EXTENDED REALITY TECHNOLOGIES AND THEIR IMPLICATIONS FOR SCIENCE SYSTEMS IN THE GLOBAL SOUTH

CENTRE FOR SCIENCE FUTURES
International Science Council

To cite this report: International Science Council (May 2026). *Extended Reality Technologies and their Implications for Science Systems in the Global South.*

Funding acknowledgement: This work was conducted with the aid of a grant from the International Development Research Centre (IDRC), Ottawa, Canada. The views expressed herein do not necessarily represent those of the IDRC or its Board of Governors.

Authors: Martin Moreno Guzmán, Carlos Vargas Pedroza

Reviewer: Lucia Marchetti

Project coordination: Felix Dijkstal, Vanessa McBride

Project chair: David Castle

Design: Mr Clinton

Cover photo: Moyo Studio

About the International Science Council

The ISC is an international non-governmental organization with a unique global membership that brings together 250 international scientific unions and associations, national and regional scientific organizations, including science academies, research councils, regional scientific organizations, international federations and societies, and academies of young scientists and associations.

The ISC works at the global level to catalyse change by convening scientific expertise, advice and influence on issues of major importance to both science and society.

Executive summary

Extended reality (XR) technologies encompass virtual reality, augmented reality and mixed reality, and serve two distinct roles for science in the Global South. The first responds to a persistent infrastructural deficit: laboratories, instruments and training facilities remain critically insufficient across many low-income countries, and traditional construction cannot close this gap at the pace scientific capacity demands. The second responds to the transformation of science itself. Research increasingly depends on the analysis of complex, multi-dimensional datasets and the modelling of large-scale systems – urban environments, planetary surfaces and dynamic biological processes. These demands exceed the capabilities of even the most well-equipped conventional laboratories.

As an infrastructural bridge, XR provides scalable virtual laboratories, clinical simulators and training environments that sustain essential scientific education where physical facilities are absent. As a frontier scientific medium, XR enables entirely new forms of inquiry – from immersive navigation of planetary surfaces to city-scale predictive experimentation on digital twin populations and borderless surgical collaboration across continents. These capabilities cannot be replicated by any physical laboratory.

This report analyses XR deployment across Global South science systems, examining three impacts: the democratization of scientific infrastructure, the enhancement of scientific research and training and the integration of Indigenous Knowledge. Each is evaluated through its scientific opportunity, associated challenges and risks. The evidence is already substantial. Astronomers in South Africa are navigating three-dimensional data cubes using commercial headsets; researchers at the Indian Space Research Organisation are conducting collaborative planetary surface visualizations in custom-built virtual reality (VR) environments; and surgeons in Uganda and Germany are meeting as digital avatars in shared virtual operating theatres to plan procedures in real time. As an infrastructural bridge, XR is simultaneously closing immediate gaps through AR-guided telesurgery in conflict zones, VR-based surgical training in Sub-Saharan Africa and virtual laboratories reaching institutions from India to Latin America.

However, XR also introduces risks that require deliberate management. The technologies originate predominantly in the Global North, and most available content reflects Western pedagogical assumptions. Cloud-based deployments can transfer control over sensitive biometric and spatial data to foreign providers, reproducing the extractive dynamics of data colonialism. Algorithmic systems trained on unrepresentative datasets compound this risk by producing flawed scientific inferences. Without strategies to build local capacity and institutional ownership, XR risks deepening the very dependencies it could help overcome.

The report offers recommendations for public science, technology and innovation agencies, research and academic institutions and private sector innovators – emphasizing institutional ownership, open science, South–South collaboration and the integration of XR into long-term science capacity plans. Priority actions include requiring open-standard procurement clauses in publicly funded XR projects, establishing shared XR facilities that serve multiple departments and co-developing reusable simulation libraries through South–South partnerships to reduce duplication and build regional capability.

Key finding: XR is both a bridge to essential scientific training where physical infrastructure is absent and an advanced medium for frontier science that no conventional laboratory can replicate. The institutions that treat XR as shared scientific infrastructure – rather than as a novelty – will capture its full benefits for capacity building, workforce development and knowledge sovereignty.

Introduction

The requirements of modern science are outpacing the infrastructure available to deliver it, and this mismatch is especially acute in the Global South. On one side is an enduring infrastructural deficit. Scientific research and training depend on adequate physical infrastructure – laboratories, instruments and field facilities – yet state investments consistently fall short of demand, especially across the natural and applied sciences. The facilities that do exist are concentrated in a small number of flagship institutions or large enterprizes (Kiyuka et al., 2024). This gap reinforces a consumer role in much of the Global South, and addressing it through traditional construction is both exceedingly slow and cost-prohibitive. On the other side is an equally consequential shift: the nature of scientific inquiry is changing. Research increasingly demands the analysis of complex, multi-dimensional datasets and the modelling of dynamic, large-scale systems, including urban environments, planetary surfaces, climate processes and epidemiological networks. These demands exceed what even well-equipped physical laboratories can deliver using conventional instruments and two-dimensional displays (Hlal et al., 2025).

Extended reality technologies respond to both dimensions. As an infrastructural bridge, XR provides practical digital environments for practising critical operations, visualizing complex scenarios and exploring scientific data interactively – without requiring the physical facility each time (de Giorgio et al., 2023). The scale of this bridging function is already substantial: India’s national Virtual Labs consortium – a twelve-institution partnership coordinated by the Indian Institute of Technology Delhi – delivers over 175 virtual laboratories comprising approximately 1,590 web-enabled experiments to students nationwide (Virtual Labs India, 2025). As a frontier scientific medium, however, XR goes further – enabling forms of inquiry that no physical laboratory can replicate, from immersive navigation of planetary surfaces to city-scale predictive experimentation on digital twin populations. It is in this second role that extended reality (XR) represents its most significant opportunity for the Global South.

Yet XR also introduces risks. The technologies originate overwhelmingly from the Global North. Cloud-based deployments can transfer data control to foreign providers. Most available content reflects Western pedagogical assumptions. Without deliberate strategies to build local production capacity and institutional ownership, XR risks deepening the very dependencies it could help address.

This report examines XR technologies, analyses their deployment and collective impacts on science and innovation systems in the Global South, identifies the enabling conditions for equitable uptake and offers strategic recommendations for leaders in public agencies, research institutions and the private sector. Its central argument is that XR represents two distinct investments – a bridge that compensates for absent physical infrastructure and a frontier medium that enables forms of scientific inquiry no conventional laboratory can provide – and that funding instruments, procurement frameworks and institutional strategies must distinguish between these roles to capture XR's full returns.

Understanding extended reality technologies

XR is an umbrella term for a spectrum of immersive technologies that bridge the physical and digital worlds, operating along the reality-virtuality continuum to alter or extend human perception (Milgram and Kishino, 1994; Rauschnabel et al., 2022). It encompasses augmented reality (AR), virtual reality (VR) and mixed reality (MR). For science systems, XR's core value is practical: it provides cost-effective, scalable and risk-free environments in which researchers and learners can conduct experiments, manipulate abstract scientific concepts and practise complex technical procedures without expensive disposable materials or the safety risks of hazardous real-world scenarios (Kiyuka et al., 2024; Crogman et al., 2025; Prasetya et al., 2024; Naudé et al, 2024; Aziz et al., 2020; Carmona-Galindo, et al., 2025). The three technologies differ in cost, infrastructure requirements and immersive depth – differences that determine which is viable in a given institutional context.

