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VIRTUAL REALITY-ENHANCED HIGHER EDUCATION FOR INCLUSIVE, INNOVATIVE, AND SUSTAINABLE LEARNING

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ABSTRACT

This study aims to develop and validate a Virtual Reality (VR)-based laboratory model and examine its effects on student engagement, confidence, perceived conceptual understanding, and short-term cognitive performance in undergraduate science learning. Using a design-based research and development approach with iterative cycles, the VR laboratory was designed following Outcome-Based Education (OBE) principles and validated through expert judgment and classroom implementation. Data were collected using questionnaires, observations, qualitative reflections, and pretest-posttest assessments. The results indicate that the VR laboratory model demonstrates high pedagogical feasibility and is associated with increased student engagement, learning motivation, operational confidence in using immersive technology, and short-term improvements in conceptual understanding. Qualitative findings highlight the benefits of safe simulation, enhanced spatial visualization, and contextualized experiential learning, while usability issues and learner comfort remain practical challenges that require further refinement. At the institutional level, the validated VR laboratory model is positioned as a pilot-ready digital learning infrastructure that has the potential to support inclusive and quality science education (Sustainable Development Goal 4) and foster educational innovation and digital infrastructure development (Sustainable Development Goal 9). However, the findings primarily reflect short-term, context-specific outcomes; therefore, further large-scale, longitudinal studies with controlled comparisons are required to substantiate claims about long-term learning retention, scalability, and systemic SDG impact.

Keywords: virtual reality; immersive learning; virtual laboratory; Science education; educational technology

INTRODUCTION

Higher education institutions are currently confronted with increasing demands to provide learning experiences that are not only academically rigorous but also inclusive, equitable, innovative, and sustainable. Higher education in Indonesia is no exception, as it continues to be encouraged to implement an outcome-based curriculum (Kementerian Pendidikan Tinggi, Sains, dan Teknologi Republik Indonesia, 2025). In alignment with the United Nations' Sustainable Development Goals (SDGs), SDG 4 emphasizes the need for equitable access to education, while SDG 9 calls for resilient digital infrastructure in education (OECD, 2021; UNESCO, 2023; United Nations Department of Economic and Social Affairs [UN DESA], 2025). Unlike previous studies on virtual reality (VR) that focused primarily on student engagement or cognitive outcomes (Radianti et al., 2020; Hamilton et al., 2021), this study validates a VR laboratory model integrated with Outcome-Based Education (OBE) and the SDG framework. By linking technical simulati-

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on performance to SDG indicators, it provides a practical guide for higher education institutions to implement sustainable, resilient digital infrastructures. In response to these global agendas, universities are increasingly expected to adopt pedagogical innovations that enhance learning outcomes while remaining aligned with institutional capacity and long-term sustainability.

Despite these commitments, many higher education institutions, especially in developing countries, continue to rely heavily on lecture-centered instruction and limited physical laboratory facilities. Such instructional conditions constrain experiential learning, restrict the visualization of abstract or complex phenomena, and reduce opportunities for active student engagement (Bond et al., 2020; Radianti et al., 2020; Lehtinen, 2023). In Indonesia, large-scale transitions to digital and online learning, particularly during the COVID-19 pandemic, have exposed structural limitations in instructional preparedness and institutional support systems, which continue to influence the feasibility of adopting advanced immersive technologies beyond experimental or pilot stages (Pannen, 2021; Cahyadi et al., 2022). These limitations are particularly evident in science education and teacher education programs, where conceptual understanding, spatial reasoning, and procedural competence are essential learning outcomes.

From the perspective of Outcome-Based Education (OBE), effective learning is evaluated through demonstrable competencies rather than content coverage alone. However, conventional instructional approaches often fail to adequately support cognitive, psychomotor, and affective learning outcomes simultaneously (Dengel & Mägdefrau, 2018; Biggs & Tang, 2019; Dengel & Mägdefrau, 2020; Huang et al., 2020; Hamilton et al., 2021; Makransky & Mayer, 2022; Liu et al., 2023; Xie et al., 2023). As a result, there is a growing need to identify scalable instructional models that bridge theoretical knowledge and practical experience while remaining aligned with OBE principles.

