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Virtual Reality in Indian Science Education: A Review of Pedagogical Benefits, Systemic Barriers, and Implementation Pathways

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Abstract

Virtual Reality (VR) is increasingly positioned as a transformative tool for science education, offering immersive visualization, repeatable virtual experimentation, and interactive engagement with abstract concepts. In India, the National Education Policy (NEP) 2020 explicitly promotes experiential and technology-enabled learning, creating a favorable policy environment for VR adoption. However, the gap between policy ambition and classroom reality remains wide. This review synthesizes peer-reviewed literature and policy documents from 2015 to 2025 to examine three dimensions of VR integration in Indian science education: (a) empirically demonstrated pedagogical benefits, (b) systemic barriers related to infrastructure, teacher readiness, linguistic diversity, and assessment alignment, and (c) strategic pathways for equitable implementation. The review identifies a clear gap in the existing literature: while numerous studies document VR's affordances in controlled settings, few examine the conditions under which these benefits translate to resource-constrained Indian classrooms at scale. The analysis further highlights that VR is not a pedagogical panacea; evidence of its effectiveness is context-dependent, and uncritical adoption risks deepening rather than bridging educational inequities. The paper concludes with a phased implementation framework and specific directions for future empirical research.

Keywords: *Virtual Reality, Science Education, NEP 2020, Educational Equity, Digital Divide*

1. INTRODUCTION

Science education in India faces persistent structural challenges that impede deep conceptual learning across diverse socio-economic contexts. Under-equipped laboratories, high student-to-teacher ratios, and an examination system that rewards rote recall over inquiry continue to limit the development of scientific reasoning and spatial thinking (Aneesh et al., 2024). These constraints are particularly acute in disadvantaged and under-resourced schools, where unequal access to digital infrastructure can constrain opportunities for technology-supported learning and deepen existing educational inequalities (Jafar et al., 2023).

The National Education Policy (NEP) 2020 provides a strategic framework for addressing these gaps by emphasizing experiential, inquiry-based pedagogy and greater technology integration in schools and higher education (Ministry of

Education, 2020). Within this framework, Virtual Reality (VR) has attracted significant attention as a tool that can make abstract scientific phenomena tangible through immersive three-dimensional environments (Asad et al., 2021; Radianti et al., 2020). Globally, a growing body of evidence suggests that VR can enhance spatial visualization, student engagement, and conceptual retention in STEM disciplines when implemented with appropriate pedagogical scaffolding (Pirker & Dengel, 2021; Makransky & Petersen, 2021).

However, translating these global findings to the Indian context is far from straightforward. India's educational landscape is characterized by substantial variation in infrastructure, connectivity, accessibility, and teacher preparedness(Kaur & Dhillon, 2025; Singh & Sarkar, 2023). Introducing advanced digital technologies into this environment without addressing underlying systemic inequalities risks creating a two-tier system: immersive learning for the well-resourced few, and status quo for the many (Aneesh et al., 2024; Mkwizu & Bordoloi, 2024).

This narrative review synthesizes academic research, policy frameworks, and emerging case studies to evaluate the potential of VR in Indian science education. It examines four core areas: the pedagogical affordances of VR in visualizing complex scientific concepts, the supportive policy landscape under NEP 2020, ground-level barriers to accessibility, and strategic pathways for sustainable implementation. Ultimately, this discussion argues that technological deployment must be matched by inclusive policy measures, localized content development, and structured teacher support to ensure that immersive learning benefits all Indian students equitably.

1.1. GAP IN THE LITERATURE

Several existing reviews have examined VR's pedagogical applications in STEM education globally (Radianti et al., 2020; Pirker & Dengel, 2021) or its potential within Indian classrooms (Thangavel et al., 2025). However, three gaps persist. First, most reviews treat pedagogical benefits and implementation barriers as separate discussions, without integrating them into a unified analysis of what conditions are necessary for VR to deliver on its promise in resource-constrained settings. Second, few reviews critically examine the counterarguments and limitations of VR, including context-dependent learning effects and the possibility of cognitive overload in highly immersive environments (Makransky & Petersen, 2021). Third, no existing review maps the specific policy-to-classroom pathway within the Indian NEP 2020 framework, identifying where institutional support exists and where it falls short.