Augmented reality

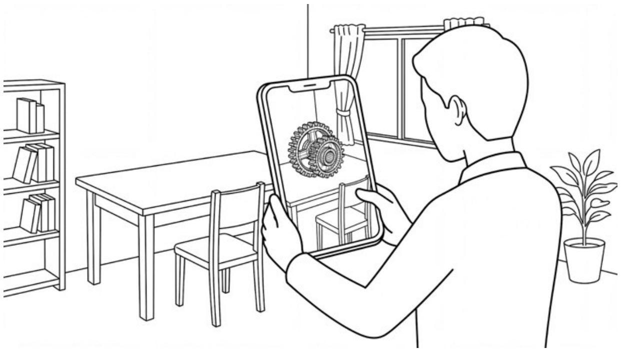

Figure 1: A person holding a tablet, previewing a digital object in relation to the physical surroundings.

AR overlays digital content, such as text, instructions and three-dimensional models, onto the user's physical surroundings (Siddiqui et al., 2025), typically through a device's camera or see-through lenses (Figure 1). Users interact with this augmented world through touch interfaces, hand gestures, eye gaze control and voice commands (Wang et al., 2024; Çöltekin et al., 2020). AR runs on portable mobile devices, desktops, wearable smart glasses and projectors that display data directly onto a physical workspace (Veas et al., 2013).

For science systems, AR is most immediately deployable for field documentation in environmental research (Veas et al., 2013), procedural guidance in laboratories, site annotation in geology and archaeology, maintenance support for scientific instrumentation (Akçayır et al., 2016; Melelli et al., 2023) and remote medical telementoring (Arboleda et al., 2024). Because it can be deployed on ubiquitous mobile devices, AR represents the lowest-cost, most accessible entry point into XR for institutions that lack the infrastructure or economic resources for more demanding configurations (Cárdenas-Sainz et al., 2023).

Virtual reality

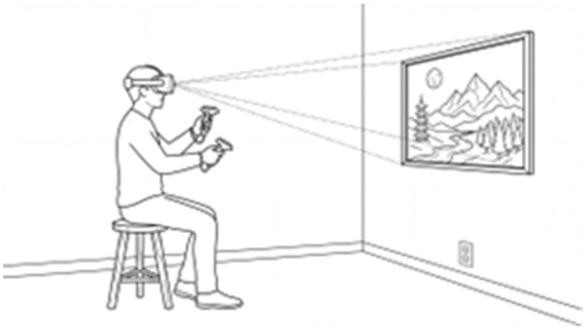

Figure 2: A person wearing a standalone virtual reality headset and holding handheld controllers, viewing content visible only to them on the internal screens.

VR provides total immersion in a digital environment (Figure 2). Through a headset, the user enters a digital world and interacts with it via physical controllers, hand tracking, eye tracking and voice commands (Crogman et al., 2025; Siddiqui et al., 2025; Wang et al., 2024). VR is deployed in two main configurations: standalone headsets, which are portable, run independently and now start at approximately $300 for capable devices (VR/AR Association, 2025); and tethered systems that rely on high-performance computers and high-speed connectivity for advanced simulations requiring high visual fidelity (Kumm et al., 2022).

In science and training, VR serves four primary functions: virtual laboratories where physical facilities are unavailable or prohibitively expensive (de Giorgio et al., 2023); clinical simulation for standardized, repeatable medical training (Li et al., 2024); scientific visualization that transforms complex datasets into interactive three-dimensional environments; and hazardous-environment training that allows personnel to practise procedures in realistic but risk-free conditions (Buthelezi et al., 2024).

Mixed reality

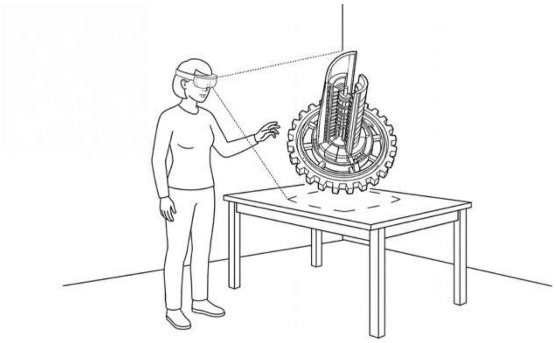

Figure 3: A person wearing an mixed reality headset can fully interact with physical and digital objects produced by the headset.

MR fuses the physical and digital worlds so that their elements coexist and interact in real time (Crogman et al., 2025) (Figure 3). Unlike basic AR, which overlays digital data onto a view of the real world, MR positions digital objects within physical space, allowing users to manipulate them while remaining fully aware of their surroundings (Alkaeed et al., 2024). This integration requires real-time spatial mapping between physical and virtual objects in three dimensions (Buthelezi et al., 2024).

MR advances science through interactive dataset visualization (Zhang et al., 2025), remote surgical telementoring (Li et al., 2024) and hands-on engineering education through simulated design and construction tasks (Jackson et al., 2025). However, MR is the most technically demanding and expensive of the three technologies, with costs ranging from thousands to tens of thousands of dollars for specialized hardware and platform licenses (Arboleda et al., 2024; Huang and Tseng, 2025). For most institutions in the Global South, MR remains a longer-term prospect, viable primarily where established research partnerships or external funding underwrite the infrastructure investment.

Extended reality: Limitations, cognitive overload and usability

Three technical limitations constrain XR's current utility for science. First, immersive environments remain primarily audio-visual: touch, weight, texture and physical resistance are not yet reliably simulated, reducing fidelity for experiments that depend on tactile or haptic feedback (Garcia-Ruiz et al., 2021; Li, et al., 2024; Supranovich and Kurilla, 2023). Second, because XR engages only a subset of human senses while delivering large volumes of artificial information, extended use can induce cybersickness – nausea, dizziness and disorientation – requiring sessions to remain short (Emma, 2026; Meenaakshisundaram et al., 2025). Third, current simulations do not yet incorporate the full complexity of physical laws, meaning that the unpredictability, hidden variables and spontaneous errors present in real environments may be absent from virtual ones (Akula and Garibay, 2021; Supranovich and Kurilla, 2023). These constraints are being actively addressed, but they define the operational boundaries for current deployments.

Taken together, these three technologies offer a graduated spectrum: AR is the most accessible entry point, running on smartphones already in widespread use; VR delivers deeper immersion at moderate and declining hardware costs; and MR demands the highest infrastructure investment but enables the richest integration of physical and digital worlds. In the Global South, where connectivity, power supply and technical support vary enormously, this spectrum determines which role XR can play – a practical bridge where physical facilities are absent, or an advanced medium for frontier inquiry that no conventional laboratory can replicate.

Current status in the Global South

Across diverse scientific disciplines, traditional physical laboratories and conventional training methods impose spatial, ethical and biological limitations that are becoming increasingly pronounced as datasets grow in dimensionality and systems-level research demands accelerate (Çöltekin et al., 2020; Dsouza et al., 2024). Researchers cannot physically travel to extraterrestrial surfaces, intuitively manipulate terabytes of spatial data on static two-dimensional screens, or ethically run socio-economic experiments on living urban populations (Cordes et al., 2024; Singla, 2022). XR's most transformative impact lies not in replicating physical laboratories but in unlocking entirely new capabilities that physical laboratories alone cannot provide (Çöltekin et al., 2020). The following examples illustrate how institutions in the Global South are deploying XR as an advanced medium for frontier science, followed by its equally critical role as an infrastructural bridge where physical facilities are absent.