Recent advances in immersive Virtual Reality (VR) technology have attracted considerable attention as a potential response to these challenges. VR enables learners to interact with simulated environments that represent complex, abstract, or otherwise inaccessible phenomena in a safe, controlled environment. A growing body of empirical research and systematic reviews has demonstrated that VR can enhance student engagement, motivation, and conceptual understanding, particularly in science and STEM-related disciplines (Cheng & Tsai, 2019; Radianti et al., 2020; Makransky et al., 2021). These immersive environments foster a strong sense of presence, which has been shown to positively influence learning persistence and affective engagement (Makransky & Lilleholt, 2018; Slater & Sanchez-Vives, 2016).

Beyond the general promise of immersion, contemporary VR learning research emphasizes that learning outcomes depend on the interaction between technological affordances (such as immersion and interactivity), psychological processes (including presence, agency, and emotion), and instructional design decisions (task structure, signaling, and scaffolding). The Cognitive Affective Model of Immersive Learning (CAMIL) posits that immersion and interactivity can enhance learning through increased presence and motivation, but may also impose additional cognitive load when instructional guidance is insufficient (Makransky & Mayer, 2022; Makransky & Petersen, 2021; Sari et al., 2024; Skulmowski & Xu, 2022). Meta-analytic evidence suggests that immersive VR produces a small but reliable advantage for learning outcomes overall ($g \approx 0.38$), with larger gains observed when learning activities are tightly aligned with measurable objectives and incorporate opportunities for practice and feedback (Wu et al., 2020; Hamilton et al., 2021; Coban et al., 2022; Liu et al., 2023).

One critical research challenge is not whether VR is engaging, but rather how specific instructional conditions influence its effectiveness, efficiency, and equity. While high levels of presence can enhance engagement, they may also be accompanied by reduced learning performance due to novelty effects, split attention, or excessive cognitive load (Chen et al., 2017; Makransky et al., 2019). Additionally, emerging research highlights potential adverse effects of immersive VR, including cybersickness, visual fatigue, and mental overload. These issues may disproportionately affect learners and introduce accessibility barriers, especially if not mitigated through ergonomic design and inclusive implementation strategies (Rebenitsch & Owen, 2016; Weech et al., 2019; Souchet, 2023; Biswas et al., 2024). These concerns align with UNESCO's governance-oriented stance, which holds that educational technology adoption should be evidence-based, inclusive, scalable, and sustainable rather than driven solely by technological novelty (UNESCO, 2023). From an institutional perspective, the adoption of immersive VR should therefore be understood not merely as a technological upgrade but as a systemic educational intervention involving governance, infrastructure, faculty capacity, and inclusivity. Indonesian scholars have emphasized that educational technology integration must be framed within broader considerations of access, equity, and quality assurance, particularly for under-resourced universities (Persichitte et al., 2017). This perspective is reinforced by recent scholarly work highlighting the need to design immersive learning environments that remain accessible and pedagogically viable across diverse institutional contexts (Sudimantara et al., 2025).

However, the effectiveness of VR in higher education varies across contexts. Meta-analytical and review studies indicate that learning gains from VR are highly dependent on instructional design quality, alignment with learning objectives, and institutional infrastructure readiness (Jensen & Konradsen, 2018; Makransky & Mayer, 2022; Won et al., 2023). Inadequate integration may even result in cognitive overload or reduced learning efficiency (Makransky et al., 2019). These findings suggest that VR should be conceptualized not merely as an instructional medium but as an educational infrastructure requiring systematic design, validation, and institutional support.

Global data further reveal substantial disparities in the adoption of immersive technology. UNESCO reports that fewer than 35% of higher education institutions in developing regions possess sufficient digital infrastructure to support immersive learning at scale (UNESCO, 2024). In the Indonesian context, VR implementation remains largely limited to small-scale classroom trials or short-term experimental studies, with limited evidence of institutionalized VR laboratories integrated into OBE-oriented curricula (Radianti et al., 2020; Sari et al., 2023). This situation highlights a persistent gap between the pedagogical potential of VR and its sustainable implementation within public universities.

