

The Untapped Potential of Extended Reality for Indigenous Medicinal Knowledge: A Review of Cross-Disciplinary XR Applications

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Abstract—Many sectors are quickly moving toward XR for education and professional training. These technologies, which include Virtual, Augmented, and Mixed Reality, are not being applied equally across different types of knowledge preservation. This study aims to review how effective these technologies are and whether they have overlooked the preservation of Indigenous Medicinal Knowledge. Following the PRISMA 2020 guidelines, relevant literature from 2019 to 2026 was gathered from major academic databases, including IEEE Xplore, Scopus, and ScienceDirect. After removing duplicates and non-English papers, 23 out of 39 publications met the selection criteria. The findings show that while XR is a proven technology in many sectors, it remains underused for documenting the medicinal knowledge of communities such as the Kayan and Kenyah. This lack of progress is not caused by technical limitations, but by internal organizational barriers and weak project planning. The evidence, therefore, points to a procedural problem rather than a technological one.

Keywords—*Extended Reality; Indigenous Medicinal Knowledge; Virtual Reality; Augmented Reality; Mixed Reality; gamification; cultural heritage preservation; Task-Technology Fit; PRISMA*

I. INTRODUCTION

Indigenous medicinal knowledge is considered an important foundation for cultural history and community well-being. It includes traditional healing methods and plant knowledge that have been passed down orally across many generations [1]. In this system, medicinal uses are combined with the ecological and cultural values that shape Indigenous worldviews. One example of this can be seen in the Kenyah and Kayan communities of Sarawak, Malaysia, where plant identification and preparation are part of traditional healing practices that have long supported community health. However, this continuity is now under threat.

Traditional ways of passing down this knowledge have been disrupted by modernization, putting these practices at risk of being lost [1]. As younger generations adopt digital lifestyles and attend formal schools that are disconnected from their ancestral roots, these oral traditions face the danger of disappearing permanently.

Extended Reality (XR) is a technology that combines Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), and it can be proposed as a way to document and preserve

this intangible cultural heritage. XR is an umbrella term that covers AR, which can be accessed through smartphones, tablets, or wearable devices such as the Microsoft HoloLens 2. AR layers images and text onto the user's real physical environment. VR, on the other hand, covers the user's entire field of vision through a headset and places them in a fully virtual space. Mixed Reality sits between AR, VR, and the real world [2].

XR technologies have been shown to create more immersive and effective learning experiences [2], [5]. They have been linked to better learning motivation, interest, creativity, and academic performance, while also being a more time-efficient option compared to traditional methods. XR is already being used as a training tool in medicine, the military, and sports education.

A notable gap exists: although XR is a well-established tool across many high-stakes fields such as chemistry, aviation, mental health, and medical training, it has rarely been applied to preserving Indigenous Medicinal Knowledge. In medicine, XR is used for neurosurgery and dental training [2], [7], [8], [9]. In chemistry education, it supports 3D molecular visualization [21]. Aviation uses it for flight simulation [5], and mental health practitioners apply it in cognitive rehabilitation and exposure therapy [13], [18]. The fact that XR is technically mature in these areas but largely absent from cultural preservation efforts suggests that the main obstacles are not technological, but procedural.

This review addresses the following research questions: 1) How is XR currently used for training in advanced professional fields such as medicine and aviation? 2) What are the main barriers to adopting XR, and how can inclusive design help address them? 3) How can XR technologies be adapted to preserve Indigenous Medicinal Knowledge in community settings?

II. RESEARCH METHODOLOGY

This systematic literature review was carried out using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework [3], which ensures that the process is transparent, reproducible, and methodologically sound. The review comprised four stages: identification, screening, eligibility, and inclusion.

A. Database Selection and Search Strategy

Three major databases were selected for their coverage of interdisciplinary research in computer science, cultural studies, and educational technology: IEEE Xplore, Scopus, and ScienceDirect. They were chosen because they provide access to peer-reviewed studies and include research on XR and gamification in education and cultural preservation. These three databases were considered sufficient for this review because they jointly index the majority of peer-reviewed venues publishing XR research, including IEEE VR, IEEE BigComp, MetroXRaine, JMIR, Frontiers, and MDPI journals that appeared in the final included set. A preliminary coverage check confirmed that extending the search to additional databases (e.g., ACM Digital Library, Web of Science) returned substantial overlap with records already indexed in Scopus and IEEE Xplore. The review was restricted to English-language publications to ensure consistency in screening and appraisal; this restriction is acknowledged as a limitation in Section IV.E.

