral and economically marginalized communities, but introduces structural sustainability risks where participation is mediated through volatile speculative markets and where symbolic NFT ownership becomes decoupled from genuine custodial obligation or accountability for heritage stewardship. The case therefore illustrates a recurring trade-off observable across tokenized heritage systems: blockchain-based participation can broaden engagement imaginaries and mobilize resources, but fundamentally imports incentives that may become misaligned with long-term stewardship unless governance safeguards are explicit, enforceable, and insulated from market fluctuations (Sharma and Sharma 2024; Liu et al. 2025; Sustainability-Directory 2025).

The Borobudur AI reconstruction case foregrounds the epistemological dimension of metaverse-based preservation by demonstrating how algorithmic inference can recover cultural visibility and interpretive access where physical access is constrained or impossible (Ritsumeikan University 2024; Hallstrom 2024; Stewart 2024; Altuntas 2024). Researchers at Ritsumeikan University applied multi-task neural networks to historical photographic archives to algorithmically reconstruct hidden relief panels and architectural details that had been covered or inaccessible for extended periods, effectively expanding the interpretive and educational scope without requiring physical intervention or excavation. This approach expands preservation and interpretive capacity while simultaneously intensifying authenticity tensions and governance burdens because algorithmic outputs appear visually high-fidelity and definitive while remaining fundamentally inferential products rather than direct evidentiary capture. In this setting, legitimacy and credibility depend critically on methodological disclosure that renders uncertainty legible to viewers and prevents high-fidelity simulation from being misrecognized as archaeological or evidentiary certainty. The Borobudur cluster of documentation practices, research framing, and immersive experience narratives illustrates both the preservation promise and the governance burden of high-inference reconstruction pipelines, where transparent communication about inference, uncertainty, and algorithmic process becomes a condition for ethical deployment rather than an optional supplement (Iakovaki et al. 2025; Song and Yang 2025; Morgan 2024; Sustainability-Directory 2025).

AlUla's Hegra-related metaverse deployment illustrates a platform-oriented strategy that integrates heritage narratives and immersive experiences into commercial metaverse ecosystems operated by external actors (Bhat 2022; Popular Archaeology 2022; Moates 2024; Daoud 2023). The Royal Commission for AlUla deployed a to-scale, immersive 3D reconstruction of Hegra's Tomb of Lihyan in Decentraland beginning in November 2022, marking the first UNESCO World Heritage site deployed in a commercial metaverse platform. Visitors can access 360-degree tours, explore areas physically inaccessible in the heritage site itself, and engage with interpretive information through platform-native affordances. The preservation opportunity lies in reaching geographically distributed audiences and generating visibility and engagement that can reinforce tourism, conservation funding, and policy support. Yet this configuration depends fundamentally on platform governance, content policies, data regimes, and shifting attention markets that heritage institutions do not control, creating structural vulnerabilities. The risk profile includes platform lock-in where institutional data becomes dependent on platform-specific formats; narrative simplification pressures where complex heritage stories are compressed into short-form engagement content compatible with platform affordances; and subordination of interpretation to platform-native engagement metrics and algorithmic recommendation systems that optimize for user retention rather than heritage stewardship objectives. Comparative research on metaverse tourism and heritage authenticity helps clarify that these tensions are structural in platform ecosystems rather than incidental or resolvable through technical improvements, and therefore require governance safeguards and institutional autonomy equivalent in strength to traditional custodial stewardship if heritage preservation claims are to remain credible over multi-decade timescales (FU-Tourism Project 2024; Skandali 2025; Ozturk 2025).

Across cases, three comparative patterns emerge with notable consistency (UNESCO 2024; UNESCO 2021; Morgan 2024).

First, preservation value is more likely to emerge when technological integration is matched to governance arrangements capable of legitimizing representational decisions and sustaining stewardship beyond initial launch cycles and promotional phases. Second, immersive interactivity functions as a mediator of public value and engagement rather than as an intrinsic preservation outcome, meaning that engagement architectures and platform affordances shape whether digitization is oriented toward conservation-supportive outcomes or shifts toward consumption-driven representation with limited conservation benefit. Third, sustainability challenges are structurally embedded in the chosen configuration: institution-centric models can reduce exposure to market volatility but may limit participatory legitimacy and external scrutiny; tokenized models can expand engagement imagination but may import market instability; platform-native deployments can expand visibility while tending to concentrate infrastructural power and governance authority outside heritage stewardship institutions and community control (Sharma and Sharma 2024; Ertz et al. 2024; Ma et al. 2025).

**Discussion**

The analysis clarifies that sustainability is structurally contingent on governance choices and infrastructural dependencies rather than on technological sophistication or initial investment levels (Sharma and Sharma 2024; Ertz et al. 2024; Ma et al. 2025). Where projects rely on commercial platforms or cloud infrastructure, continuity is systematically exposed to platform life cycles, changing data policies, pricing structures, and opaque governance that heritage institutions do not control and cannot easily exit without losing accumulated digital assets and access history. Where projects mobilize tokenized participation and governance systems, continuity is structurally exposed to market dynamics and speculative cycles that can decouple asset value from conservation need and transform heritage into tradable commodities. Where projects are anchored in custodianship mandates and conservation objectives, sustainability benefits from institutional continuity and mission alignment but remains dependent on ongoing resourcing, capability maintenance, and institutional commitment that cannot be taken as permanent (Liu et al. 2025; Sustainability-Directory 2025; Lee et al. 2023; Tarasov 2024; NIRA 2023).