A preliminary needs analysis conducted at Universitas Negeri Semarang (UNNES) reinforces this concern. Survey findings indicate that students strongly perceive VR as beneficial for enhancing conceptual understanding (M = 4.21), yet report only moderate initial comfort with immersive technologies (M = 3.88), reflecting limited prior exposure. Lecturer interviews further identify constraints related to laboratory accessibility, visualization of abstract concepts, and alignment with curriculum-based learning outcomes. These findings underscore the necessity of a VR learning model that is pedagogically sound, institutionally feasible, and aligned with OBE principles.

Although international research on VR in higher education has expanded substantially over the past decade, several critical gaps remain. First, most studies focus on short-term experimental comparisons between VR and traditional instruction, rather than on design-based validation of VR laboratories embedded within OBE systems (Dinet & Kitajima, 2018; Radianti et al., 2020). Second, empirical research explicitly linking VR implementation with SDG achievement, particularly SDG 4 and SDG 9, remains limited and predominantly conceptual. Third, studies published in reputable journals often emphasize learner perceptions and immediate learning outcomes, while giving limited attention to feasibility, expert validation, and sustainability of VR infrastructure within public higher education institutions. Kustandi et al. (2020) reported that VR-supported online learning environments contributed to improved learner interaction and perceived learning effectiveness. Similarly, Irwanto et al. (2025) found that immersive VR significantly enhanced secondary students' understanding of chemical reaction rates, suggesting that VR can be pedagogically effective when aligned with curricular objectives and appropriately scaffolded.

Departing from these gaps, the present study positions VR not merely as an instructional medium but as a validated educational infrastructure integrated with OBE and sustainability frameworks. Rather than assuming that immersion alone guarantees learning effectiveness, this study argues that learning outcomes depend on structured laboratory design, expert validation, and infrastructural readiness.

Accordingly, this study aims to: develop and validate a VR laboratory model for higher education through expert judgment and classroom trials; empirically examine the impact of VR-based learning on student engagement, confidence, and conceptual understanding; and analyze the contribution of VR-supported instruction to OBE implementation and the advancement of SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure).

This study is limited to undergraduate science-related courses at Universitas Negeri Semarang and focuses on feasibility, engagement, and perceptual learning indicators rather than long-term academic achievement. Such delimitation ensures methodological rigor, operational clarity, and replicability. Overall, this research contributes theoretically, methodologically, and practically by offering an empirically validated VR laboratory framework suitable for higher education institutions in developing contexts.

METHODS

Research Design

This study employed a Research and Development (R&D) approach with a design-based research (DBR) orientation to develop, validate, and evaluate a Virtual Reality (VR)-based laboratory learning model aligned with Outcome-Based Education (OBE). A DBR approach was selected because it emphasizes iterative design, contextual validation, and the practical applicability of educational innovations rather than isolated experimental comparisons, which is particularly appropriate for immersive technology development in higher education contexts (van den Akker et al., 2006; McKenney & Reeves, 2018; Radianti et al., 2020).

To operationalize the development process, an ADDIE-oriented instructional design framework (Analyze-Design-Develop-Implement-Evaluate) was adopted. ADDIE was applied not as a rigid, linear model but as a flexible, iterative structure embedded within DBR cycles, enabling continuous refinement of the VR laboratory model based on empirical evidence and classroom feedback. This integration ensures constructive alignment, feasibility testing, and sustainability of VR-based learning implementation in higher education (Branch, 2009; Dick et al., 2015; Reeves & McKenney, 2019).

Development Procedures

The study was conducted through five iterative stages, consistent with the logic of design-based research.

Needs Analysis

The needs analysis stage aimed to identify instructional challenges, learner readiness, and institutional constraints related to laboratory-based learning. Data were collected from undergraduate students and lecturers through structured questionnaires and semi-structured interviews. The analysis focused on perceived usefulness of VR for conceptual understanding, prior exposure to immersive technologies, and alignment between existing laboratory practices and curriculum-based learning outcomes.

Design and Development

Based on the findings of the needs analysis, the VR laboratory was designed to support cognitive, psychomotor, and affective learning outcomes, in accordance with principles of constructive alignment and OBE. Learning outcomes were translated into immersive learning tasks, simulations, and assessment indicators to ensure coherence between objectives, learning activities, and evaluation criteria (Biggs & Tang, 2019).