Urban management and digital twins (city-scale experimentation)

Urban digital twins scale the laboratory to the size of a metropolis, allowing researchers to run predictive simulations on complex socio-economic and environmental variables before enacting real-world policy (Cárdenas-León et al., 2024). Researchers from Curtin University, Australia, developed a digital twin of Tetegu, a low-income urban community in Ghana (150 households plus businesses and community services), to monitor the real-time economic impacts of introducing a targeted e-commerce intervention. By providing participating local businesses with computer tablets, funded internet access and GH¢3,000 (approximately $220) in working capital, the digital twin allowed researchers to safely track complex, systemic economic shifts, such as the transition from cash to mobile money (Cordes et al., 2024).

In Brazil, the NBSouth project – led by the Politecnico di Milano and the University of Brasília – created an urban digital twin for Paranoá, a district facing rapid growth and a mix of formal and informal housing. Researchers integrated the Integrated Modification Methodology into the digital twin to process mapping data across 30 m grids, turning static information into dynamic indicators – such as Green Space Diversity and Green Continuity – that predict the area's climate resilience. Planners can then virtually test large-scale regeneration interventions before committing to physical construction, exposing spatial injustices such as unequal access to nature and turning raw data into targeted improvements for marginalized communities (Dong and Tadi, 2025). These deployments demonstrate that digital twins are not merely technical platforms but instruments of spatial justice – capable of exposing inequalities that conventional planning methods overlook.

Space science and astronomy (navigating the inaccessible)

The University of Cape Town and the Inter-University Institute for Data Intensive Astronomy in South Africa developed the immersive Data Visualisation Interactive Explorer (iDaVIE). This VR software allows scientists to don commercial headsets and immerse themselves entirely within massive 3D astronomical data cubes (University of Cape Town, 2024). Crucially, the intentional development of iDaVIE as a free, open-source platform directly mitigates common implementation barriers in the Global South, where the adoption of high-end VR systems is frequently impeded by prohibitive hardware costs and a lack of robust institutional technical support (Arboleda et al., 2024; Jackson et al., 2025).

A complementary approach emerged in India, where scientists at the Space Applications Centre of the Indian Space Research Organisation developed a custom, collaborative multi-projector VR system to overcome the single-user constraints of commercial headsets and the rendering limitations of processing massive datasets. Using Indian high-resolution remote sensing data and digital elevation models, this platform enables groups of scientists to conduct 3D surface visualizations of the Moon and Mars together (Singla, 2022) – a level of topographical analysis and rover landing-site evaluation impossible to replicate using traditional laboratory equipment, provided institutions can secure the specialized technical knowledge required to sustain such environments (Jackson et al., 2025; Singla, 2022).

Advanced medical anatomy and borderless surgical telementoring

In the Global South, immersive VR applications are shifting foundational medical education from passive observation to active exploration. Where medical students in resource-constrained environments have historically relied on static textbooks or faced severe scarcity of physical cadavers, trainees today can use spatial tools such as the Tetralogy of Fallot Colour VR model to explore and manipulate complex congenital heart defects in three dimensions – simulating blood flow and visualizing structures from angles impossible in traditional settings (Li et al., 2024). These immersive technologies offer realistic, repeatable encounters that bridge the gap between theoretical knowledge and practical expertise.

XR is transforming how doctors collaborate across the globe by creating a borderless operating room. At a medical centre in Uganda, doctors lacking expensive imaging equipment used a smartphone app (MagiScan) to create 3D digital models of 15 patients from photographs, generating high-quality models in under six minutes per case (Obst et al., 2025). Surgeons in Uganda and Germany then met as digital avatars in a shared VR room, where they examined the models in real time, using virtual pens to mark scars, map blood vessels and draw surgical incision lines directly on the digital patients (Obst et al., 2025). The surgeons affirmed that the technology could enhance surgical care in low-resource settings (Obst et al., 2025), enabling global medical experts to assist in underserved clinics affordably, bypassing the costs and logistical barriers of international travel.

Extended reality as an infrastructural bridge in the Global South

Beyond its role as a frontier scientific medium, XR serves an equally critical function as an infrastructural bridge – sustaining essential research, clinical care and vocational training through scalable digital simulations where physical facilities, medical equipment or industrial machinery are restricted by cost or geography (Sobel et al., 2019; Kumbo et al., 2024).

This bridging function is already operational across diverse disciplines. In Gaza, Palestine, AR enabled a remote expert in Beirut to live-guide a complex hand reconstruction following a bomb blast injury, annotating the local surgeon’s visual field in real time through tablets and a smartphone camera (Greenfield et al., 2018). In Baja California, Mexico, educators deployed a mobile AR system for remote industrial training that yielded productive technical skill development despite the area’s deficient technological infrastructure (López-Hernández et al., 2022). In Colombia, a VR platform for rural university students studying soil science significantly enhanced both learning motivation and comprehension of complex agricultural content (Bigonah et al., 2025; de la Puente et al., 2025).

Core analysis:
Three key impacts on science systems

XR technologies shape how science is taught, practiced and communicated across the Global South (Jackson et al., 2025). The central question is whether XR can move beyond compensating for what institutions lack towards enabling what modern science increasingly demands. These requirements are the capacity to visualize complex multi-dimensional datasets, model dynamic systems at scale and collaborate across geographic boundaries in real time (Dhurumraj and Ramaila, 2023). The following analysis examines three major impacts, each evaluated through scientific opportunity, challenges and risks.

Impact 1: Democratization of access to scientific infrastructure

XR technologies expand access to scientific training by producing standards-aligned learning environments accessible online (Allison et al., 2025). Beyond delivering instruction where physical infrastructure is absent, XR serves as an advanced medium for experiential learning that enhances outcomes even when conventional facilities exist – eliminating the constant need to procure hazardous or expensive physical supplies and levelling the playing field for students in underfunded areas (Alnagrat et al., 2021).

Scientific opportunity

Virtual laboratories break down geographic barriers, allowing people in different locations to co-develop complex tasks in real time (Allison et al., 2025). A recent meta-analysis confirms that XR demonstrates substantial efficacy in enhancing educational outcomes, knowledge retention and student motivation across disciplines (Salem and Gareeb, 2025), with research into XR healthcare applications growing by over 12 percent annually over the last decade (Moreira et al., 2025). The operational deployments documented earlier in this report – AR-guided telesurgery in Gaza, mobile AR vocational training in Mexico and VR-based agricultural education in Colombia – illustrate how these mechanisms translate into practice.

Addressing challenges

Sustaining XR as a tool for broadening access requires stable internet connectivity, accessible hardware and maintenance support – conditions that remain unevenly distributed across the Global South (Allison et al., 2025). Many educators currently lack the digital competencies to integrate XR pedagogically (Emma, 2026) and XR introduces novel privacy risks through its collection of sensitive biometric and psychographic data (Voinov et al., 2024).

Risks

To reduce upfront costs, institutions often rely on foreign cloud computing, weakening digital sovereignty and risking data colonialism – where user data is extracted from the Global South and monetized by corporations in the Global north (De Freitas, 2025). If XR remains confined to isolated pilot projects without investment in local capacity and open-source infrastructure, it risks widening the existing digital divide rather than closing it (Abeywardena et al., 2023; Rullyana and Triandari, 2025). In sum, XR can democratize access to scientific infrastructure, but only when deployments are embedded within institutional strategies that address connectivity, faculty readiness and data governance. Without these conditions, the technology risks reproducing the inequalities it is intended to overcome. The policy priority is to move beyond isolated pilots towards systemic, institutionally owned deployments.