B. Search Strategy

The following Boolean search string was applied across all three databases:

"extendedreality" AND (((("indigenous" OR "tradition*" OR "heritage") AND ("medicin*")) OR "ethnobotan*" OR "ethnopharma*"))

A time restriction was applied to focus on studies published from 2019 to 2026. Only peer-reviewed publications written in English were included. After searching the three selected databases, 39 records were identified for evaluation.

C. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: 1) published from 2019 to 2026; 2) written in English and published in a peer-reviewed venue; 3) used XR technologies such as VR, AR, or MR in gamified or interactive applications; 4) focused on the preservation of Indigenous, cultural, or medicinal knowledge; and 5) used mobile or mobile-compatible XR applications that support accessibility and community participation.

Exclusion criteria comprised: 1) non-English or non-peer-reviewed works; 2) lack of relevance to XR in educational or cultural contexts; 3) non-interactive XR applications without engagement elements.

D. Screening and Selection Process

Initially, 39 unique records were identified: 25 from Scopus, 10 from IEEE Xplore, and 4 from ScienceDirect. Within the Scopus collection, 3 records were removed for not being written in English, 2 were identified as duplicates, and 11 did not meet the inclusion requirements, leaving 9 Scopus papers. IEEE Xplore (n=10) and ScienceDirect (n=4) records all met the inclusion criteria. After full-text analysis, 23 papers were selected: IEEE Xplore (n=10), Scopus (n=9), and ScienceDirect (n=4). The PRISMA flow diagram is shown in Fig. 1.

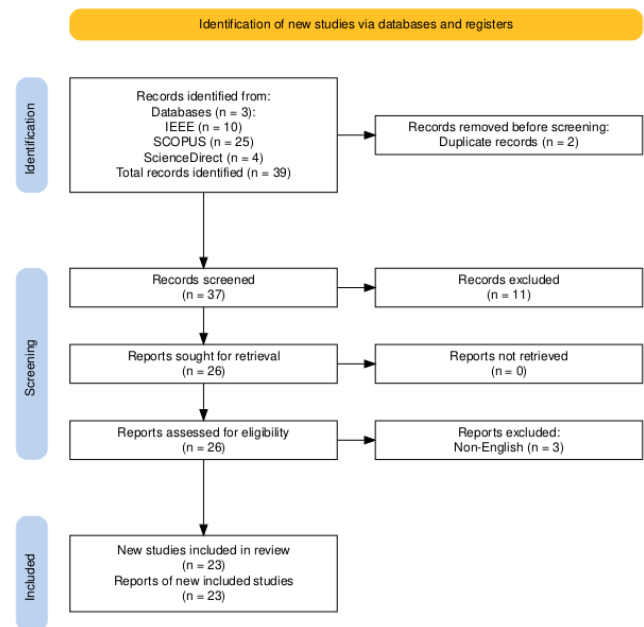


Fig. 1. PRISMA flow diagram

E. Data Extraction and Thematic Coding

After final selection, data extraction was carried out to gather key information from each of the 23 included studies. Each study was coded across several fields: 1) author(s) and publication year; 2) XR modality (AR, VR, MR, or hybrid); 3) presence of gamification elements; 4) domain of application, such as heritage, education, accessibility; 5) methodology used; 6) key outcomes; and 7) reported challenges or limitations.

F. Analytical Framework

This review uses the Task-Technology Fit (TTF) framework to assess how well XR technologies match the needs of knowledge preservation. TTF argues that a technology's effectiveness depends on how closely its features match the demands of the task [24]. The framework was originally developed to explain individual performance in information systems [4] and has since been applied to technology adoption in educational settings [24]. In knowledge preservation, the "task" includes cultural transmission, environmental learning, and community participation, while the "technology" refers to the different XR modalities and their capabilities.

