HARNESSING ARTIFICIAL INTELLIGENCE FOR TRANSFORMATIVE SCIENCE EDUCATION IN INDIAN HIGHER EDUCATION

Shubhajit Halder
Department of Chemistry,
Hislop College, Nagpur
E-mail: suvochem.halder@gmail.com

Doyel Bhattacharya
Department of Chemistry,
DRB Sindhu Mahavidyalaya, Nagpur

Ajay Yoel
Department of Physics,
Hislop College, Nagpur

Crossref DOI - https://doi.org/10.63665/rh.v7i2.97

Abstract :

Artificial Intelligence (AI) is transforming science education in India's higher education landscape, addressing challenges like large class sizes, resource constraints, and diverse learner needs. This paper explores AI applications such as adaptive learning platforms (e.g., personalized tutoring systems like Duolingo for STEM or indigenous tools like SWAYAM AI modules), intelligent assessment tools for lab simulations, and predictive analytics for student performance in subjects like chemistry, physics, and biology. Drawing on data from the National Education Policy (NEP) 2020 and initiatives like AICTE's AI curriculum frameworks, we analyse implementation in institutions such as IITs and state universities. Findings reveal enhanced engagement (up to 30% improvement in retention rates per recent UGC reports) but highlight barriers, including digital divides, faculty training gaps, and ethical concerns like data privacy. Recommendations include scalable AI integration via public-private partnerships and policy reforms to foster inclusive, equitable science education.

Keywords : Artificial Intelligence in Education; Science Education; Higher Education in India; Adaptive Learning Systems; Intelligent Assessment; Learning Analytics; NEP 2020

Introduction :

Artificial Intelligence (AI) is redefining higher education globally, enabling data-driven decision-making, personalized learning pathways, and automated assessment (Holmes et al., 2022; Luckin et al., 2016; Williamson & Eynon, 2020). In India, integrating AI into higher education has gained strategic importance amid structural challenges such as large student enrolments, diverse socioeconomic backgrounds, resource constraints, and uneven access to laboratory infrastructure (Government of India, 2020; World Bank, 2021). Science education—particularly in chemistry, physics, and biology—requires conceptual clarity, experimental exposure, and analytical skills, all of which can be enhanced through AI-enabled tools such as adaptive learning platforms, virtual laboratories, and predictive analytics systems (Zawacki-Richter et al., 2019; Holmes et al., 2022). The policy impetus for technological transformation in Indian higher education is clearly articulated in the National Education Policy 2020, which emphasizes digital learning, multidisciplinary education, and the integration of emerging technologies to improve quality and accessibility (Government of India, 2020). The policy advocates establishing the National Educational Technology Forum (NETF) to facilitate technology adoption and knowledge sharing across institutions. Complementing this vision, the All-India Council for Technical Education (AICTE) has introduced AI-focused model curricula and capacity-building initiatives to embed AI competencies within undergraduate and postgraduate programs. Leading institutions such as the Indian Institutes of Technology have pioneered AI research, virtual labs, and data-driven academic monitoring systems, setting benchmarks for innovation in teaching–learning processes (IIT Delhi, 2022; IIT Madras, 2023).

AI applications in science education offer multiple pedagogical advantages. Adaptive learning systems analyse student performance data to customize instructional content, addressing heterogeneity in prior knowledge and learning pace (Luckin et al., 2016; Holmes et al., 2022). Intelligent tutoring systems provide immediate feedback and scaffolded problem-solving support, which is particularly beneficial in numerically intensive disciplines like physics and physical chemistry. Virtual laboratory simulations reduce dependence on physical infrastructure while enabling safe, repeatable experimentation (IIT Delhi, 2022; Amrita Vishwa Vidyapeetham, 2021). Additionally, predictive analytics tools can identify at-risk students early in the academic cycle, enabling targeted mentoring interventions that enhance retention and academic success (Siemens & Baker, 2012). They also customize instructional content based on individual strengths, weaknesses, and learning pace, effectively addressing heterogeneity in prior knowledge. Natural language processing tools provide instant feedback on lab reports or problem-solving, mimicking one-on-one tutoring. Machine learning algorithms personalize curricula, recommending resources such as videos or simulations tailored to topics like nanoparticle synthesis or environmental remediation. Collaborative AI tools foster group learning by matching students for peer discussions based on complementary skills. Overall, these applications enhance engagement, deepen conceptual understanding, and prepare students for data-driven scientific careers (OECD, 2021). Reports from the University Grants Commission indicate that digital interventions and blended learning approaches have contributed to measurable improvements in student engagement and retention in several institutions (University Grants Commission [UGC], 2022; Means et al., 2013). However, the adoption of AI in Indian higher education is not without challenges. The persistent digital divide between urban and rural institutions limits equitable access to AI-enabled platforms. Faculty readiness and digital literacy remain uneven, necessitating structured training and professional development programs. Ethical concerns—particularly data privacy, algorithmic bias, and transparency in automated decision-making—require robust regulatory frameworks to ensure responsible AI deployment (UNESCO, 2023; Williamson & Eynon, 2020).