Impact 2: Enhancement of scientific research and training

XR has an immediate and profound utility across scientific disciplines, where datasets are growing in dimensionality and complexity faster than conventional display technologies can accommodate (Emma, 2026; Salem and Gareeb, 2025). Immersive three-dimensional environments allow researchers to interact with spatial, biological and mathematical data in ways that static two-dimensional screens cannot – revealing patterns, anomalies and structural relationships invisible in tabular or graphical formats (Zhang et al., 2025). Learners can also practise step-by-step procedural skills in risk-free 3D simulations, accelerating experiential learning (Crogman et al., 2025; Salem and Gareeb, 2025).

Scientific opportunity

As data volumes grow, XR translates complex phenomena – often buried in massive datasets – into interactive visual layers that traditional formats cannot provide (Zhang et al., 2025), enabling dynamic simulations that improve higher-order problem-solving, spatial comprehension and long-term knowledge retention (Çöltekin et al., 2020; Jackson et al., 20025; Salem and Gareeb, 2025; Dsouza et al., 2024). The deployments documented earlier in this report illustrate these dynamics in practice: astronomers in South Africa navigate three-dimensional data cubes that would be unintelligible on flat screens, while scientists at the Indian Space Research Organisation explore planetary surfaces collaboratively in custom-built VR environments.

Addressing challenges

Many scientific disciplines are grounded in physical realities and high-stakes outcomes, requiring XR technologies to meet rigorous technical standards. Current systems often lack realistic haptic feedback – such as physical resistance, weight and texture – which is critical for high-precision disciplines like medicine (Li et al., 2024; Hoshi et al., 2021). Furthermore, rendering multi-dimensional scientific data can exceed the processing capacity of standalone portable headsets (Zhang et al., 2025). Pedagogically, if highly immersive environments are not carefully designed, they risk inducing cognitive overload and distraction, requiring dedicated teacher training to ensure strict curricular alignment (Crogman et al., 2025; Emma, 2026).

Risks

XR introduces epistemic risks: heavy reliance on virtual environments can blur the boundary between simulation and reality, prompting questions about the scientific validity of virtual experiences (Voinov et al., 2024). The integration of AI within XR systems compounds this – algorithms trained on skewed datasets can yield flawed scientific inferences, while the collection of sensitive biometric data introduces risks of surveillance abuse (Emma, 2026; Voinov et al., 2024). The implication for science is clear: XR's capacity to render complex datasets tangible and to enable repeatable procedural training represents a qualitative advance over conventional display technologies. Realizing this potential, however, requires rigorous technical standards, careful pedagogical design and institutional safeguards against the epistemic and surveillance risks that accompany AI-integrated immersive systems.

Impact 3: Fostering public understanding of science and integrating Indigenous Knowledge

The third impact centres on epistemic inclusion. XR provides learners in remote areas with virtual access to advanced research environments that would otherwise remain inaccessible (Kiyuka et al., 2024), while also enabling immersive engagement with complex knowledge systems – including Indigenous Knowledge – that resist conventional two-dimensional documentation. These capabilities empower researchers from marginalized regions to participate in cross-regional consortia rather than remaining dependent on knowledge produced predominantly in the Global North (De Freitas, 2025).

Scientific opportunity

XR can bridge the gap between global research and local epistemologies, integrating Indigenous Knowledge into formal science systems as well as informal learning environments, such as science festivals and museums (Dsouza et al., 2024). Initiatives like the KEMRI-Wellcome Trust Research Programme used VR to provide rural Kenyan students with risk-free virtual tours of advanced laboratories. This exposed learners to scientific careers they would otherwise not have known about and directly stimulated their interest in science (Kiyuka ET AL., 2024). Through Afrocentric XR design, educators can merge traditional practices with scientific inquiry – such as using VR to simulate the traditional South African beer-brewing process (Umqombothi) to teach complex chemistry concepts like fermentation. This safeguards cultural heritage, makes scientific inquiry relevant to local realities and actively contributes to decolonizing participatory design (Ramnarain et al., 2025).

Addressing challenges

Implementing XR for science communication and cultural preservation faces significant infrastructural hurdles: remote deployment is expensive, requiring specialized maintenance, stable electricity and high-speed connectivity (Jackson et al., 2025; Hollo, 2025). Most available XR educational content is produced in the Global North and lacks the linguistic and socio-cultural relevance needed by local learners, making integration into local curricula difficult without bespoke, localized development (Ramnarain et al., 2025; Rullyana and Triandari, 2025).

Risks

If XR applications are developed and deployed solely from the perspective of the Global North, students may experience a profound disconnect between classroom experiences and local realities, where their own culture is subjugated to a Global North worldview, preventing them from reaching their full scientific potential (Ramnarain et al., 2025). Left unaddressed, this dynamic risks reinforcing existing structural inequalities and creates a knowledge dependency that actively limits local agenda-setting, theoretical innovation and digital sovereignty in the Global South (De Freitas, 2025; Ramnarain et al., 2025). Ultimately, XR's value for public understanding of science and Indigenous Knowledge integration depends on who designs the content. Culturally grounded, locally produced XR applications can strengthen knowledge sovereignty; externally imposed content risks deepening epistemic dependency. The policy imperative is to ensure that local communities are co-creators, not merely consumers, of immersive scientific experiences.

Enabling conditions for equitable uptake

Simply importing XR technologies from the Global North risks reproducing historical patterns of technological dependency and entrenching epistemic subordination (De Freitas, 2025). Equitable uptake depends on addressing three interconnected barriers:

- The scarcity of open content, tools and technical skills;
- The absence of pedagogy and instructional design adapted to immersive environments; and
- The lack of scalability strategies that move deployments beyond isolated pilots (Abeywardena, 2023).

Overcoming these barriers requires not only stable connectivity and affordable hardware but institutional readiness – the expertise to develop locally relevant content, the data governance frameworks to manage sensitive biometric and spatial datasets and the partnerships to embed XR within long-term scientific agendas. Underpinning all of this is digital sovereignty – the capacity to own, audit and adapt the technologies and data involved (De Freitas, 2025).

Strategic policy, targeted funding and regional innovation hubs

To deploy XR successfully, long-term investment in indigenous digital public infrastructure is paramount (De Freitas, 2025). Strategies must be carefully adapted to resource-constrained realities, fostering creative peripheral innovation rather than relying on dominant cultural centres (Martí-Testón et al., 2025). Regional educational hubs for XR serve as anchors for localized innovation, ensuring that technology design reflects the linguistic, cultural and infrastructural realities of underrepresented communities (Rullyana and Triandari, 2025).

The medical and space science cases examined in this report illustrate what becomes possible with sustained institutional support. For instance, the iDaVIE VR software in South Africa succeeds because it is embedded within the Inter-University Institute for Data Intensive Astronomy – an established partnership dedicated to developing, maintaining and freely disseminating open-source tools to build local data-intensive research capacity (University of Cape Town, 2024). Ultimately, for XR to be viable, governments and institutions must collaborate to move beyond fragmented, isolated, pilot projects by adopting scalable, open educational practices and coordinated operationalization strategies (Abeywardena, 2023).