The instructional design emphasized guided interaction, task sequencing, and feedback mechanisms to minimize extraneous cognitive load while maintaining immersive engagement, consistent with contemporary principles of immersive learning design (Makransky & Mayer, 2022).

Expert Validation

The VR laboratory prototype underwent expert validation involving subject-matter experts and instructional media specialists. Validation was conducted using structured rubrics that assessed content accuracy, pedagogical suitability, usability, and technical feasibility. This validation process followed established procedures in educational design research to ensure internal coherence and practical viability of the developed learning model (McKenney & Reeves, 2018; van den Akker et al., 2006).

Classroom Implementation

Following expert validation, the VR laboratory was implemented in an undergraduate science-related course under supervised classroom conditions. Implementation adhered to established human-computer interaction and immersive interaction principles, including session duration limits, guided navigation, and monitored user interaction, to minimize cybersickness and visual fatigue (Chang et al., 2020; Slater & Sanchez-Vives, 2016).

All VR sessions were facilitated by instructors trained in immersive learning procedures to ensure consistency of instructional delivery and learner support.

Evaluation and Revision

Quantitative and qualitative data were collected to evaluate student engagement, confidence, perceived conceptual understanding, and the feasibility of implementing a VR laboratory. Evaluation results informed minor design revisions, consistent with the iterative refinement principles of design-based research (Reeves & McKenney, 2019).

Participants and Sampling Procedure

Participants in this study included undergraduate students and lecturers from Universitas Negeri Semarang (UNNES). During the needs analysis phase, 78 undergraduate students and 4 lecturers participated. For the classroom implementation phase, 28 undergraduate students were selected through purposive sampling based on their course relevance and prior exposure to laboratory-based learning. While the sample size for the implementation phase (n = 28) may appear relatively small, this is consistent with the principles of Design-Based Research (DBR), which emphasizes deep, contextualized insights over statistical generalization. In DBR, the focus is on iterative design, developmental validation, and the refinement of interventions in real-world settings. Thus, the sample size is adequate for the exploratory, formative nature of this phase, enabling rich, context-specific data to inform further design iterations.

Purposive sampling is appropriate for design-oriented and developmental research, where the primary objective is contextual validation rather than statistical generalization (Creswell & Creswell, 2018). Similar sampling strategies are commonly reported in immersive VR studies in higher education (Makransky & Lilleholt, 2018).

Instruments and Data Collection

Multiple data collection instruments were employed to support methodological triangulation: (1) Likert-scale questionnaires measuring student engagement, confidence, and perceived conceptual understanding, adapted from validated immersive learning instruments (Parong & Mayer, 2018; Makransky & Mayer, 2022); (2) Expert validation rubrics evaluating pedagogical alignment, usability, and technical feasibility; (3) Observation protocols documenting behavioral engagement and interaction patterns during VR sessions; (4)cOpen-ended response items capturing students' experiential perceptions of immersion and usability.

Questionnaire reliability was assessed using Cronbach's alpha, yielding $\alpha = 0.766$, indicating acceptable internal consistency for exploratory educational research (Field, 2018; Hair et al., 2022).

To evaluate the VR/AR laboratory's effectiveness, we included both perception-based questionnaires and knowledge tests (multiple-choice and essays) to assess students' understanding and application of astronomical concepts in simulated scenarios. This approach offers a clearer view of how VR-based learning enhances cognitive outcomes, alongside improvements in motivation and engagement.

Data Analysis

Quantitative data were analyzed using descriptive statistics and effect size analysis (Cohen's d) to assess the practical magnitude of learning-related outcomes. Effect size analysis was prioritized given the contextual sample size and the exploratory nature of DBR, where practical significance is emphasized over inferential generalization (Cohen, 1988; Hiemstra et al., 2019; Makransky & Lilleholt, 2018).

Qualitative data were analyzed using thematic analysis following Braun and Clarke's (2023) six-phase procedure, enabling the systematic identification of recurring experiential patterns related to immersion, visualization, motivation, and implementation constraints.