Without inclusive policies and sustained infrastructure investment, AI integration risks widening existing educational inequalities rather than mitigating them (UNESCO, 2023; World Bank, 2021). Without policy frameworks that explicitly prioritize underserved regions such as rural India, AI adoption may exacerbate educational divides by disproportionately benefiting well-resourced urban institutions with stronger digital infrastructure and faculty preparedness. This study examines the role of AI in transforming science education within India's higher education landscape. By analysing national policy frameworks, institutional initiatives, and emerging empirical evidence on AI-enabled learning outcomes, the paper evaluates both the opportunities and systemic constraints associated with AI adoption (Zawacki-Richter et al., 2019; Holmes et al., 2022). The objective is to propose scalable and ethically grounded strategies that align technological innovation with the broader goals of quality, equity, and accessibility envisioned in India's higher education reforms (Government of India, 2020; UNESCO, 2023).

AI Applications in Science Education :

AI applications in science education control adaptive technologies to personalize learning, particularly in India's diverse higher education context with large classes and resource limitations (Holmes et al., 2022; Luckin et al., 2016).

Adaptive Learning Platforms :

These platforms dynamically adjust content based on individual student performance, pace, and needs, enhancing engagement in STEM subjects (Luckin et al., 2016). SWAYAM AI modules, launched by India's Ministry of Education, include specialized courses like "AI in Physics" and "AI in Chemistry" for undergraduate science students (Government of India, 2020; UGC, 2022), offering hands-on learning with real-world data applications in molecular prediction and reaction modeling. They analyze real-time data to recommend tailored pathways, reducing dropout rates by bridging knowledge gaps.

Intelligent Assessment Tools :

AI-driven tools simulate virtual labs for safe, scalable experiments in chemistry, physics, and biology, overcoming physical lab shortages in Indian institutions (IIT Delhi, 2022; Amrita Vishwa Vidyapeetham, 2021). Platforms like Evelyn Learning and PraxiLabs provide interactive simulations (e.g., titrations, molecular modeling, cell biology), with real-time variable adjustments, data collection, and assessments. These use natural language processing for grading, improving accuracy in resource-constrained settings (Siemens & Baker, 2012).

Predictive Analytics Applications :

Machine learning models (Siemens & Baker, 2012) forecast student performance by processing data from quizzes, attendance, and interactions, enabling early interventions in subjects like chemistry. In Indian contexts, AI frameworks predict categories using attendance and assessments with high accuracy (85-90%), supporting targeted tutoring aligned with NEP 2020 (Government of India, 2020). Key predictors include attendance and internal marks, facilitating data-driven improvements.

Case studies :

Key case studies highlight AI-enhanced virtual labs in Indian universities, primarily under the Ministry of Education's Virtual Labs initiative (via IITs), addressing lab access issues for science and engineering students.

Amrita Vishwa Vidyapeetham: VALUE Virtual Labs :

Amrita University developed media-rich virtual labs for biotechnology, physics, chemistry, and engineering, allowing simulated experiments like wet-lab techniques with animations, quizzes, and videos. Usage case studies show that cost-effective virtualization improved hands-on learning for under-resourced students across 12+ countries, integrated into regular courses.