Development of culturally relevant content:

Because most XR applications reflect a dominant Western cultural perspective, the Global South must build multilingual indexing platforms and representative AI datasets that reflect its linguistic diversity and infrastructural realities (De Freitas, 2025; Rullyana and Triandari, 2025; The Economist, 2026). Afrocentric design approaches – exemplified earlier in this report – demonstrate how XR content can embed Indigenous Knowledge systems into science pedagogy, transforming cultural practise into a vehicle for scientific instruction rather than treating local contexts as obstacles to be bypassed (Ramnarain et al., 2025).

Infrastructural sovereignty, scalable technologies and open science

Institutional data governance – the capacity to control, audit and legally own locally generated data – is a precondition for avoiding the extractive dynamics of data colonialism (De Freitas, 2025). Furthermore, resource constraints can catalyze locally appropriate solutions that outperform imported alternatives in cost, maintainability and cultural fit (Martí-Testón et al., 2025). Underfunded research institutions, particularly those serving ethnic minority communities, can foster this innovation by testing scalable, low-cost XR solutions, including mobile-based systems and other affordable hardware (Khuong and Duong, 2026). Open science frameworks, such as the *UNESCO Recommendation on Open Science*, provide the policy scaffolding necessary to maximize public research investment and position educators as co-creators of knowledge (Abeywardena, 2023; UNESCO. 2021). Interactive digital content distributed directly across the web – such as browser-based AR or WebXR/WebVR platforms – runs on standard smartphones without requiring expensive, dedicated head-mounted displays, representing a highly scalable entry point for resource-limited institutions (Cárdenas-Sainz et al., 2023; Salem and Gareeb, 2025). Prioritizing open standards and free and open-source software repositories in procurement and development decisions strengthens institutional digital sovereignty by reducing technological dependency and ensuring that content developed for one platform can function seamlessly across others (Abeywardena, 2023; De Freitas, 2025; UNESCO, 2021).

Strategic recommendations for science, technology and innovation organizations

The following recommendations translate the preceding analysis into potential pathways for action for science, technology and innovation organizations.

For public science, technology and innovation agencies (governments, funders)

- **Integrating XR into national research capacity plans:** Funders should approach XR as scientific infrastructure – on par with laboratory construction and connectivity investments – rather than as isolated technology projects, requiring operational continuity plans as a condition for public funding: specifying who operates, who maintains and how outcomes are measured. Funding instruments should differentiate between deployments focused on training access (such as virtual laboratories and clinical simulators) and those focused on advanced research capability (such as immersive data visualization and digital twin environments), since each requires distinct institutional capacity (Shawash et al., 2025; UNESCO, 20210).

- **Exploring open standards, security certifications and institutional ownership in procurement:** Contracts for publicly funded XR systems should guarantee content portability, data access and the institution's ability to switch providers without losing accumulated work. Decision-makers should prioritize solutions built on OpenXR, WebXR and open file formats (Abeywardena, 2023; De Freitas, 2025, UNESCO, 2021). Furthermore, policy-makers can explore accelerating the development of industry standards and adopting stringent certifications for improving security (UNESCO, 2021; Voinov et al., 2024).

- **Coordinating XR deployment with connectivity and sustainable energy investments:** Since advanced XR applications require low-latency, high-throughput connectivity (Jagatheesaperumal et al., 2024), deployment plans should be synchronized with network rollout and with actions to address the environmental footprint of virtual worlds (Voinov et al., 2024). This alignment helps ensure that XR investments are not hindered by unstable connections and high costs in areas that urgently need more reliable digital infrastructure.

For research and academic institutions

- **Approaching XR as a shared institutional service:** Institutions should invest in shared technical infrastructure, maintenance support and accessible XR resources to lower adoption barriers for faculty and staff. This includes establishing centralized XR facilities that serve multiple departments – housing virtual laboratory platforms for teaching alongside immersive visualization tools for research – rather than allowing hardware and expertise to fragment across isolated units. Readiness programmes can be co-designed with administrative policies that provide time allocation, equipment access and recognition for XR innovation (Khuong and Duong, 2026).

- **Building content capacity and ethical readiness:** Universities should benefit from partnerships with local technology providers to establish XR training hubs that provide continuous support, contextualized content and localized pedagogical materials. Because effective XR pedagogy relies on more than just technology, professional development programmes should embed ethical reflection as a core competence (Khuong and Duong, 2026). Producing in-house content allows institutions to pursue digital sovereignty and reduce dependence on external providers (De Freitas, 2025; Ramnarain et al., 2025).

- **Fostering South–South collaboration through reusable content:** Institutions should co-develop simulation libraries and training modules with peer institutions in their region. Sharing improvements through open repositories – such as institutional GitLab instances, regional content platforms or frameworks coordinated through National Research and Education Networks – can be highly beneficial (Abeywardena, 2023; Rullyana and Triandari, 2025; UNESCO, 2021).

For private sector innovators (technology developers)

- **Co-developing with research institutions:** Developers should design XR tools by collaborating with universities and research laboratories from the outset (Siddiqui et al., 2025). This helps ensure that solutions fit actual research and training workflows rather than imposing generic products. The Global South market comprises institutions with vastly different needs – from universities requiring affordable, browser-based laboratory simulations to research centres pursuing high-fidelity immersive data visualization – and product strategies should reflect this range rather than defaulting to a single tier. Developers must partner with local institutions to ensure XR content is highly contextualized and aligns with localized pedagogical realities, involving educational professionals as active collaborators (Khuong and Duong, 2026).

- **Considering open-source software and open formats:** Using open-source software can lower adoption barriers, support institutional auditing and adaptation and strengthen local developer ecosystems, reducing the risk of institutions becoming dependent on a single supplier (Siddiqui et al., 2025; UNESCO, 2021).

- **Exploring sustainable service models:** Technology providers should offer ongoing support, content updates, instructor training, maintenance and content adaptation as recurring services. Building service relationships can reduce abandonment and create stable, long-term revenue, helping to prevent platforms from being discarded due to insufficient post-funding technical support (Shawash et al., 2025).

Conclusion

The evidence examined in this report yields a clear strategic conclusion: XR is not a single intervention but two distinct investments that serve fundamentally different purposes. Bridging deployments – virtual laboratories, clinical simulators, AR-guided field training – address the immediate deficit in physical infrastructure that constrains scientific education across the Global South (Garzón et al., 2022). But the more consequential finding is that XR simultaneously opens analytical capabilities that no amount of physical construction can provide: the capacity to inhabit multi-dimensional datasets, to model complex systems at scales ranging from cellular to metropolitan and to conduct real-time collaborative procedures that dissolve geographic distance. No virtual simulation can yet replicate the full sensory complexity of a physical experiment (Li et al., 2024). Funding instruments, procurement frameworks and institutional strategies that fail to distinguish between these two roles will systematically underinvest in XR's most transformative returns.

What distinguishes the successful deployments documented in this report – whether in astronomy, urban planning, surgery or agricultural science – is not the sophistication of the hardware but the institutional architecture surrounding it. Where XR is embedded within established research partnerships, supported by open-source development strategies and integrated into long-term scientific agendas, it delivers measurable outcomes. Where it is introduced as a standalone technology project without operational continuity, maintenance capacity or pedagogical redesign, even well-funded pilots stall after initial enthusiasm fades (Abeywardena, 2023). The question facing science leaders is therefore not whether XR works – the operational evidence is now substantial – but whether institutions can transition from episodic experimentation to systemic integration.