This paper addresses these gaps by providing an integrated review that synthesizes pedagogical evidence, policy analysis, and equity considerations. It asks three guiding questions:

1. What pedagogical benefits does VR offer for science education, and under what conditions are these benefits empirically supported?
2. What systemic barriers limit equitable VR adoption in Indian schools, and how do these barriers interact?
3. What implementation strategies can reconcile VR's potential with the realities of India's diverse educational landscape?

2. METHODOLOGY

This paper adopts a narrative review methodology to synthesize research from the past decade examining the integration of Virtual Reality (VR) in Indian science education.

2.1. SEARCH STRATEGY

Literature was searched across Scopus, Web of Science, IEEE Xplore, Google Scholar, and ScienceDirect, along with publisher repositories from Springer, Elsevier, Taylor and Francis, and SAGE. Policy documents were retrieved from the Ministry of Education (Government of India), the National Council of Educational Research and Training (NCERT), and the Press Information Bureau (PIB).

Search queries combined three Boolean clusters:

- **Technology terms:** "Virtual Reality" OR "VR" OR "Immersive Learning" OR "Extended Reality" OR "XR"
- **Pedagogy and domain terms:** "Science Education" OR "STEM" OR "Experiential Learning" OR "Conceptual Understanding" OR "Physics Education" OR "Chemistry Labs"
- **Context terms:** "India" OR "Indian Classrooms" OR "NEP 2020" OR "National Education Policy" OR "Digital Divide" OR "Accessibility"

2.2 INCLUSION AND EXCLUSION CRITERIA

Table 1. Inclusion and Exclusion Criteria

Criterion	Inclusion	Exclusion
Time frame	2015 to 2025	Before 2015
Context	Indian institutions, NEP 2020, or developing-country settings with clear applicability to India	High-resource international contexts without comparative relevance
Domain	STEM education and pedagogical practices	Non-educational VR (gaming, industrial, entertainment)
VR scope	VR, AR, XR, or metaverse in education	Non-immersive digital tools (smartboards, standard e-learning)
Source type	Empirical studies, systematic or narrative reviews, policy reports	Blog posts, opinion pieces, non-academic commentaries
Language	English	Non-English

3. PEDAGOGICAL AFFORDANCES OF VR IN SCIENCE EDUCATION

The literature identifies several distinct pedagogical mechanisms through which VR can enhance science learning.

3.1. VISUALIZATION OF ABSTRACT PHENOMENA

A primary affordance of VR in science education is its ability to represent phenomena that are difficult to observe directly because of their scale, complexity, or dynamic nature (Asad et al., 2021; Pirker & Dengel, 2021). In chemistry education, VR-based systems have been used to support the visualization and exploration of three-dimensional crystal structures, providing learners with opportunities to interact with spatial representations that are difficult to communicate through conventional two-dimensional materials (Kumar et al., 2021b). Similarly, immersive VR-based science lessons have been associated with improvements in students' learning performance and engagement in comparison with conventional instruction in experimental classroom research (Liu et al., 2020).

These findings suggest that VR can provide additional opportunities for spatial exploration and active interaction with scientific representations (Asad et al., 2021; Liu et al., 2020; Pirker & Dengel, 2021). However, systematic reviews emphasize that the educational value of VR depends on the design of the learning experience and the way the technology is integrated into instruction rather than on immersion alone (Pirker & Dengel, 2021; Radianti et al., 2020).

3.2 SAFE AND REPEATABLE VIRTUAL EXPERIMENTATION

Virtual laboratory environments can provide opportunities for students to conduct and repeat experiments without some of the material constraints associated with physical laboratory activities (Jennifer et al., 2022). VR-based virtual laboratories address this constraint by eliminating chemical hazards, equipment breakage, and consumable costs, while allowing students to repeatedly conduct experiments such as chemical titrations, dissections, or physics demonstrations without time pressure (Jennifer et al., 2022).

The ability to pause, rewind, and replay dynamic processes fosters mechanistic understanding rather than passive memorization. Students can make errors, observe consequences, and retry without real-world costs, which aligns with inquiry-based learning principles emphasized in NEP 2020 (Ministry of Education, 2020). Additionally, gamified VR modules and serious games have shown promise in optimizing engagement and problem-solving during complex physics tasks (Villada Castillo et al., 2025).