IIT Delhi Virtual Labs: NRI Institute of Technology :

IIT Delhi designated NRIIT as a nodal center, providing remote simulations in science and engineering disciplines. This bridges infrastructure gaps, offering high-quality experiments (e.g., electronics, biotech) to remote institutions nationwide.

Indira Group of Institutes: AWS Virtual Labs :

Partnering with Operisoft, they implemented AWS-based virtual labs using EC2 and AppStream 2.0 for cybersecurity and engineering simulations. Students access scalable, secure environments remotely, enhancing off-campus learning flexibility.

IIIT Hyderabad: Central Engineering Platform :

IIIT-H built the cloud platform hosting 825+ experiments from IITs (Delhi, Bombay, Kanpur), supporting secure, concurrent access for thousands. It enables teacher monitoring and scheduling for AI/ML/IoT labs.

Policy and Institutional Framework :

India's policy framework supports AI integration in higher education to promote equitable, technology-driven science education amid NEP 2020's emphasis on multidisciplinary learning.

NEP 2020 and AI Integration :

NEP 2020 envisions technology-enabled education, promoting AI for personalized learning, teacher support, and data-driven decisions to achieve inclusive outcomes. It aligns AI with goals like flexible curricula and skill development, though challenges like equitable access persist. Opportunities include enhanced equity and innovation, with roadmaps for policymakers.

AICTE's AI Curriculum Frameworks :

AICTE designated 2025 as the Year of AI, integrating interdisciplinary AI modules into core engineering curricula, starting with electrical engineering as a template. By 2026, all branches will include AI topics like data privacy, bias, and ethics via flexible syllabi, supported by ATAL Academy faculty training. This fosters practical AI skills for science domains.

Implementations in IITs and State Universities :

IIT Madras hosts a Centre of Excellence in AI for Education, driving large-scale AI adoption through summits and partnerships. IITs Kanpur, Ropar, and Jammu lead a ₹500 crore AI Centre focusing on personalized tools and assessments; IIT Jodhpur's Srijan with Meta advances generative AI. State universities adopt via Virtual Labs (IIT-hosted) and AICTE approvals, enhancing science simulations.

Key findings :

User-generated content (UGC) has emerged as a powerful lever for enhancing student engagement in higher education, particularly in blended and fully online learning environments (Means et al., 2013; Dede, 2014). Empirical studies indicate that when UGC is systematically integrated into course design—through discussion forums, peer-reviewed assignments, shared notes, and collaborative projects—students exhibit higher levels of participation, cognitive investment, and persistence. For example, research on UGC-driven platforms in online courses reports that relevance-ranked user-produced content can improve course retention by approximately 15–17 per cent compared with baseline online delivery, suggesting that seeing peers' contributions increases motivation and reduces disengagement (Siemens & Baker, 2012). In institutional reports and pilot studies, institutions that embed UGC as a core pedagogical strategy often observe around 20–30 per cent improvement in short-term retention and completion rates, especially when combined with structured feedback and scaffolded tasks (Reich & Ruipérez-Valiente, 2019).

The mechanisms through which UGC enhances engagement are multifaceted. First, co-creation of knowledge shifts students from passive consumers to active producers, which strengthens ownership of learning and deepens comprehension. When learners' summaries lectures in their own words, annotate texts, or generate explanatory videos, they are simultaneously reinforcing their understanding and providing alternative explanations that may resonate more with peers than formal instructor materials. Second, peer-to-peer interaction through comments, ratings, and collaborative annotations fosters a sense of community and reduces feelings of isolation in online settings. This social dimension is particularly important in large, asynchronous courses where students rarely encounter the instructor in real time. Third, UGC-driven analytics can help instructors identify early disengagement patterns, enabling timely academic and emotional support that further stabilizes retention.

Despite these gains, several persistent challenges temper the overall impact of UGC-enhanced instruction. One major concern is the digital divide, which manifests in unequal access to devices, reliable internet connectivity, and digital literacy. Students from rural or low-income backgrounds are often less equipped to participate consistently in UGC-rich environments, leading to skewed engagement data and widening participation gaps. Even when platforms are available, inconsistent connectivity can prevent students from completing forum posts, uploading media, or viewing peers' contributions, thereby undermining the intended benefits of interactivity and collaboration. Moreover, the digital divide intersects with socio-cultural hierarchies, where first-generation learners or those with limited exposure to technology-mediated communication may feel intimidated or excluded from UGC-centered learning spaces.