That transition must be sovereignty-conscious. The risks documented in this report – data extraction through cloud architectures, algorithmic bias from unrepresentative training datasets and epistemological displacement through culturally decontextualized content – are not unique to XR. They mirror the broader dynamics described in debates on data colonialism, digital sovereignty and the political economy of technology transfer in the Global South (De Freitas, 2025). What distinguishes XR is the intimacy of the data involved: biometric, spatial and behavioural information generated through immersive interaction represents a qualitatively different category of exposure than conventional digital platforms (Emma, 2026; Ramnarain et al., 2025; Voinov et al., 2024). These are not hypothetical concerns – they are design parameters that must shape every procurement decision, partnership agreement and institutional data governance framework. Yet the tools to address them already exist. Open technical standards reduce vendor dependency. Open-source platforms demonstrate that frontier scientific visualization need not require proprietary licences (Bakthavatchaalam et al., 2021; University of Cape Town, 2024). And culturally grounded design approaches – embedding Indigenous Knowledge into science pedagogy rather than bypassing it – show that XR can strengthen knowledge sovereignty rather than erode it (Ramnarain et al., 2025; UNESCO, 2021).

The Global South does not need to wait for the next generation of hardware. Browser-based AR runs on smartphones already in students' hands (Cárdenas-Sainz et al., 2023). National virtual laboratory consortia are already serving hundreds of thousands of learners (Virtual Labs India, 2025). The foundational building blocks – affordable devices, open standards, operational case studies and policy frameworks such as the *UNESCO Recommendation on Open Science* (UNESCO, 2021) – are in place. What remains is the institutional commitment to treat XR as shared scientific infrastructure deserving the same strategic attention as laboratory construction, connectivity expansion and energy access. The science systems that make this commitment will not merely close an infrastructural gap – they will position themselves to participate in and shape the forms of inquiry that define twenty-first-century research.

Glossary of terms

- **Augmented Reality (AR):** Digital content – such as labels, instructions or three-dimensional models – overlaid on the user's real-world view, typically through a smartphone or tablet. Used for field guidance, laboratory procedures and documentation.

- **Cloud rendering:** A computing architecture in which graphically intensive processing runs on a remote server and the resulting image is streamed to a lightweight device. Enables complex simulations on inexpensive hardware, but requires reliable, low-latency network connections.

- **Data colonialism:** A condition in which data generated by populations in the Global South is extracted, processed and monetized by corporations or institutions based predominantly in the Global North, reproducing historical patterns of resource extraction and economic dependency in digital form. Used in this report to describe the sovereignty risks of cloud-based XR deployments.

- **Digital public infrastructure:** Shared institutional systems – such as content repositories, identity management and computing resources – that serve as common foundations, preventing XR from becoming a set of isolated departmental efforts.

- **Digital sovereignty:** The capacity of an institution or state to retain control over the digital assets, content and data it produces – ensuring they remain usable, portable and auditable regardless of changes in technology suppliers.

- **Digital twin:** A dynamic virtual replica of a physical system – such as a city district, building or industrial process – that integrates real-time or near-real-time data to simulate, predict and test the effects of interventions before they are implemented in the physical world. Used in this report to describe city-scale experimentation in Ghana and Brazil.

- **Extended reality (XR):** An umbrella term for immersive technologies including VR, AR and MR. XR creates digital environments that allow users to train, simulate, visualize and collaborate using interactive three-dimensional content.

- **Mixed reality (MR):** A hybrid environment in which users see the physical world while interacting with digital objects that appear anchored in the same space. Used for collaborative technical review, planning and shared visualization of scientific data.

- **Motion-to-photon latency:** The delay between a user's physical movement and the corresponding visual update in the headset. Must remain below approximately 20 milliseconds to avoid disorientation and nausea – establishing a hard performance threshold for network and computing infrastructure.

- **OpenXR / WebXR:** Open technical standards that enable XR applications and content to function across different devices and platforms, reducing dependence on any single vendor's proprietary ecosystem.

- **Vendor Lock-in:** A condition in which switching from one technology provider to another becomes prohibitively costly because content, data or workflows are not portable across platforms.

- **Virtual reality (VR):** A fully digital environment accessed through a headset that replaces the user's view of the physical world. Used for simulation, repeatable training, hazardous-environment practice and scientific visualization.

- **Web AR:** Augmented Reality delivered through a standard web browser rather than a dedicated application. Eliminates installation barriers and enables cross-platform access, making AR deployable on virtually any modern smartphone.

References

Abeywardena, I. S. 2023. OXREF: Open XR for education framework. *The International Review of Research in Open and Distributed Learning*, Vol. 24, No. 3, pp. 185–206. https://doi.org/10.19173/irrodl.v24i3.7109

Akçayır, M. et al. 2016. Augmented reality in science laboratories: The effects of augmented reality on university students' laboratory skills and attitudes toward science laboratories. *Computers in Human Behavior*, Vol. 57, pp. 334–342. https://www.sciencedirect.com/science/article/abs/pii/S0747563215303253

Akula, R. and Garibay, I. 2021. Ethical AI for Social Good. *ArXiv*. https://arxiv.org/abs/2107.14044

Alkaeed, M. et al. 2024. Privacy preservation in Artificial Intelligence and Extended Reality (AI-XR) metaverses: A survey. *Journal of Network and Computer Applications*, Vol. 231, p. 103989. https://doi.org/10.1016/j.jnca.2024.103989

Allison, J. et al. 2025. From Generative AI to Extended Reality: Multidisciplinary Perspectives on the Challenges, Opportunities, and Future of Educational Computing. *Journal of Educational Computing Research*, Vol. 63, No. 6, pp. 1327–1363. https://doi.org/10.1177/07356331251359964

Alnagrat, A. J. A. et al. 2021. Extended reality (XR) in virtual laboratories: A review of challenges and future training directions. Journal of Physics: Conference Series, Vol. 1874, p. 012031. https://doi.org/10.1088/1742-6596/1874/1/012031

Arboleda, V. et al. 2024. Augmented Reality (AR) in Surgery in Low- and Middle-Income Countries (LMICs): A Scoping Review. *Cureus*, Vol. 16, No. 7, p. e64278. https://doi.org/10.7759/cureus.64278

Aziz, F. A. et al. 2020. Mixed reality improves education and training in assembly processes. *Journal of Engineering and Technological Sciences*, Vol. 52, No. 4, pp. 598–607. https://cendekia.unisza.edu.my/neuaxis-e/Record/upm-86775/Details?sid=24516240

Bakthavatchaalam, V. et al. 2021. Academic Dishonesty and Research Productivity in a Changing Higher Education Environment: The Case of India's Engineering Institutions. *Educational Studies Moscow*, No. 2, pp. 126–151. https://doi.org/10.17323/1814-9545-2021-2-126-151

Bigonah, M. et al. 2025. A Systematic Review of Extended Reality (XR) Technologies in Agriculture and Related Sectors 2022–2024. *IEEE Access*, Vol. 13, pp. 49721–49735. https://doi.org/10.1109/ACCESS.2025.3550891

Buthelezi, S. M. et al. 2024. The status of extended reality technology in South Africa’s mining industry. *Journal of the Southern African Institute of Mining and Metallurgy*, Vol. 124, No. 6, pp. 303–310. https://doi.org/10.17159/2411-9717/2035/2024

Cárdenas-León, et al. 2024. Urban digital twin-based solution using geospatial information for solid waste management. *Sustainable Cities and Society*, Vol. 115, p. 105798. https://doi.org/10.1016/j.scs.2024.105798

