Research Article

Virtual and Augmented Reality in STEM Education: Enhancing Students' Learning Outcomes

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Introduction

In India, STEM (Science, Technology, Engineering, Mathematics) education is widely recognized as critical for national development, yet it faces significant challenges. Despite India's emphasis on technology, only about a quarter of higher-education enrollments are in STEM fields, and engineering/technology undergraduates declined from 16% in 2014–15 to just 11.8% in 2021–22. STEM courses are often viewed as "elite" and costly. At the school level, large resource gaps persist: for example, UNESCO reported over 1.1 million (19%) teacher vacancies, 69% of which are in rural schools. National data (UDISE+) show that only ~57% of schools have functional computers and [1]~54% have Internet access, and less than 25% have smart classrooms. Rural and under-resourced areas suffer acute disadvantages (only ~32% of schools have computers, rural internet penetration <40%). These challenges – lack of infrastructure, teacher shortages, rote-learning culture and urban–rural disparities – underscore the need for innovative teaching methods. India's National Education Policy (2020) calls for more experiential, competency-based learning, implying a role for educational technologies such as Virtual Reality (VR) and Augmented Reality (AR). This paper examines how VR/AR are being applied in Indian STEM education, their pedagogical benefits, real-world use cases, challenges, and policy implications.

Keywords: Virtual and Augmented Reality, STEM education, Learning Outcomes, Teaching Effectiveness

Current State of STEM Education in India: STEM fields remain underrepresented and unequal in India. Notably, women comprise only ~29% of engineering undergraduates. Many high-value STEM programs are in private institutions with high fees, limiting access. The pandemic and other factors have highlighted deficiencies in basic learning: for instance, high-school assessments indicate many students lack foundational skills in science and math (ASER reports). Government efforts like the *Sakshat Virtual Labs* by MHRD/IIT Delhi show the demand for simulated lab experiences, but VR/AR is now emerging as the next frontier. Globally, VR/AR immersion is gaining traction in education, but in India the adoption is nascent. Early studies suggest that without new methods, students struggle with abstract concepts, and many remain disengaged. Thus, innovative tools like VR/AR are being explored to make STEM learning more accessible, concrete, and engaging across India's diverse classrooms.

Immersive Technologies and Pedagogical Benefits: Virtual Reality creates a fully immersive, interactive environment, while Augmented Reality overlays digital 3D content onto the real world. Research shows clear educational benefits. VR allows students to experience 3D structures or processes (such as molecular models, anatomy, or solar systems) as if present in person, reducing cognitive load compared to 2D diagrams. Immersive VR (six-degrees-of-freedom) has been found to significantly increase both cognitive and affective learning outcomes for students. In one study, high-school students using an immersive VR history simulation achieved higher test scores than those in a

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non-VR control, due to the deeper, more engaging experience. Another experiment found that VR learners reported greater attention, presence, and satisfaction than peers using 360° video. Student motivation also improves: in one survey, 72% of students in a VR-enhanced science course reported increased attention, and 71% reported higher satisfaction with learning. AR similarly boosts engagement by making abstract concepts tangible – for example, an AR app can animate physics experiments or overlay anatomical models over textbooks, prompting active "learning-by-doing" instead of rote memorization. Importantly, immersive VR can create safe "virtual laboratories" where experiments (even dangerous or expensive ones) can be repeated without hazard, and multi-sensory stimuli (visual, auditory, haptic) reinforce understanding. Education experts note that VR/AR shifts passive students into active explorers, dramatically increasing interest and inquiry. For instance, NCERT/EON pilots in India report that immersive science lessons lead to more curiosity, easier explanation of complex topics, and higher classroom engagement. In sum, the pedagogical literature and pilot data indicate that VR/AR in STEM can deepen conceptual understanding, improve retention, and motivate diverse learners.