To operationalize the TTF framework, this review explicitly maps four core task characteristics against the technology features offered by XR systems reported in the 23 included studies. The task characteristics derived from the domain of Indigenous Medicinal Knowledge (IMK) preservation are: (T1) spatial and sensory knowledge representation (e.g., plant identification, preparation gestures); (T2) narrative and oral transmission; (T3) community-based, in-field accessibility; and (T4) cross-generational engagement.

The corresponding technology features observed across the included studies are: (F1) immersive 3D visualization and spatial interaction [5], [17], [21]; (F2) scenario-based and simulation modalities [5], [19]; (F3) mobile and low-cost form factors [1], [6], [14]; and (F4) gamified feedback loops such as rewards, exploration, and progression [1], [5], [21]. Table V in Section IV-B presents the explicit task-to-feature mapping.

G. Quality Assessment

To strengthen methodological rigor, a post-hoc quality appraisal was applied to all 23 included studies after final selection. A five-item checklist adapted from common critical-appraisal tools was used, covering: (Q1) clarity of research aim and objectives; (Q2) appropriateness of the methodological approach; (Q3) transparency of data collection or study procedure; (Q4) validity and traceability of findings; and (Q5) relevance to XR and to knowledge-preservation or training contexts. Each item was scored as 1 (met), 0.5 (partially met), or 0 (not met). A study was retained in the synthesis if it scored at least 3.0 out of 5.0. All 23 studies met this threshold, which is consistent with their selection from peer-reviewed indexed venues (IEEE Xplore, Scopus, and ScienceDirect). This appraisal does not replace a full risk-of-bias assessment, which is typically reserved for interventional studies; the current review is descriptive and cross-disciplinary, and the checklist therefore focuses on methodological transparency and relevance rather than internal bias.

III. RESULTS AND ANALYSIS

A. Overview of Included Studies

From the initial 39 records retrieved, the following were excluded from Scopus during screening: non-English language (n=3), duplicates (n=2), and papers that did not meet the inclusion criteria (n=11). All records from IEEE Xplore records (n=10) and ScienceDirect records (n=4) met the inclusion criteria. The final set included 23 peer-reviewed studies

published from 2019 to 2026: IEEE Xplore (n=10), Scopus (n=9), and ScienceDirect (n=4). The included studies spanned clinical, educational, and assistive domains, covering the healthcare metaverse and next-generation care ecosystems [10], image-guided pain-procedure navigation [12], mixed-reality pre-surgical planning for epilepsy [15], digital-twin applications for pediatric assessment [20], adaptive-optics corrections in XR visualization [22], and VR-based ecological memory assessment [23].

B. XR Modalities and Applications

The 23 included studies show a range of XR applications across educational and cultural contexts. Augmented Reality (AR) and Mixed Reality (MR) were the most used modalities [1], [2], [5]. The studies spanned multiple disciplines, including educational technology, medical education, cultural heritage preservation, and accessibility frameworks [8], [9], [14]. Fig 2 presents the distribution of XR modalities across application domains for the 23 included studies, and Table I summarizes the XR modalities and their primary applications.

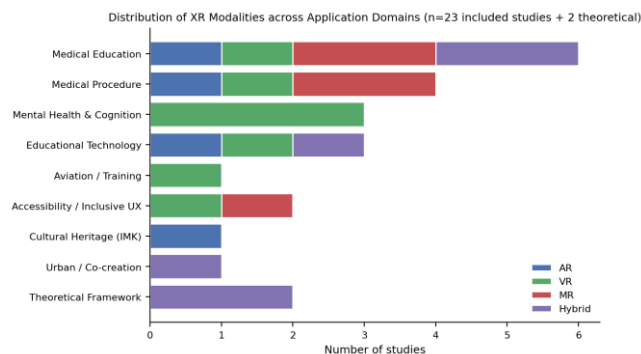


Fig. 2. Distribution of XR modalities (AR, VR, MR, Hybrid) across application domains in the 23 reviewed studies plus theoretical-framework references.