Ethical Considerations

Ethical procedures included informed consent, voluntary participation, and assurances of confidentiality. All VR activities were conducted under supervised conditions, adhering to established principles of immersive interaction and ergonomics to minimize discomfort and cybersickness (Slater & Sanchez-Vives, 2016). The study also aligns with UNESCO's recommendations for responsible, evidence-based, and sustainable adoption of educational technologies in higher education (UNESCO, 2023).

RESULTS AND DISCUSSION

Baseline Readiness toward Virtual Reality-Based Learning

Pretest data collected during the needs analysis phase (n = 78) indicate that students' initial comfort with Virtual Reality (VR)-based learning was moderate (M = 3.88, SD = 0.74), suggesting limited prior exposure to immersive technologies. In contrast, students reported a high expectation of VR's pedagogical value for enhancing conceptual understanding (M = 4.21, SD = 0.72).

This discrepancy reflects a readiness gap between perceived usefulness and operational familiarity, a phenomenon commonly observed in higher education contexts where immersive technologies are emerging but have not yet been systematically institutionalized. It is important to note that the data collected in this phase primarily reflect perceptual outcomes (i.e., students' perceptions and expectations) rather than objective cognitive outcomes. These perceptual measures, such as perceived usefulness, serve as indicators of students' subjective experiences and emotional responses to VR technology rather than their actual cognitive understanding or retention of course content.

Radianti et al. (2020) argue that such gaps often stem from fragmented adoption practices, where enthusiasm for immersive learning precedes the development of instructional design capacity and infrastructure support. Similar patterns have been reported in controlled experimental and review-based studies emphasizing that early-stage VR adoption frequently relies on perceived potential rather than experiential competence (Makransky & Petersen, 2019).

These baseline findings provide empirical justification for developing a structured, validated VR laboratory model rather than isolated or ad hoc classroom implementations that risk inflating expectations without ensuring pedagogical readiness.

Post-Implementation Outcomes: Engagement, Confidence, and Learning Attractiveness

Following classroom implementation of the validated VR laboratory model (n = 28), posttest results demonstrated consistent improvements across affective and engagement-related indicators. Pretest and posttest results showed a significant improvement in students' understanding of astronomical concepts, with scores rising from 70% to 85%, highlighting the VR laboratory's effectiveness in promoting cognitive learning. These cognitive gains were accompanied by perceptual outcomes, including increased engagement (M = 4.87) and motivation (M = 4.52) reported in the post-implementation. Students reported increased confidence in operating VR environments (M = 4.10), strong learning engagement and a willingness to continue using VR (M = 4.52), and high perceived learning attractiveness (M = 4.48).

While these improvements are valuable, it is crucial to acknowledge that these outcomes are largely affective and perceptual, reflecting students' emotional engagement and self-reported learning experiences. This study does not directly measure cognitive learning outcomes such as knowledge retention or understanding, which would require objective assessments to differentiate from students' emotional or motivational responses.

Although paired-sample statistical tests did not reach conventional significance thresholds ($p > .05$), effect size analysis revealed Cohen's d values ranging from 0.34 to 0.38, indicating small-to-moderate practical effects. Within immersive learning research, effect sizes of this magnitude are widely regarded as educationally meaningful, particularly in design-based and developmental studies where contextual validity and ecological relevance are prioritized over purely statistical inference (Makransky & Lilleholt, 2018ab; Makransky & Mayer, 2022).

These findings support the argument that immersive VR interventions may yield incremental yet pedagogically relevant gains, especially when evaluated in authentic classroom contexts rather than tightly controlled laboratory settings.

Expert Validation of the VR Laboratory Model

Expert validation results yielded an overall feasibility score of 93%, classifying the VR laboratory model as highly feasible for higher education implementation. Experts emphasized the clarity of instructional sequencing, alignment with course learning outcomes, and coherence with the principles of Outcome-Based Education (OBE). Minor recommendations related to technical stability and user safety protocols were incorporated prior to classroom deployment.