VR/AR Adoption in Indian STEM Education: While still early, several initiatives in India illustrate the growing VR/AR adoption. Government and academic institutions are building capacity: for example, the Ministry of Electronics & IT (MeitY) launched a "FutureSkills Prime" AR/VR program that trained thousands of government officials and students in AR/VR development (over 7,000 certifications awarded). IIT Bhubaneswar hosts the Virtual and Augmented Reality Center of Excellence (VARCoE), a national hub established with MeitY support to foster VR/AR innovation, research and skill development. In schools, NCERT's *e-Pathshala* initiative includes an AR app to "energize textbooks", enabling students to go beyond traditional texts by directly experimenting with augmented content. EdTech companies and NGOs are active: for example, Jnana Prabodhini's *Prabodh Virtual Reality Science Lab* offers a cost-effective VR solution with 35 immersive experiments for grades 8–10. This Marathi/English VR lab runs on simple mobile headsets and addresses the lack of physical labs in urban and rural schools. It has already reached over 3,000 students across Maharashtra (including remote locations in Pune district, Sindhudurg, and Jammu) and is hailed as a "game-changer" in under-resourced areas.

Private ventures and pilot projects complement these efforts. For instance, the Surat Municipal Corporation (SMC) installed "immersive 7D VR chairs" in a high school as a first-of-its-kind VR lab, in collaboration with industry sponsor Ganga Fashions. Each VR chair (costing ~₹150,000) allows students to conduct virtual experiments through 3D simulations. School officials reported that the new lab not only enhanced understanding of complex STEM topics but also sparked interest among students who had struggled in conventional classes. Universities are experimenting too: one university in Gujarat integrated a virtual chemistry lab for reaction simulations, enabling students to practice experiments virtually before using real chemicals – this reduced consumable waste by ~25–30% and improved accuracy. Other pilots include mobile VR vans, AR-enabled tablets, and VR field trips (e.g. virtual tours of the Taj Mahal for history). In surveys, Indian students express eagerness: in one industry report, ~78% of students knew what VR was and ~61% believed it would revolutionize education. Teachers have begun integrating VR content for biology dissections, physics labs, and math visualizations, often with support from companies like EON Reality, FotonVR, and Photonic VR. Overall, early adopters in India report that VR/AR can make STEM lessons more "fun, memorable, and self-paced", aligning well with national goals for competency-based, experiential learning.

Pedagogical Benefits of Immersive Learning: Immersive VR/AR offers concrete benefits documented in research. By turning abstract STEM concepts into interactive visual experiences, VR helps lower cognitive load and accommodate diverse learning styles. Visualization is a key advantage: educators note that VR/AR "makes complex concepts tangible through interactive 3D experiences". Rather than passively listening, students explore virtual environments (e.g. walking through a cell structure or orbiting planets), which strengthens comprehension. Studies consistently find higher

engagement and knowledge mastery in VR settings. For example, in immersive STEM sessions, students recall details better – one study reported significantly higher test scores for VR learners versus traditional learners. Another noted that virtual labs lead to "steady skill normalization" without the need for extra motivation. In our context, Indian pilots echo this: after using VR, teachers observed that even low-performing students showed curiosity and understanding that textbooks alone had not elicited.

Immersive learning also fosters soft outcomes. In an Indian high-school VR science course, students reported greater attention span (72%), stronger relevance perception (61%), higher trust in instruction (64%), and satisfaction (71%) compared to non-VR classes. By engaging emotions and senses, VR can boost confidence and reduce anxiety about difficult topics. Moreover, the fun, game-like aspects of VR (when well-designed) encourage active participation and collaboration. Educator feedback from an NCERT/XR pilot found 93% of teachers agreed that VR boosted student engagement in science and geography lessons. In essence, VR/AR transforms STEM learning from rote reception to exploration-driven inquiry, which can improve retention: educators note that "interactive and experiential learning through VR improves memory retention as students are more likely to remember concepts they've physically interacted with". These pedagogical strengths make immersive methods especially valuable for abstract or challenging STEM topics (e.g. molecular biology, electromagnetism, organic chemistry) that are otherwise hard to demonstrate in a typical classroom.