TABLE I. XR MODALITIES AND APPLICATIONS ACROSS INCLUDED STUDIES

XR Modality	Primary Applications	Freq.	Key Characteristics	References
Augmented Reality (AR)	Educational enhancement; Cultural heritage visualization	High	Smartphone/tablet compatible; Real-world overlay; High accessibility	[1],[2],[5]
Mixed Reality (MR)	Medical training; Educational contexts	High	Immersive while maintaining spatial awareness; Wearable compatible	[5],[8]
Virtual Reality (VR)	Specialized training; Spatial memory assessment	Moderate	Full immersion; High cognitive engagement; Requires dedicated hardware	[5],[17],[18]
Hybrid (AR+VR+MR)	Complex medical and educational applications	Moderate	Combines AR/VR/MR capabilities; Flexible deployment	[1],[5],[9]

C. XR for Educational Enhancement

Several studies showed that XR technologies improve learning outcomes in educational settings. XR offers spatial understanding, greater peripheral awareness, and three-dimensional graphics, allowing for a level of realism that traditional classroom settings cannot provide [5], [17]. It has also been shown to strengthen cognitive ability, improve attention, and support neuroplasticity [5]. XR environments further encourage experimental and active learning [5], [21].

D. Gamification in XR Environments

Gamified XR applications were a strong category in the literature, with a focus on learning engagement, motivation, and retention. Game-based XR has been linked to higher scores in interest and enjoyment, perceived competence, and perceived usefulness [1]. Gamification elements such as progression, rewards, and exploration were found to be effective in encouraging curiosity and discovery-based learning, especially among younger audiences [1], [5], [21]. Table II presents the gamification mechanics identified across the reviewed studies.

TABLE II. GAMIFICATION MECHANICS IN XR APPLICATIONS

Mechanic	Description	Learning Impact	Cultural Fit	References
Interactive task completion	Users complete tasks to unlock narratives	High – promotes discovery	Excellent – aligns with quest traditions	[1],[5]
Achievement Systems	Rewards for mastering traditional practices	High – increases motivation	Good – recognizes mastery	[1],[5],[21]
Peer-based interaction and knowledge sharing	Peer-based knowledge sharing	High – promotes collaborative learning	Excellent – honors oral traditions	[1],[5],[21]
Immersive experiential learning	Exploration-driven experiences in educational contexts	High – immersive engagement	Excellent – connects to cultural narratives	[1],[5],[21]
Progression Systems	Level-based knowledge mastery	Moderate–High – clear goals	Good – structured learning path	[1],[5]

A cultural fit assessment represents the authors' analysis of potential alignment with Indigenous knowledge preservation needs.

E. Barriers to XR Adoption

Although XR applications have advanced technologically, their use in community settings remains limited due to technical, cultural, and ethical constraints. Common technical barriers

include hardware costs, limited mobile compatibility, and poor infrastructure in rural areas [5], [2], [14]. From a TTF perspective, these barriers reflect a "mismatch", where technology's characteristics do not align with task requirements of remote, low-bandwidth environments [5], [4]. Other barriers include a lack of teacher training, few available educational experiences, limited research, and insufficient institutional support [2], [8], [9]. Table III summarizes the barriers identified.

TABLE III. BARRIERS TO XR ADOPTION IN COMMUNITY CONTEXTS

Barrier Category	Specific Barriers	Impact	TTF Analysis	References
Technical	Hardware costs; Limited mobile compatibility; Inadequate rural infrastructure	High	Technology mismatch: high-end requirements vs. low infrastructure	[5],[2],[14]
Infrastructure	High-speed internet; Stable power; Low bandwidth	High	Task–Technology mismatch: infrastructure unavailable	[4],[5]
Implementation	Lack of teacher training; Few educational experiences; No institutional support	Moderate–High	Organizational readiness issues	[2],[8],[9]
Economic	Initial hardware costs; Licensing fees; Maintenance expenses	High	Budget constraints for institutions	[2],[8],[9]

F. Opportunities for XR Integration

Despite the existing barriers, the review found emerging opportunities for XR in knowledge preservation. The potential of mobile-based XR platforms is supported by general XR education literature [6], and community-based testing has also

been demonstrated [1]. Mobile-compatible XR platforms appear to be the most realistic option for community settings [1], [6]. Existing research also highlights the value of gamified and interactive approaches for passing down knowledge [1], [5], [21]. Table IV outlines the identified opportunities and their implementation strategies.