Cárdenas-Sainz, B. A. et al. 2023. Evaluation of eXtended reality (XR) technology on motivation for learning physics among students in Mexican schools. *Computers and Education: X Reality*, Vol. 3, p. 100036. https://doi.org/10.1016/j.cexr.2023.100036

Carmona-Galindo, V. D. et al. 2025. The Ecology of Climate Change: Using Virtual Reality to Share, Experience, and Cultivate Local and Global Perspectives. *Education Sciences*, Vol. 15, No. 3, p. 290. https://doi.org/10.3390/educsci15030290

Cordes, D. et al. 2024. Developing digital twins of urban low-income communities in Sub-Saharan Africa: a case study in Ghana, West Africa. *Discover Analytics*, Vol. 2, No. 18. https://doi.org/10.1007/s44257-024-00026-x

Crogman, H. T. et al. 2025. Virtual Reality, Augmented Reality and Mixed Reality in Experiential Learning: Transforming Educational Paradigms. *Education Sciences*, Vol. 15, No. 3, pp. 303. https://doi.org/10.3390/educsci15030303

Çöltekin, A. et al. 2020. Extended reality in spatial sciences: A review of research challenges and future directions. *ISPRS International Journal of Geo-Information*, Vol. 9, No. 7, pp. 439. https://doi.org/10.3390/ijgi9070439

De Freitas, M. V. 2025. *Digital sovereignty and data colonialism: Shaping a just digital order for the Global South* (Policy Paper PP-38/25). Policy Center for the New South. https://www.policycenter.ma/publications/digital-sovereignty-and-data-colonialism-shaping-just-digital-order-global-south

de Giorgio, A. et al. 2023. Adopting extended reality? A systematic review of manufacturing training and teaching applications. *Journal of Manufacturing Systems*, Vol. 71, pp. 645–663. https://doi.org/10.1016/j.jmsy.2023.10.016

de la Puente, M. et al. 2025. Digital immersion technologies transform agricultural learning: A study of interactive educational platforms among rural Colombian university students. *Research in Science and Technological Education*, Vol. 21, No. pp. 1–18. https://doi.org/10.1080/02635143.2025.2491079

Dhurumraj, T. and Ramaila, S. 2023. Alleviation of social injustices in STEM education: Harnessing pedagogical affordances of virtual and augmented reality applications through open learning. *African Journal of Teacher Education*, Vol. 12, No. 2, pp. 210–227 https://doi.org/10.21083/ajote.v12i2.7522

Dong, T. and Tadi, M. 2025. Digital twin-assisted urban resilience: A data-driven framework for sustainable regeneration in Paranoá, Brasilia. *Urban Science*, Vol. 9, No. 9, p. 333. https://doi.org/10.3390/urbansci9090333

DSouza, P. et al. 2024. Extended Reality for Public Understanding of Science: A Systematic Literature Review. In *Proceedings of the 27th International Academic Mindtrek Conference,* pp. 168–175. https://doi.org/10.1145/3681716.3681734

Emma, O. 2026. Extended reality in the digital age: A literature review on technology-driven learning environments. *Computers and Education*: *X Reality*, Vol. 8, p. 100127. https://doi.org/10.1016/j.cexr.2025.100127

Garcia-Ruiz, M. et al. 2021. Towards Effective Odor Diffusion with Fuzzy Logic in an Olfactory Interface for a Serious Game. In C. Stephanidis et al. (eds) *HCI International 2021 - Late Breaking Papers: Multimodality, eXtended Reality, and Artificial Intelligence*. HCII 2021. Lecture Notes in Computer Science. Cham: Springer International Publishing, Vol. 13095, pp. 31–43. pp. 3–16. https://doi.org/10.1007/978-3-030-90963-5_1.

Garzón, J. et al. 2022. Promoting eco-agritourism using an augmented reality-based educational resource: a case study of aquaponics. *Interactive Learning Environments*, Vol. 30, No. 7, pp. 1200–1214. https://doi.org/10.1080/10494820.2020.1712429

Greenfield, M. J. et al. 2018. Demonstration of the Effectiveness of Augmented Reality Telesurgery in Complex Hand Reconstruction in Gaza. *Plastic and Reconstructive Surgery - Global Open*, Vol. 6, No. 3, p. e1708. https://doi.org/10.1097/GOX.0000000000001708

Hlal, M. et al. 2025. Digital Twin Technology for Urban Flood Risk Management: A Systematic Review of Remote Sensing Applications and Early Warning Systems. *Remote Sensing*, Vol. 17, No. 17, p. 3104. https://doi.org/10.3390/rs17173104

Hollo, L. 2025. Accelerating Digitalization and Sustainability through Cloud-Based Immersive Work and Education Environments [Master’s thesis, Lappeenranta–Lahti University of Technology LUT, Industrial Engineering Management]. https://lutpub.lut.fi/bitstream/handle/10024/170896/Mastersthesis_Lauri_Hollo.pdf?sequence=1

Hoshi, Y. et al. 2021. Haptic Finger Glove for the VR Keyboard Input. In C. Stephanidis et al. (eds) *HCI International 2021 - Late Breaking Papers: Multimodality, eXtended Reality, and Artificial Intelligence*. HCII 2021. Lecture Notes in Computer Science. Cham: Springer International Publishing, Vol. 13095, pp. 31–43. https://doi.org/10.1007/978-3-030-90963-5_3

Huang, T.-C. and Tseng, H.-P. 2025. Extended Reality in Applied Sciences Education: A Systematic Review. *Applied Sciences*, Vol. 15, No. 7, p. 4038. https://doi.org/10.3390/app15074038

Jackson, H. et al. 2025. The potential of extended reality in engineering education: a systematic review. *Cogent Education*, Vol. 12, No. 1, p. 2541442. https://doi.org/10.1080/2331186X.2025.2541442

Jagatheesaperumal, S. K. et al. 2024. Advancing Education Through Extended Reality and Internet of Everything Enabled Metaverses: Applications, Challenges and Open Issues. *IEEE Transactions on Learning Technologies*, Vol. 17, pp. 1120–1139. https://doi.org/10.1109/TLT.2024.3358859

Khuong, P. D. and Duong, L. T. 2026. Assessing teachers’ readiness for AI-driven XR integration: Scale development and multigroup validation in ethnic minority boarding high schools in Viet Nam. *Computers and Education: X Reality*, Vol. 8, p. 100144. https://doi.org/10.1016/j.cexr.2026.100144

Kiyuka, P. K. et al. 2024. Impact of virtual reality on promoting understanding of research in rural Africa: The KEMRI-Wellcome Trust virtual tour of research laboratories. *Wellcome Open Research*, Vol. 9, No. 141. https://doi.org/10.12688/wellcomeopenres.20756.1

Kumbo, L. I. et al. 2024. Enhancing competency-based education training in Dar es Salaam, Tanzania, with augmented reality and virtual reality technologies. *The Cradle of Knowledge: African Journal of Educational and Social Science Research*, Vol. 12, No. 4, pp. 178–191. https://doi.org/10.4314/ajessr.v12i4.1

Kumm, A. J. et al. 2022. The Digital Divide in Technologies for Autism: Feasibility Considerations for Low- and Middle-Income Countries. *Journal of Autism and Developmental Disorders*, Vol. 52, No. 5, pp. 2300–2313. https://doi.org/10.1007/s10803-021-05084-8