By integrating expert judgment into the development process, this study addresses a critical limitation in prior immersive VR research: the tendency to privilege learner perceptions while neglecting instructional feasibility, sustainability, and institutional scalability (Radianti et al., 2020). While expert validation reinforces the credibility of the VR laboratory model's pedagogical design, it is important to note that this validation primarily assesses perceptual qualities, such as usability and instructional clarity, rather than cognitive outcomes of student learning.

Observational Evidence of Behavioral Engagement

Classroom observations revealed very high levels of behavioral engagement, peer interaction, and adaptive use of VR interfaces. Students actively explored immersive environments, engaged in collaborative discussions, and linked simulated experiences with course-related concepts. The mean observational engagement score reached M = 4.87 (SD = 0.34), indicating very strong engagement, although a potential ceiling effect should be acknowledged.

These behavioral observations focus on the affective and perceptual dimensions of student engagement, which are important for understanding how VR contributes to the emotional and motivational aspects of learning. However, it is critical to separate these measures from objective cognitive outcomes, which would require further assessment to capture knowledge acquisition and retention.

These behavioral patterns are consistent with cognitive-affective models of immersive learning, which posit that VR enhances learning engagement by increasing presence, attention, and situational interest when instructional guidance is explicit and task-oriented (Makransky & Lilleholt, 2018; Parong & Mayer, 2018).

Figure 1 is inserted here to visually document students' enthusiasm, excitement, and peer interaction during immersive VR-based learning activities.

Figure 1. Students' Interaction with Immersive Learning Environments During the Implementation of VR

Qualitative Learning Experience Patterns

Thematic analysis of open-ended student responses identified five dominant experiential dimensions: (1) safe and repeatable simulation, (2) immersion and interactivity, (3) visualization of abstract concepts, (4) contextual realism, and (5) enhanced motivation and retention.

Although these findings provide valuable qualitative insights into students' perceptions and emotional responses to the VR environment, it is essential to distinguish these perceptual outcomes from cognitive learning, which would be measured through more traditional assessment methods (e.g., written tests, quizzes, or problem-solving tasks). Students consistently reported improved understanding of conceptually demanding topics requiring spatial reasoning and three-dimensional visualization. These qualitative insights reinforce existing empirical evidence that immersive VR is particularly effective for supporting the acquisition of abstract, spatial, and procedural knowledge, especially when learners are allowed to repeatedly explore simulated scenarios without real-world risk (Parong & Mayer, 2018; Cheng & Tsai, 2019).

Taken together, the qualitative and quantitative findings indicate that immersive VR learning environments not only enhance affective engagement but also support meaningful conceptual learning when embedded within a structured instructional framework.

The findings of this study indicate that virtual reality (VR)-based learning environments enhance student engagement and *perceived* conceptual understanding. This result is consistent with prior international studies suggesting that immersive learning promotes deeper cognitive processing through experiential and embodied interaction (Makransky & Petersen, 2019; Radianti et al., 2020). From the perspective of multimedia and experiential learning theory, VR extends traditional instructional media by incorporating spatial presence and sensorimotor involvement, which are critical for meaningful learning (Mayer, 2020).

Importantly, the present findings also resonate with empirical evidence from the Indonesian educational context. While international studies have demonstrated the effectiveness of VR in controlled and well-resourced settings, local research confirms that similar pedagogical benefits can be achieved within Indonesian institutions. For example, Kuncoro et al. (2025) found that immersive VR significantly improved students' understanding of complex engineering concepts, while Maulana et al. (2024) reported increased learning activity and academic achievement among senior high school students using VR-based instructional media. The convergence between international and Indonesian findings strengthens the external validity of this study and suggests that the benefits of VR-based learning are not contextually isolated.

From a theoretical standpoint, these results reinforce constructivist learning assumptions that knowledge is actively constructed through interaction with learning environments. International literature emphasizes that VR facilitates situated learning by placing learners within authentic or semi-authentic contexts (Radianti et al., 2020). Indonesian studies further demonstrate that such contextualization is particularly valuable in environments where access to physical laboratories or field practice is limited, thereby extending the practical relevance of constructivist principles.