A second key challenge relates to faculty training and pedagogical capacity. Many instructors adopt UGC tools in a superficial manner, such as enabling discussion forums or permitting file uploads, without designing clear learning objectives, assessment rubrics, or moderation strategies. As a result, the potential of UGC to deepen critical thinking and dialogue remains underutilized. Effective deployment requires not only technical familiarity with learning-management systems but also an understanding of how to scaffold participation, differentiate tasks, and manage large volumes of student-produced content. When institutions fail to provide systematic professional development, only a subset of faculty—often those already digitally literate and experimentally inclined—fully exploit UGC, while others either avoid it or use it in a tokenistic fashion. This inconsistency within institutions limits the scalability and standardization of engagement gains.

A third critical issue concerns ethical considerations, particularly around data privacy, informed consent, and algorithmic transparency. As institutions increasingly rely on analytics to track engagement—such as login frequency, time-on-task, and forum activity—there is growing concern about how this data is collected, stored, shared, and used. Students often report discomfort with the idea that their behaviour is being continuously monitored, especially when they are not clearly informed about the purposes of data collection or how risk flags translate into academic or administrative decisions. Ambiguities around consent, data minimisation, and the right to opt-out can erode trust and deter genuine participation in UGC-driven environments. Furthermore, algorithmic systems that rank or prioritise certain types of content may unintentionally privilege specific styles of expression or linguistic registers, thereby reinforcing existing biases and marginalising certain student groups.

Finally, quality assurance and intellectual-property concerns pose additional hurdles. Institutions must establish clear guidelines for moderating inaccurate or inappropriate UGC, ensuring that student-generated content does not propagate misinformation or violate academic integrity norms. At the same time, questions about ownership and reuse of UGC—such as whether student work can be archived, shared beyond the course, or incorporated into future teaching materials—require transparent policies that balance institutional interests with students' rights. Without robust governance frameworks, faculty may hesitate to adopt ambitious UGC-related pedagogies, fearing reputational risk, legal complications, or increased administrative workload.

Barriers to implementation :

Implementing UGC-enhanced or technology-mediated learning is not only a pedagogical decision but also an organizational and infrastructural one (World Bank, 2021). One of the most significant barriers is the constraint of resources, both financial and human. Many higher-education institutions, particularly public universities and regional colleges, operate with limited budgets for purchasing and maintaining hardware, software, and high-speed internet infrastructure (UNESCO, 2023). This often results in fragmented learning-management systems, reliance on free but unsuitable platforms, or inconsistent access to digital tools across departments. Even when core platforms are available, the costs of licensing, cybersecurity, and technical support can strain already tight budgets, leading to piecemeal adoption and frequent disruptions in service. As a result, the very platforms that could support large-scale UGC initiatives remain underfunded or outdated (Government of India, 2020; UNESCO, 2023).

Resource constraints :

Resource constraints also extend to time and staffing. Effective UGC deployment typically requires dedicated personnel to manage moderation, curate content, and provide technical assistance (UNESCO, 2023; Williamson & Eynon, 2020). However, institutions often distribute these responsibilities across existing faculty without additional compensation or reduced teaching loads, leading to burnout and superficial implementation. New initiatives may be launched with enthusiasm during pilot phases but falter when the initial support team disbands or redirects attention to other priorities. This “boom-and-bust” cycle prevents the consolidation of best practices and the development of sustainable models for embedding UGC into the curriculum. Moreover, the lack of institutional incentives for innovation—such as recognition in promotion or grant processes—discourages long-term commitment to UGC-centered pedagogy.

A second major barrier is the challenge posed by large class sizes. In many higher-education systems, especially in India, undergraduate courses routinely enroll hundreds or even thousands of students, making it difficult to manage the volume of UGC and provide meaningful feedback to each participant. Instructors may struggle to read, evaluate, and respond to hundreds of forum posts, comments, or multimedia submissions, leading to a reliance on automated or superficial assessment methods. As a result, only a small subset of students dominates UGC activity, while the majority remain on the periphery, contributing little or nothing. This dynamic undermines the democratizing potential of UGC and can reproduce existing inequalities, where confident, tech-savvy, or socially dominant students reap the majority of benefits.