TABLE IV. OPPORTUNITIES FOR XR INTEGRATION IN KNOWLEDGE PRESERVATION

Opportunity	Implementation Strategy	Expected Outcome	Scalability	References
Mobile-Based XR	Deploy AR through smartphone/tablet apps	Accessible to remote communities	High – smartphone penetration	[1],[6]
Participatory Co-Creation	Co-design with community members and diverse age groups	Culturally authentic content and shared ownership	Moderate – requires engagement	[1]
Gamified Storytelling	Embed quests, achievements, collaborative gameplay	High engagement and knowledge retention	Moderate – effectiveness demonstrated in educational contexts	[1],[5],[21]

G. Usability and User Experience

Evaluations using the System Usability Scale (SUS) in existing literature show that XR applications generally achieve moderate to high usability scores [1]. Data from the Intrinsic Motivation Inventory (IMI) subscales indicated that users view

XR tools as both effective and useful for learning, with particularly high scores in perceived competence and value [1]. A clear preference for AR over VR in certain environments also suggests that AR-based platforms may be more effective due to their ease of use and wider accessibility [1].

H. Accessibility and Inclusive Design

The literature also identified the importance of inclusive user experience design for diverse populations. Older adults and those with varying levels of digital literacy often find complex interfaces difficult to use, which points to the need for inclusive design approaches [14]. The digital divide continues to leave certain populations behind [2], [14]. Introducing XR in educational and community settings may help reduce this gap in access and adoption [2], [14].

IV. DISCUSSION AND LIMITATIONS

A. Theoretical Frameworks

The findings connect to several theoretical frameworks that link learning, technology, and knowledge preservation. XR technologies support experiential and active learning theory by allowing users to build understanding through immersive exploration [5], [17], [21]. Gamification elements also align with the intrinsic motivation indicators measured through the

IMI [1]. Central to this discussion is the Task-Technology Fit (TTF) model, which looks at whether the capabilities of gamified mobile XR match the environmental and pedagogical tasks involved in knowledge preservation [4], [5].

B. Task-Technology Fit Analysis

The review also points to a clear mismatch in current research, where high-end XR hardware often requires infrastructure that is not available in rural or resource-limited settings [4], [5]. Task characteristics require that knowledge preservation supports mobile, in-field documentation within community environments [1], [6]. The task is not only technical but social, requiring a medium that supports oral, narrative, and practice-based transmission of knowledge [1]. Mobile XR platforms provide the portability and accessibility necessary to bridge the infrastructure gap [1], [6]. By utilizing mobile-compatible platforms, the objective of accessible community-based knowledge transmission is supported [1], [6].

TABLE V. TASK-TECHNOLOGY FIT MAPPING FOR XR IN INDIGENOUS MEDICINAL KNOWLEDGE PRESERVATION

Task characteristic (IMK preservation)	Required capability	XR feature observed in reviewed studies	Supporting refs
T1. Spatial/sensory knowledge (plant ID, preparation gestures)	3D visualization, spatial interaction, gesture capture	Immersive VR/MR environments; stereoscopic XR video; acupoint annotation pipelines	[5], [11], [17], [21]
T2. Narrative/oral transmission	Scenario-based storytelling, audio-visual layering	AR overlays on real environments; simulation-based interprofessional scenarios	[2], [7], [19]
T3. Community-based, in-field accessibility	Portable, low-cost, low-bandwidth deployment	Mobile-compatible XR; low-cost VR for rehabilitation; inclusive UX for non-expert users	[1], [6], [14], [18]
T4. Cross-generational engagement	Motivation, retention, gamified feedback	Gamified XR with rewards and exploration; educational XR with measured motivation gains	[1], [5], [21]

C. Addressing Research Questions Through Findings

Table VI presents a synthesis of the research questions and the evidence-based answers derived from the 23 reviewed studies.

D. Practical Implications

The practical implications drawn from the synthesis focus on co-creation [16], accessibility, and ethical management of cultural content—areas essential for the sustainable preservation of knowledge [1], [6]. Table VII presents strategic recommendations for community-based XR implementation.