3.3 EVIDENCE OF LEARNING OUTCOMES

Empirical studies across STEM disciplines suggest that VR-based simulations, when integrated with guided pedagogical reflection (pre-briefing and post-debriefing), can produce higher conceptual clarity, superior spatial reasoning, and improved knowledge transfer compared to traditional instruction alone (Asad et al., 2021; Thangavel et al., 2025). A systematic review by Pirker and Dengel (2021) found that 360-degree VR videos and fully interactive VR applications can support conceptual understanding, spatial reasoning, and knowledge acquisition under appropriate instructional conditions. However, it is essential to note that these positive outcomes are consistently linked to specific design conditions: scaffolding by trained educators, alignment with curriculum objectives, and integration of reflective activities.

4. VR WITHIN INDIA'S POLICY LANDSCAPE

4.1. NEP 2020 AND THE MANDATE FOR EXPERIENTIAL LEARNING

The National Education Policy (NEP) 2020 provides a strategic foundation for integrating immersive technologies into Indian education (Ministry of Education, 2020; Venkata et al., 2025). By explicitly advocating a shift from rote learning toward experiential, inquiry-based, and multidisciplinary pedagogy, the policy positions digital tools as instruments for modernizing science education (Kumar et al., 2021a; Ashokkumar et al., 2025).

NEP 2020 further emphasizes the expansion of open digital infrastructure and multilingual educational content, aiming to ensure that technological advancements reach underserved regional populations rather than remaining confined to urban centers (Ministry of Education, 2020; Betsurmath & Chidambaram, 2024).

4.2. NATIONAL AND REGIONAL DIGITAL PLATFORMS

Several platforms have emerged to operationalize NEP 2020's digital learning goals. DIKSHA (Digital Infrastructure for Knowledge Sharing) and OLabs (Online Labs) have played notable roles in increasing access to science experiments across state syllabi (Ministry of Education, 2020). DIKSHA and virtual laboratories represent important components of India's technology-enabled education ecosystem (Ministry of Education, 2020). In 2025, SCERT Delhi reported that more than 300 virtual laboratories were available free of cost through DIKSHA (SCERT, 2025)

4.3. INSTITUTIONAL PILOT PROJECTS

Targeted research and pilot programs are expanding VR-based instruction in specific contexts. Researchers at IIT Madras have developed low-cost VR models engineered for rural schools, using context-sensitive content to bridge resource gaps (Press Information Bureau, 2023). Assam's "Gyandhara" project, a collaboration between IIT Guwahati and the Assam Department of Education, aims to deploy localised VR metaverse modules in regional languages across PM-SHRI schools (Press Trust of India, 2025). Early institutional deployments, including a dedicated VR classroom at Smt M. G. Patel Sainik School for Girls in Gujarat, have reported positive student responses to immersive learning (FotonVR, 2019; XROM, 2019).

While these initiatives demonstrate institutional commitment, they remain isolated pilot programmes. Bridging the gap between macro-level policy vision and micro-level classroom execution requires addressing the systemic barriers (Kulal et al., 2024).

5. BARRIERS TO EQUITABLE VR ADOPTION

Despite favourable policy directions and promising pilot programs, integrating VR into Indian science education faces structural obstacles that, if unaddressed, have risks of deepening existing educational inequalities.

5.1. INFRASTRUCTURE DEFICITS AND COST BARRIERS

The most immediate barrier is the prohibitive cost of hardware procurement, setup, and maintenance (Bulman & Fairlie, 2015; Javaid et al., 2024). High-end standalone headsets, dedicated workstation graphics processing, and motion-tracking equipment impose financial burdens that underfunded government schools cannot absorb (Chauhan et al., 2025; Mondal & Mondal, 2025).

India's digital infrastructure remains uneven across schools. UDISE+ 2023–24 data indicate substantial variation in the availability of computer and internet facilities across states and school systems, with particularly pronounced gaps in several states and regions (Ministry of Education, 2024). Rural–urban disparities in electricity, broadband availability, and access to digital devices further restrict access to immersive technology for under-resourced rural and remote institutions, thereby exacerbating educational inequality (Kaur & Dhillon, 2025; Aneesh et al., 2024).

5.2. TEACHER READINESS AND PROFESSIONAL DEVELOPMENT

A major implementation bottleneck is the gap between technological availability and educator preparedness (Choudhury et al., 2024; Choudhury & Dutta, 2024). Indian research indicates that teachers' knowledge, perceptions, and readiness are important determinants of successful integration of VR and extended-reality technologies into classroom practice. Research on K–12 VR implementation further indicates that teachers face challenges related to classroom management, technical use of head-mounted displays, and integration of VR activities into existing pedagogical practices (Fransson et al., 2020). Without targeted professional development, educators may treat VR devices as novelty tools rather than instruments for scientific inquiry (Buragohain et al., 2024).