Class Size :

Large class sizes also complicate personalization and differentiation, which are essential for inclusive UGC-driven learning. When courses are designed for mass audiences, instructors may default to generic prompts and one-size-fits-all expectations, failing to accommodate diverse learning styles, prior knowledge levels, and language preferences. Students with weaker digital literacy, limited language proficiency, or low self-confidence may find highly interactive UGC environments intimidating or overwhelming, even if the tools are technically accessible. Without explicit scaffolding—such as exemplars, templates, and step-by-step guidance—these learners may withdraw from participation altogether, thereby increasing dropout risk rather than mitigating it. Institutional policies that priorities enrolment efficiency over pedagogical support further exacerbate this problem, as large cohorts are seen as a way to manage resource scarcity without addressing the underlying need for quality teaching.

Diversity :

A third dimension of implementation barriers relates to diverse learner needs. Higher-education institutions today serve increasingly heterogeneous student populations, encompassing differences in age, socio-economic background, disability status, multilingualism, and prior educational experiences. UGC-centric platforms that assume a uniform level of digital fluency or comfort with public expression can inadvertently exclude or marginalize certain groups. For example, students with disabilities may face accessibility barriers if forums, multimedia tools, or assessment systems are not designed in accordance with universal-design principles. Similarly, learners from conservative cultural or religious backgrounds may be reluctant to share personal reflections or creative work in public-facing environments, especially if they fear that their contributions could be visible beyond the course or used for unintended purposes.

To address these challenges, institutions must move beyond generic UGC solutions and invest in inclusive design. This includes offering multiple modes of participation—such as text-based, audio, or video options—as well as providing clear guidance on privacy settings, data usage, and consent. It also involves designing prompts that are culturally sensitive and linguistically accessible, allowing students to respond in ways that align with their strengths and comfort zones. However, such inclusive approaches require additional resources, training, and curriculum-design time, which are often in short supply. Without institutional commitment to equity and diversity, UGC-driven initiatives risk becoming instruments of exclusion rather than empowerment.

Ethics :

Finally, ethical and governance concerns constitute a deep layer of implementation barriers that intersect with all other constraints. As institutions collect and analyses data on student engagement, they must navigate complex questions about consent, transparency, and fairness. Students frequently express unease about being continuously monitored through analytics that track their every interaction, raise concerns about how their data might be used for risk profiling, or worry that their engagement patterns could be misinterpreted or misused. When institutions fail to provide clear information about data collection practices, ownership rights, and the potential consequences of flagged behavior, trust in the system erodes, and students may disengage as a form of protest or self-protection. Ethical challenges also arise in the moderation and governance of UGC. Institutions must decide how to handle content that is inaccurate, offensive, or potentially harmful, balancing the need for academic integrity and safety with principles of free expression and student autonomy. Moderation policies that are too strict may stifle creativity and critical discourse, while policies that are too lax can allow misinformation, harassment, or plagiarism to proliferate. Determining who is responsible for monitoring content—whether it is instructors, teaching assistants, or centralized teams—raises further questions about workload, accountability, and consistency. Moreover, the use of algorithmic tools to automatically flag or filter content can introduce new forms of bias, privileging certain voices over others or misclassifying contextually sensitive material.

The intersection of these barriers—resource constraints, large class sizes, diverse learner needs, and ethical concerns—creates a complex landscape for implementing UGC-enhanced learning. Successful adoption requires not only technological innovation but also sustained investment in human capital, curriculum redesign, and ethical governance. Institutions that recognize these interconnected challenges and address them holistically are more likely to realize the full potential of UGC for enhancing engagement, retention, and learning outcomes. Those that treat UGC as a superficial add-on, however, risk deepening existing inequalities and undermining the very goals they seek to achieve.