TABLE VI. RESEARCH QUESTIONS AND EVIDENCE-BASED ANSWERS

Research Question	Key Findings	Evidence	References
Current state of XR adoption for cultural heritage and education?	XR is becoming more common in educational institutions, though widespread adoption is still in its early stages. AR is generally preferred due to its accessibility through smartphones. Studies show that XR produces moderate to significant improvements in educational outcomes, including motivation, competence, and engagement.	Across the reviewed studies, educational settings consistently included engagement and interactivity features. Gamification was identified as a key design element in applications focused on cultural and educational purposes.	[1],[2],[5],[6],[8],[9],[14],[17]
What are the main barriers to adopting XR, and how can inclusive design overcome them?	Common barriers include hardware costs, limited mobile compatibility, inadequate rural infrastructure, lack of teacher training, and lack of institutional support. Inclusive design through mobile-based XR, participatory co-creation, and low-cost platforms can overcome these barriers.	TTF framework reveals technology-task mismatch in remote, low-bandwidth environments. Mobile XR platforms provide portability and accessibility to bridge the infrastructure gap.	[2],[4],[5],[8],[9],[14]
How can XR preserve and transmit knowledge in community contexts?	Mobile-based XR combined with gamification is optimal. Participatory co-design ensures cultural authenticity. Gamified storytelling bridges generational gaps.	Gamified mobile XR enhances knowledge retention and engagement. TTF framework explains adoption barriers and implementation solutions.	[1],[5],[6],[21]

TABLE VII. STRATEGIC RECOMMENDATIONS FOR COMMUNITY-BASED XR IMPLEMENTATION

Focus Area	Recommended Action	Intended Outcome	References
Community Participation	Co-design sessions with community members and diverse age groups	Ensure cultural accuracy and shared ownership of XR content	[1],[6]
Mobile XR Platform Selection	Select mobile-compatible XR platforms based on community technical capacity, budget, and ownership needs	Expand access in rural areas; ensure sustainability and community control over digital heritage	[1],[6]
Gamification Elements	Embed story-driven quests, rewards, and interactive feedback	Increase engagement and knowledge retention among youth	[1],[5],[21]
Ethical Data Governance	General XR literature recommends ethical and inclusive adoption	Safeguard knowledge ownership and promote trust in digital preservation	[6]

E. Limitations

While this systematic literature review followed PRISMA 2020 guidelines, several limitations must be acknowledged. The review was limited to three academic databases (IEEE Xplore, Scopus, ScienceDirect) and to English-language publications, which may have excluded regional, local, and Indigenous repository studies. The search string centered on the phrase "extended reality" combined with indigenous-, heritage-, and medicinal-related terms; it did not include the abbreviation "XR" as a separate keyword, nor narrower medicinal-domain terms such as "pharmacognosy", "healing", "herbal", "botany", or "plants". This conservative keyword set was a deliberate

methodological choice to minimize the inclusion of studies unrelated to XR-for-knowledge-preservation, but it may have reduced recall. Future systematic reviews should expand the keyword set to include these terms, apply field-specific Boolean filters, and extend coverage to additional databases (e.g., ACM Digital Library, Web of Science) as well as regional and grey-literature sources. Because direct empirical research on Indigenous Medicinal Knowledge (IMK) preservation is scarce, the synthesis had to draw on broader educational and cultural heritage XR literature. All findings are strictly based on the 23 reviewed papers to maintain rigor and traceability. Table VIII provides a structured overview of these limitations.

TABLE VIII. LIMITATIONS OF THE SYSTEMATIC LITERATURE REVIEW

Limitation Category	Specific Limitation	Impact on Findings	Mitigation Strategy
Database & Language	Restricted to IEEE, Scopus, ScienceDirect; English-only	May exclude regional/local and Indigenous repository studies	Include grey literature, Indigenous repos, non-English publications in future reviews
Temporal	Review spans 2019–2026; rapid XR evolution	Earlier studies may reflect superseded hardware	Pedagogical/design insights remain relevant despite hardware evolution
Content Scope	Scarcity of direct IMK preservation research	Synthesis relied on broader XR/education literature	Future research should focus specifically on IMK preservation applications
Community Participation	Lack of explicit community participation in many studies	Limited culturally grounded XR frameworks discussed	Recommend participatory research designs with Indigenous communities
Methodological Scope	Review based on 23 papers from a systematic search only	All claims grounded strictly in reviewed papers	Ensures rigor and traceability; prevents unsupported claims
Research Gap	Limited direct IMK-specific XR empirical evidence	Recommendations extrapolated from general education/cultural XR	Future empirical studies needed in community-based IMK contexts