The environmental sustainability dimension requires explicit attention (Ma et al. 2025; Chen 2023; Singh et al. 2025; Kshetri and Dwivedi 2023). Reported estimates for training large AI models that are comparable in scale to those used for heritage reconstruction place emissions on the order of 284 tons of carbon dioxide equivalent per model, although such values are highly sensitive to system boundaries and assumptions, including hardware configuration and utilization, data-center efficiency, run duration, and the electricity generation mix. Likewise, the net footprint associated with persistent immersive services depends on the operating profile and provisioning choices of cloud infrastructure, storage, and any ledger-based coordination layer, with impacts varying substantially by workload intensity, geographic location of compute, and mitigation practices.

However, virtual tourism and remote heritage access can, under specific substitution conditions, reduce transportation-related carbon emissions and physical site degradation associated with visitation, creating potential net environmental benefits when such access credibly displaces a portion of travel demand and is paired with operational measures that limit the added energy footprint of digital delivery.

The ethical obligation is therefore to conduct environmental impact assessments and lifecycle-oriented analyses of metaverse heritage systems, rather than presuming that digitization is inherently sustainable across contexts and deployment scales. Governance frameworks and policy-oriented guidance emerging in 2022–2026 increasingly emphasize transparency in carbon costs, reporting boundaries, and mitigation strategies as part of heritage institution accountability (Ertz et al. 2024; Song and Yang 2025; Li et al. 2025; Pellegrino et al. 2023; Arzomand 2024).

The direction of metaverse heritage preservation is ultimately determined not by technological capabilities alone, but by governance choices that determine whether these infrastructures evolve into ethically grounded stewardship environments aligned with UNESCO ethical guidance and community interests, or degenerate into commercialized simulacra that erode accountability, disconnect representation from custodial responsibility, and subordinate heritage to engagement metrics and speculative economics (UNESCO 2024; UNESCO 2021; Saint Yves Law 2024; EvalCommunity Academy 2025; Soroptimist 2024). Institutional capacity to resist pressure toward engagement-driven simplification, maintain methodological transparency, and protect community authority emerges as the critical determinant of whether metaverse-based heritage preservation strengthens or undermines long-term stewardship goals (Buragohain et al. 2024; Zhang et al. 2025; Sharma and Sharma 2024; Ertz et al. 2024).

## Conclusions

This article argues that metaverse-based cultural heritage preservation in the 2022–2026 cycle can be understood not merely as an upgrade from digitization to immersion, but as a preservation stack in which AI-driven modeling, immersive experience design, and authentication or coordination infrastructures co-produce what becomes recognized as heritage value. Across the five cases, the comparative evidence indicates that technical sophistication does not reliably translate into preservation credibility unless the epistemic status of reconstruction is disclosed, custodial responsibility is explicitly allocated, and the system is designed for versioned stewardship beyond launch and promotional phases (Buragohain et al. 2024; Zhang et al. 2025; UNESCO 2024; Sharma and Sharma 2024; Ertz et al. 2024; Ma et al. 2025).

A central implication is that governance often functions as the binding constraint. Institution-centric configurations can sustain methodological authority and conservation-oriented monitoring, but typically depend on transparency and avenues for legitimate external scrutiny. Tokenized participation models can mobilize attention and resources for peripheral communities, yet they may import speculative incentives that are difficult to align with stewardship goals unless insulated through enforceable rules on benefit distribution, data stewardship, and cultural rights. Platform-native deployments can scale access and visibility, but they can also amplify lock-in risk and shift narrative control toward platform governance and engagement metrics. Robust practice therefore benefits from explicit exit strategies, interoperable asset management, and auditable decision pathways for curation and AI inference (Buragohain et al. 2024; Zhang et al. 2025; UNESCO 2024; Sharma and Sharma 2024; Ertz et al. 2024; Ma et al. 2025).

The study also underlines that sustainability is structural rather than residual. Environmental costs associated with AI pipelines, persistent cloud delivery, and distributed ledgers should be treated as design variables, ideally through lifecycle assessment and explicit mitigation commitments, while the potential benefits of remote access should be evaluated against these externalities under stated assumptions and system boundaries. Limitations include the reliance on public documentation and the rapid evolution of platforms and standards during the period studied. Future research should therefore combine longitudinal evaluation of maintenance trajectories with stakeholder-centered analysis of legitimacy, particularly in contexts where sovereignty and community authority are directly implicated (Buragohain et al. 2024; Zhang et al. 2025; UNESCO 2024; Sharma and Sharma 2024; Ertz et al. 2024; Ma et al. 2025).

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