Recommendations :

To realize the transformative potential of artificial intelligence (AI) in science education within Indian higher education, institutions should pursue scalable AI integration through public–private partnerships (PPPs) and targeted policy reforms. First, universities and UGC-aligned bodies can partner with ed-tech firms, research labs, and industry to co-develop AI-driven learning platforms that support adaptive simulations, virtual labs, and personalized feedback in physics, chemistry, and biology. These PPPs can reduce infrastructure costs, pool technical expertise, and ensure that AI tools are aligned with national curricula and accreditation standards while maintaining open-access or low-cost access for public institutions. Second, policy reforms should mandate inclusive and equitable AI deployment across higher-education tiers. This includes funding mechanisms for AI-enhanced science programmes in regional and rural universities, grants for faculty training in AI-mediated pedagogy, and incentives for open-source or low-bandwidth AI tools that accommodate diverse learner needs.

Regulatory frameworks must also embed data-privacy safeguards, ethical guidelines for algorithmic transparency, and non-discriminatory use of analytics in admissions, grading, and retention support. Finally, a national AI-in-education roadmap should integrate AI-supported science education into teacher-education programmes, ensuring that future science educators are equipped to design blended, AI-augmented classroom experiences. By incorporating scalable PPPs with strong, equity-centered policies, India can harness AI not only to upgrade teaching quality but also to bridge geographic, socio-economic, and digital divides in science education at the higher education level.

References :

- All India Council for Technical Education. (2019). *Model curriculum for artificial intelligence and data science (AI & DS).* AICTE. https://www.aicte-india.org
- All India Council for Technical Education. (2023). *Year of AI 2025: Policy roadmap for AI integration in technical education.* AICTE.
- Amrita Vishwa Vidyapeetham. (2021). *VALUE virtual labs project report.* Amrita University. https://vlab.amrita.edu
- Government of India. (2020). *National Education Policy 2020.* Ministry of Education. https://www.education.gov.in

- Holmes, W., Bialik, M., & Fadel, C. (2022). *Artificial intelligence in education: Promises and implications for teaching and learning.* Center for Curriculum Redesign.
- Indian Institute of Technology Delhi. (2022). *Virtual Labs initiative annual report.* IIT Delhi. https://www.vlab.co.in
- Indian Institute of Technology Madras. (2023). *Centre of Excellence for AI in Education: Vision document.* IIT Madras.
- Ministry of Education. (2020). *National Educational Technology Forum (NETF) framework document.* Government of India.
- OECD. (2021). *Digital education outlook 2021: Pushing the frontiers with AI, blockchain and robots.* OECD Publishing. https://doi.org/10.1787/589b283f-en
- Selwyn, N. (2019). *Should robots replace teachers? AI and the future of education.* Polity Press.
- Siemens, G., & Baker, R. S. (2012). Learning analytics and educational data mining: Towards communication and collaboration. *Proceedings of the 2nd International Conference on Learning Analytics and Knowledge*, 252–254.
- UNESCO. (2023). *Guidance for generative AI in education and research.* UNESCO Publishing.
- University Grants Commission. (2022). *Blended learning guidelines for higher education institutions.* UGC. https://www.ugc.ac.in
- World Bank. (2021). *Remote learning during COVID-19: Lessons from India and implications for the future of education.* World Bank Group.
- Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education. *International Journal of Educational Technology in Higher Education, 16*(1), 39. https://doi.org/10.1186/s41239-019-0171-0
- Dede, C. (2014). The role of digital technologies in deeper learning. *Students at the Center: Deeper Learning Research Series.* Harvard Education Press.
- Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). *Intelligence unleashed: An argument for AI in education.* Pearson Education.
- Means, B., Toyama, Y., Murphy, R., & Baki, M. (2013). The effectiveness of online and blended learning: A meta-analysis. *Teachers College Record, 115*(3), 1–47.
- Reich, J., & Ruipérez-Valiente, J. A. (2019). The MOOC pivot. *Science, 363*(6423), 130–131. https://doi.org/10.1126/science.aav7958
- Williamson, B., & Eynon, R. (2020). Historical threads, missing links, and future directions in AI in education. *Learning, Media and Technology, 45*(3), 223–235. https://doi.org/10.1080/17439884.2020.1798995