This challenge is not merely a matter of device training. Effective VR integration requires pedagogical redesign: sequencing pre-exploration briefings, virtual exploration activities, and post-exploration reflection sessions; managing classroom logistics in head-mounted-display environments; and aligning VR activities with formative assessment strategies. These competencies go beyond basic digital literacy and require sustained, structured professional development.

5.3. LINGUISTIC AND CURRICULAR MISALIGNMENT

India's vast linguistic diversity creates additional challenges for the adoption of digital and immersive learning technologies. Educational technologies are more likely to be meaningful and accessible when digital resources account for learners' linguistic contexts and support the availability of educational content in diverse Indian languages (Wallang, 2020). In the context of VR-based science education, effective adoption therefore requires localized content, culturally relevant representations, and alignment with NCERT and state-specific science curricula. NEP 2020 also emphasizes multilingualism and the development of educational resources in Indian languages, reinforcing the importance of linguistic accessibility in technology-enabled education (Ministry of Education, 2020). Without adequate localization and curricular alignment, VR may reproduce existing inequalities between learners who have greater access to English-language and technologically enriched educational environments and those studying in less-resourced settings.

5.4. ASSESSMENT SYSTEM MISMATCH

A potential tension exists between the experiential, inquiry-oriented learning promoted by VR and conventional examination structures. NEP 2020 advocates competency-based and experiential learning, highlighting the need for greater alignment between pedagogy and assessment (Ministry of Education, 2020). Three-dimensional science assessment also presents challenges in capturing scientific reasoning and application (Furtak, 2017). Without assessment reforms that recognise and reward three-dimensional scientific practices, educators face strong systemic incentives to prioritise traditional examination preparation over immersive VR explorations. This structural issue may be the most difficult barrier to overcome, as it requires reform at the board examination level.

6. LIMITATIONS OF VR

6.1. CONTEXT-DEPENDENT EFFECTIVENESS

Research on immersive learning indicates that VR's educational benefits are context-dependent and influenced by instructional design and cognitive processes (Makransky & Petersen, 2021). In some cases, highly immersive environments have been associated with reduced learning outcomes due to extraneous cognitive load: students spend cognitive resources processing the novel virtual environment rather than engaging with the scientific content (Makransky & Petersen, 2021).

6.2. PHYSICAL AND PSYCHOLOGICAL RISKS

VR use can be associated with symptoms such as dizziness, disorientation, visual discomfort, and fatigue, although their occurrence and severity vary across users and VR experiences (Babić, 2025; Souchet et al., 2023; Szpak et al., 2020). Research involving school students also highlights the importance of considering health and comfort in the design of VR learning environments (Mukasheva et al., 2023). Broader ethical and safety concerns surrounding immersive technologies and their use with children have also been identified (Madary & Metzinger, 2016; Marks et al., 2025). These physical side effects limit the duration and frequency of VR sessions and raise health concerns that require institutional guidelines, time-use policies, and the explicit 20-20-20 supervision protocols recommended by current child-safety frameworks (Kumarapeli et al., 2025).

Beyond physical symptoms, immersive VR raises ethical and safety concerns concerning privacy, psychological well-being, and age-appropriate use among children (Madary & Metzinger, 2016; Marks et al., 2025; Kumarapeli et al., 2025). Evidence on the long-term effects of immersive VR on children remains limited, supporting the need for cautious implementation and further longitudinal research (Kumarapeli et al., 2025). XR experiences may challenge young children's ability to distinguish reality from fantasy, raising concerns about potential confabulated memories (Marks et al., 2025). Research on the psychological effects of immersive media on children remains limited, highlighting the need for longitudinal studies, age-appropriate content curation, and stronger ethical oversight before VR is integrated widely into school curricula (Kumarapeli et al., 2025; Madary & Metzinger, 2016).