F. Cultural, Ethical, and Epistemological Considerations

Although XR applications have advanced technically, their use for Indigenous Medicinal Knowledge (IMK) raises cultural, ethical, and epistemological concerns that must be explicitly addressed. Indigenous knowledge systems are often relational, place-based, and embedded in oral and ritual practice; digitizing such knowledge through XR risks decontextualizing it from the community protocols that govern who may hold, share, and transmit it [1]. Consistent with the community-based evaluation of a gamified XR prototype among the Kenyah and Kayan [1], any preservation effort must be co-designed with knowledge holders and align with free, prior, and informed consent principles. Ethical concerns also include data sovereignty, ownership of digitized plant and practice records, and the long-term stewardship of XR assets after a project concludes [6]. From an epistemological standpoint, XR tends to privilege

visual and spatial modalities; this may be a good fit for plant identification and gesture-based preparation, but it can flatten the narrative, sensory, and relational dimensions of IMK. A notable proportion of the 23 reviewed studies derive from general XR applications rather than from IMK-specific contexts; this review therefore synthesizes evidence across domains and makes its IMK inferences with appropriate caution. Public-health XR literature [2] and the broader digital-age XR review [6] converge on the view that cultural fit, equity, and ethical governance must be designed-in rather than retrofitted.

V. CONCLUSION AND FUTURE WORKS

This systematic literature review brought together findings from 23 peer-reviewed studies published from 2019 to 2026 on the use of Extended Reality in educational and cultural settings [1], [2], [5], [6]. The analysis shows that XR technologies, including AR, VR, and MR, have gained considerable use in

improving learning outcomes, visualizing cultural heritage, and encouraging public engagement [1], [2], [5], [6], [8], [9]. The key finding of this review is that gamification works well as a teaching tool within XR environments, where it consistently improves intrinsic motivation and knowledge retention [1], [5], [21].

The review identifies five key points for XR implementation. First, XR shows strong potential for improving engagement through immersive learning environments [2], [5], [17]. Second, gamification supports community-based learning by creating participatory environments that improve educational value [1], [5], [21]. Third, long-term success depends on involving diverse community members throughout the process [1]. Fourth, mobile and low-cost XR platforms are the most practical choice for community settings [1], [6]. Fifth, all digitalization efforts should be guided by ethical standards that support equity and inclusivity [6].

For future academic work, studies should move beyond general educational contexts and focus specifically on knowledge preservation in community settings [1], [6]. Empirical and field-based research is needed to assess how well XR and gamified learning approaches work in real community environments [1], [6]. Development efforts should also prioritize mobile-compatible XR systems to improve accessibility in low-resource settings. Ethical frameworks should be embedded into project design to ensure transparency and long-term cultural protection [1], [6].

Looking forward, the research agenda points to several concrete directions. First, community-anchored field trials of mobile-compatible XR prototypes should be conducted with Indigenous knowledge holders, with outcomes measured beyond usability to include cultural continuity and intergenerational transfer indicators [1]. Second, the Task-Technology Fit framework applied in this review should be extended into an evaluation instrument that can be quantitatively tested in future IMK-XR studies [4], [24]. Third, hybrid AR-plus-gamification designs warrant dedicated investigation for low-bandwidth rural deployment [1], [5], [21]. Fourth, longitudinal studies are needed to assess whether XR-mediated preservation sustains knowledge retention and community engagement over years rather than single sessions. Finally, future work should integrate ethical and data-sovereignty governance into the XR development lifecycle, supported by the public-health and digital-age XR literature [2], [6], so that preservation efforts remain accountable to the communities whose knowledge they document.

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DECLARATION OF AI ASSISTANCE

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developed solely by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the content.

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