Case Studies and Examples in India: Several Indian institutions and companies provide concrete case studies. *Surat Municipal School, Gujarat:* Using 7D VR chairs (Figure 1), students conduct virtual physics and chemistry experiments. The municipal school report highlights better grasp of concepts and rekindled interest among previously disengaged students. *Jnana Prabodhini VR Lab (Maharashtra):* The "Ābhāsī VR Science Lab" created by an educational trust offers 35 simulated experiments in local (Marathi) and English languages. It targets grades 8–10 in urban and rural schools. Since 2023, over 3,000 students in six locations (e.g. Pune, Sindhudurg, Poonch) have used the lab, which runs on inexpensive mobile VR goggles. The developers report that students achieve deeper insight and self-paced mastery – for example, complex biochemical processes become "memorable and fun" through VR visualization. *University of Gujarat (Chemistry Dept):* A virtual reality chemistry lab was integrated into the curriculum, allowing students to simulate titrations and organic reactions in VR before doing them for real. The lab reduced chemical waste by ~25–30% and improved students' procedural accuracy. Crucially, no extra "motivational push" was needed; the immersive practice alone normalized skill levels. *NCERT/EON XR Pilot:* Building on NCERT's digital curriculum, EON Reality collaborated on a large-scale pilot deploying XR modules nationwide. Official reports indicate this program has reached ~89 million students, with 93% of participating educators reporting positive educational value from the VR content. Teachers noted clearer explanation of abstract topics and higher student curiosity. These examples demonstrate that immersive STEM tools can be scaled from a single classroom to district-wide programs in India, yielding measurable learning gains and enthusiasm.

Challenges and Barriers: Despite promise, several challenges constrain VR/AR adoption in India's STEM education. **Cost and Infrastructure:** High-quality VR headsets and setups remain relatively expensive. For example, the immersive "VR chairs" used in Surat cost ~₹150,000 (~$2,000) each. A modest lab of 20 mid-range standalone headsets (₹35–60K each) with network support can total ₹10–15 lakh ($12–18K). Such capital investment is beyond the budget of most public schools. Even basic infrastructure is spotty: only about 57% of schools in India have computers and ~54% have reliable internet. VR also often requires ancillary equipment (powerful PCs, space, internet-enabled software) and safe storage. In rural areas with intermittent power or connectivity, deploying VR labs is especially difficult.

Teacher Training and Readiness: Many teachers lack familiarity with VR/AR. A recent nationwide study of 730 Indian educators found that attitudes toward AR/VR were generally only "low to

moderate" and that key barriers included "limited awareness, low motivation, inadequate infrastructure, and insufficient training". Only a minority of teachers feel "VR-ready" without support. Effective use of VR/AR requires teachers to design lessons around it, troubleshoot equipment, and integrate activities into curricula. Without targeted professional development, the technology risks being underutilized or misused. The scale of teacher training needed is vast: UNESCO has urged India to improve terms of service and training to fill teacher gaps, and similar efforts are needed for digital pedagogies. Initiatives like MeitY's FutureSkills AR/VR course and private training workshops are steps forward, but widespread teacher empowerment in immersive tech remains a work in progress.

Access and Equity: The digital divide looms large. Urban private schools and English-medium institutions have more resources to adopt VR/AR, whereas rural, government-run schools lag. For instance, rural internet penetration is under 40%, making online VR platforms or cloud-based AR challenging. There are also socio-economic disparities: the same NGO report notes that girls in rural areas are 40% less likely than boys to pursue STEM subjects after primary school. If VR/AR is implemented unevenly, it could inadvertently widen gaps. Policymakers must therefore ensure that innovations reach underserved communities – for example, by deploying shared mobile VR labs or community centers.

Content and Language: Most VR/AR content is developed for western curricula in English. Indian classrooms need regional language support and contextually relevant scenarios. Platforms like EON-XR are addressing this (its pilot supports over 85 Indian languages), but content creation remains a hurdle. Finally, maintenance and sustainability are concerns: devices must be charged, updated, and secured over years, and consumables (if any) managed.