6.3. OPPORTUNITY COST

Investing in VR infrastructure involves significant opportunity costs. Resources allocated to VR headsets, dedicated workstations, and licensed content could alternatively fund laboratory upgrades, teacher salary improvements, library expansion, or basic infrastructure such as reliable electricity, sanitation, and internet connectivity (Bulman & Fairlie, 2015). Economic analyses of educational technology investment consistently warn that financial resources allocated to ICT and computer-assisted instruction necessarily offset investment in traditional inputs such as teachers, textbooks, and physical laboratories, making the theoretical prediction of net educational gain ambiguous (Bulman & Fairlie, 2015). Although initial investment in immersive technology can yield pedagogical advantages, stakeholders must weigh these gains against the cost of other competing investments whose returns may be higher in resource-constrained contexts (Makransky & Mayer, 2022).

In contexts where schools lack functioning toilets, clean drinking water, or reliable electricity, the prioritization of VR raises equity concerns on both ethical and practical grounds (Mondal & Mondal, 2025). This does not invalidate VR investment, but it demands that VR adoption be evaluated within a holistic resource allocation framework that compares the cost per learning outcome against alternative uses of the same funds rather than treated as an isolated technological intervention (Bulman & Fairlie, 2015).

6.4. EQUITY PARADOX

Evidence on digital access in India indicates that rural and economically disadvantaged communities continue to experience disparities in infrastructure, connectivity, and access to digital resources, which can constrain the equitable adoption of immersive technologies (Aneesh et al., 2024; Kaur & Dhillon, 2025; Singh & Sarkar, 2023; Assefa et al., 2025). Persistent digital divides between rural and urban schools evidenced by disparities in infrastructure, internet connectivity, electrical grid stability, and access to basic devices further restrict immersive technology to well-resourced urban institutions (Aneesh et al., 2024; Kaur & Dhillon, 2025; Singh & Sarkar, 2023). The affordability of digital devices, infrastructure limitations, and limited digital literacy are the primary drivers of this divide, and there is evidence that the digital gap disproportionately impacts marginalized communities that already face structural inequality (Assefa et al., 2025).

Studies of EdTech deployment across 15 countries confirm that traditional "access gap" frameworks fail to capture the full architecture of digital exclusion: barriers such as hidden device and repair costs, infrastructure fragility (electricity and connectivity), cultural-linguistic irrelevance of content, and teacher digital literacy deserts disproportionately exclude marginalized learners in low-income and remote communities (Amiri, 2025). Evidence from India's DIKSHA platform and similar large-scale deployments demonstrates how these barriers compound to widen rather than narrow existing disparities in education access (Amiri, 2025; Assefa et al., 2025). Without deliberate equity-focused deployment strategies including zero-cost connectivity architectures, situated teacher capacity building, culture specific content creation, and adaptive hybrid infrastructure models VR adoption risks becoming the privilege of well-resourced urban schools and a vehicle for widening educational disparities rather than narrowing them (Amiri, 2025; Assefa et al., 2025; Munib et al., 2025).

7. LIMITATIONS OF THE STUDY

This review has several limitations. First, the search was restricted to English-language publications, which may exclude relevant research published in other Indian languages. The Indian context-specific literature on VR in science education remains relatively thin; many claims are supported by studies from other developing-country settings, whose applicability to India is assumed rather than empirically demonstrated.

8. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This review finds that VR holds genuine pedagogical promise for Indian science education, particularly in visualizing abstract phenomena, enabling safe virtual experimentation, and supporting experiential learning mandated by NEP 2020. However, this promise is conditional: VR improves outcomes only when pedagogically scaffolded, culturally localized, and equitably implemented. Without intentional policy implementation, infrastructure investment, teacher development, and assessment reform, VR adoption risks becoming a privilege of well-resourced urban schools, thereby deepening the very inequalities it could help address.

Three directions for future empirical research emerge from this review:

1. **Context-specific efficacy studies.** There is a pressing need for controlled studies measuring VR learning outcomes specifically in Indian government school settings, with diverse student populations and realistic infrastructure conditions, rather than relying on extrapolations from international or elite-institution contexts.
2. **Cost-effectiveness analyses.** Comparative studies evaluating the cost per learning outcome of VR interventions versus alternative investments (laboratory upgrades, teacher training, or content development) would provide policymakers with the evidence needed for rational resource allocation.
3. **Longitudinal adoption studies.** Research tracking VR integration over multiple years in Indian schools would illuminate sustainability challenges, teacher adaptation trajectories, and student outcome trajectories that short-term pilot studies cannot capture.

The path forward requires treating VR not as a technological fix but as one component within a comprehensive educational reform strategy. Implemented with an equity-first focus and grounded in evidence, VR can contribute meaningfully to democratizing quality science instruction across India's diverse educational landscape.

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