Li, X. et al. 2024. Advancing Medical Education Using Virtual and Augmented Reality in Low- and Middle-Income Countries: A Systematic and Critical Review. *Virtual Worlds*, Vol. 3, No. 3, pp. 384–403. https://doi.org/10.3390/virtualworlds3030021

López-Hernández, J. G. et al. 2022. The Augmented Reality Technology. An Experimental Application in the Educational and Industrial Sector of Baja California, Mexico. In Alcaraz, G. (eds). *Algorithms and Computational Techniques Applied to Industry.* Studies in Systems, Decision and Control, Vol. 435, pp. 183–232. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-031-00856-6_10

Martí-Testón, A. et al. 2025. Digital Resilience and Communication Strategies in Underfunded Museums in Argentina and Spain 2020–2024. *Heritage*, Vol. 8, No. 10, p. 413. https://doi.org/10.3390/heritage8100413

Meenaakshisundaram, K. V. et al. 2025. The Ethics of Extended Realities: Insights from a Systematic Literature Review. In M. Kurosu and A. Hashizume (Eds.), *Human-Computer Interaction*. HCII 2025 (LNCS 15770), pp. 243–261. Springer. https://doi.org/10.1007/978-3-031-93864-1_17

Melelli, L. et al. 2023. HUSH (hiking in urban scientific heritage): The augmented reality for enhancing the geological and naturalistic heritage in urban areas. *Applied Sciences*, Vol. 13, No. 15, p. 8857 https://doi.org/10.3390/app13158857

Milgram, P. and Kishino, F. 1994. A taxonomy of mixed reality visual displays. IEICE *Transactions on Information and Systems*, Vol. 77, No. 12, pp. 1321–1329. https://www.alice.id.tue.nl/references/milgram-kishino-1994.pdf

Moreira, A. et al. 2025. The impact of extended reality on healthcare: A decade-long bibliometric analysis through Web of Science and Scopus. *Procedia Computer Science*, Vol. 256, pp. 1012–1021. https://doi.org/10.1016/j.procs.2025.02.207

Naudé, D. H. et al. 2024. Extended reality in agricultural education: A framework for implementation. *Education Sciences*, Vol. 14, No. 12, p. 1309. https://doi.org/10.3390/educsci14121309

Obst, M. et al. 2025. AI-Enhanced 3D Models in Global Virtual Reality Case Conferences for Surgical Care in a Low-Income Country: Exploratory Study. *JMIR Formative Research*, Vol. 9, p. e69300. https://doi.org/10.2196/69300

Prasetya, F. et al. 2024. The impact of augmented reality learning experiences based on the motivational design model: A meta-analysis. *Social Sciences and Humanities Open*, Vol. 10, p. 100926. https://doi.org/10.1016/j.ssaho.2024.100926

Ramnarain, U. et al. 2025. Afrocentric Extended Reality Technology Design to Infuse Indigenous Knowledge into African STEM Education. In *The 5th Biennial African Human Computer Interaction Conference* (Africhi 2025. ACM. https://doi.org/10.1145/3757232.3757274

Rauschnabel, P. A. et al. 2022. What is XR? Towards a framework for augmented and virtual reality. *Computers in Human Behavior*, Vol. 133, p. 107289. https://doi.org/10.1016/j.chb.2022.107289

Rullyana, G. and Triandari, R. 2025. Extended Reality in Special Education: A Bibliometric Analysis of Global Research 2015–2024. *Journal of Education and Learning Environments*, Vol, 12, pp. 47–61. https://doi.org/10.55121/jele.v1i2.745

Salem, H. A. A. and Gareeb, R. H. 2025. A Meta-Analysis of Extended Reality (XR) Confirms Substantial Efficacy in Enhancing Educational Outcomes and Motivation. *Afro-Asian Journal of Scientific Research*, Vol. 3, No. 3, pp. 268–275. https://aajsr.com/index.php/aajsr/article/view/531

Shawash, J. et al. 2025. Reimagining Extended Reality (XR) Innovation: A Critical Study of the Finnish Ecosystem. In *28th International Academic Mindtrek (Mindtrek '25), October 07–10, 2025, Tampere, Finland.* New York, ACM, pp. 186–199. https://doi.org/10.1145/3757980.3757983

Siddiqui, M. F. et al. 2025. Integration of augmented reality, virtual reality and extended reality in healthcare and medical education: A glimpse into the emerging horizon in LMICs—A systematic review. *Journal of Medical Education and Curricular Development*, Vol. 12, pp.1–23. https://doi.org/10.1177/23821205251342315

Singla, J. G. 2022. 3D surface visualization of planetary data using Indian remote sensing datasets on a specialized multiprojector system. *Current Science*, Vol. 123, No. 10, pp. 1207–1215. https://www.currentscience.ac.in/Volumes/123/10/1207.pdf

Sobel, M. et al. 2019. An evaluation framework for virtual reality safety training systems in the South African mining industry. *Journal of the Southern African Institute of Mining and Metallurgy*, Vol. 119, No. 5, pp. 427–436. https://doi.org/10.17159/2411-9717/53/2019

Supranovich, V. and Kurilla, L. 2023. Can an unrealistic level of detail be enough to feel immersivity in Virtual Reality. In Jakimowicz, A. and Sliwecki, B. (Eds.). *1st International Conference Digital Architecture Research DARe*. Bialystok, Faculty of Architecture Bialystok University of Technology. https://pb.edu.pl/oficyna-wydawnicza/wp-content/uploads/sites/4/2023/12/DARe2023.pdf

The Economist. 2026. *Top AI models underperform in languages other than English*. The Economist. https://www.economist.com/science-and-technology/2026/03/18/top-ai-models-underperform-in-languages-other-than-english

UNESCO. 2021. *UNESCO Recommendation on Open Science*. United Nations Educational, Scientific and Cultural Organization (UNESCO). https://doi.org/10.54677/MNMH8546

University of Cape Town. 2024. *UCT and IDIA unveil groundbreaking VR software revolutionising astronomy data visualisation*. University of Cape Town, Communication and Marketing Department. https://www.news.uct.ac.za/images/userfiles/downloads/media/2024_10_02_Software.pdf

Veas, E. et al. 2013. Mobile Augmented Reality for Environmental Monitoring. Personal and Ubiquitous Computing, Vol. 17, pp. 1515–1531. https://doi.org/10.1007/s00779-012-0597-z

Virtual Labs India. 2025. *Virtual Labs project: An initiative of Ministry of Education, Government of India under NMEICT*. IIT Delhi. https://www.vlab.co.in/about-us

Voinov, C. A. et al. 2024. Mapping of risks and harms of eXtended reality (XR) technologies: a scoping review (Deliverable D2.2. The Equitable, Inclusive and Human-Centered XR Project (XR4Human), University of Oslo.

VR/AR Association. 2025. XR at the tipping point: What 2024 delivered and why 2025 matters more than ever. https://www.thevrara.com/blog/xr-at-the-tipping-point

Wang, B. et al. 2024. Towards the industry 5.0 frontier: Review and prospect of XR in product assembly. *Journal of Manufacturing Systems*, Vol. 74, pp. 777–811. https://doi.org/10.1016/j.jmsy.2024.05.002

Zhang, X. et al. 2025. XR-based interactive visualization platform for real-time exploring dynamic earth science data. *Environmental Modelling & Software*, Vol. 183, p. 106193. https://doi.org/10.1016/j.envsoft.2024.106193