Outcomes and Effectiveness: Measuring the impact of VR/AR in India is still emerging. Apart from the qualitative successes noted, a few studies provide quantitative evidence. In controlled trials elsewhere (one involving Indian university students), VR learners outperformed controls on both knowledge tests and engagement metrics. One Indian study with physics undergraduates found significantly higher post-test scores after VR instruction (though small sample size). Anecdotally, schools report improved exam scores after incorporating VR modules (e.g. some teachers noted higher pass rates in science after adding virtual labs). The NCERT/EON pilot plans to study "competency metrics" derived from VR sessions, which may reveal retention gains. We also expect indirect outcomes: by making learning more enjoyable, VR/AR may improve STEM enrollment and retention over time – students who feel successful in virtual simulations may pursue STEM fields further.

Despite limited hard data in India, global and local evidence consistently points to at least three benefits: **(1)** Increased student motivation and engagement, which is known to correlate with achievement; **(2)** Enhanced conceptual understanding and higher-order thinking as students manipulate 3D models; **(3)** Opportunity for safe, repeated practice (e.g. virtual labs) that can accelerate mastery. When combined with traditional teaching, these tools appear to yield better academic performance and confidence among students, especially those who struggled in passive learning environments. Future research in India should track standardized test gains, course grades, and STEM program entry rates to quantify these effects.

Future Outlook and Recommendations: The future of STEM education in India is likely to be increasingly immersive. Projections suggest that by 2027, up to half of Indian schools could adopt AR/VR in some form (as seen in pilot studies). To realize this, a multi-pronged strategy is needed:

- **Policy and Investment:** The government should incorporate VR/AR into education policies (NEP 2020 already advocates experiential learning) and fund pilot programs. Public–private partnerships can accelerate deployment (e.g. linking CSR funds to VR labs in rural schools). The new Centre of Excellence (VARCoE) should collaborate with state education boards to develop scalable

models. Incentivizing low-cost VR solutions (smartphone-based or rented labs) can make technology reach poorer schools.

- **Infrastructure Upgrade:** Expanding digital infrastructure is essential. Continued rollout of broadband to schools (e.g. via PM-WANI) and provision of computing devices will lower entry barriers. Solar-powered charging stations, portable VR kits, and offline VR libraries can help where electricity is unreliable.
- **Teacher Training and Curriculum:** Massive teacher training is critical. Programs like FutureSkills AR/VR are a start, but teacher education institutes (NCERT, SCERTs) should embed VR/AR pedagogy in their courses. Master trainers and ICT coaches can mentor classroom teachers. Additionally, curricula and textbooks should be updated to include VR/AR lab work as a component. For example, incorporating virtual dissections in biology textbooks via AR apps (building on NCERT's e-Pathshala) would normalize immersive learning.
- **Localized Content Creation:** Investment is needed in creating culturally and linguistically relevant VR content. Indian universities, institutes (IISc, IITs, IIITs) and startups (FotonVR, PhotonicVR, etc.) can produce modules aligned to NCERT and state syllabi. Open-access VR libraries in Hindi, Tamil, Marathi, etc., will broaden reach.
- **Equity and Accessibility:** Special efforts should target girls and rural students. For example, girls' science clubs could be equipped with VR sessions to build confidence, addressing the gender gap. Mobile "VR science vans" visiting villages or drone-enabled VR tours for remote schools could bridge the urban–rural divide.
- **Assessment and Research:** Finally, ongoing evaluation is key. The Ministry of Education should fund longitudinal studies on VR/AR interventions' impact on learning outcomes (similar to ASER but focusing on higher-order skills). Data from VR usage (engagement logs, quiz scores) can be analyzed to refine pedagogy. Sharing best practices through conferences and publications will help build an Indian knowledge base on immersive STEM education.

Conclusion

In sum, VR and AR hold transformative potential for STEM education in India. By making abstract concepts concrete, engaging diverse learners, and compensating for resource gaps, immersive technologies can enhance understanding, motivation, and retention in science, math, and engineering fields. Early Indian case studies – from municipal school VR labs to university simulations – demonstrate promising outcomes. However, realizing this potential at scale requires addressing costs, infrastructure, and teacher training. Policymakers should thus invest in infrastructure upgrades, teacher capacity building, and localized VR content, guided by evidence from ongoing pilots. With coordinated action by government, educators, and industry, immersive STEM learning can become an integral part of India's education system, helping produce the skilled workforce needed for the future.

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