In addition to learning effectiveness, VR has been widely discussed in international literature as a promising tool for flexible and distance learning. Studies by Makransky et al. (2021) indicate that immersive technologies can partially compensate for the absence of physical presence in remote learning environments. This argument is empirically supported in the Indonesian context by Casmat and Muralitharan (2025), who showed that VR and AR technologies enhance learning engagement and effectiveness in distance learning settings. Taken together, these findings suggest that VR can function as a strategic medium for expanding access to experiential learning, particularly in geographically diverse countries such as Indonesia.

However, both international and local studies caution that the effectiveness of VR-based learning depends on user acceptance and system usability. The Technology Acceptance Model (TAM) posits that individuals' intention to use technology is driven by perceived usefulness and perceived ease of use (Davis, 1989). This foundational model remains widely applied and has been extended in recent research to examine technology acceptance in educational and digital learning environments (García et al., 2024; Lee, 2025). Rahmawati and Narsa (2019) demonstrated that perceived usefulness and ease of use significantly influence students' acceptance of e-learning systems in Indonesia, reinforcing the importance of user-centered design in VR-based learning systems.

Despite its pedagogical potential, challenges related to usability and learner comfort remain significant. International reviews have identified cybersickness as a persistent limitation in VR-based education, particularly during prolonged exposure (Radianti et al., 2020; Rebenitsch & Owen, 2016). Indonesian empirical studies provide further confirmation of this issue. Rizal et al. (2020) reported usability constraints in multi-user VR learning environments, while Irfan et al. (2024) documented cybersickness symptoms among users of VR-based educational applications. A recent bibliometric review further indicates that cybersickness remains a dominant concern in VR research within educational contexts (Rafiq et al., 2025).

While this study aligns with the United Nations SDGs, particularly SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure), the contribution of the proposed VR laboratory model can be strengthened by articulating concrete pathways for scaling and institutionalization that translate conceptual alignment into measurable SDG-related indicators (OECD, 2021; UN DESA, 2023; UNESCO, 2023).

One viable pathway for scaling the VR laboratory model is its integration into national and regional higher education infrastructures through policy-driven adoption and multi-stakeholder partnerships involving universities, government agencies, and industry actors, consistent with contemporary Triple Helix-inspired innovation ecosystems (Figueiredo et al., 2023; Weidenfeld, 2025). Such integration requires coordinated policy frameworks, sustainable funding mechanisms, and shared technical capacity to support large-scale deployment of immersive learning systems (OECD, 2021; UNESCO, 2023). In the Indonesian context, this pathway aligns with national higher education quality assurance and digital transformation policies (Kementerian Pendidikan Tinggi, Sains, dan Teknologi Republik Indonesia, 2025). Institutionalizing VR within higher education curricula can expand equitable access to high-quality laboratory experiences, thereby contributing more directly to SDG 4 targets related to inclusive and equitable quality education (UN DESA, 2023; UNESCO, 2023).

With respect to SDG 9, scaling the VR laboratory model may catalyze innovation in educational technologies and provide a transferable framework for embedding immersive learning within existing curricular and infrastructural systems (OECD, 2021). The development of scalable VR laboratories also opens pathways for sustained university-industry collaboration in designing future-ready STEM curricula aligned with evolving workforce demands (Cai & Lattu, 2022; Simões et al., 2022). Furthermore, institutionalization through continuous professional development programs can strengthen instructors' pedagogical and technological competencies, ensuring sustainable and pedagogically grounded implementation of VR in teaching and learning (UNESCO, 2023).

Finally, localizing VR content to reflect cultural, linguistic, and regional contexts may enhance institutional ownership and contextual relevance, critical factors for sustainable educational technology adoption across diverse higher education ecosystems (OECD, 2021; UNESCO, 2023). Such localized development supports inclusive digital transformation in education and reinforces SDG 9 objectives related to resilient infrastructure and innovation capacity within national education systems (UN DESA, 2023).

The convergence between international and Indonesian evidence indicates that challenges associated with VR adoption are primarily pedagogical rather than merely technical. Without careful instructional design, appropriate session duration, and systematic usability evaluation, the pedagogical benefits of immersive learning may be offset by cognitive overload and physical discomfort. VR should therefore be embedded within a comprehensive pedagogical strategy rather than implemented as a standalone technological intervention. Situating the present findings within both international scholarship and Indonesian empirical research demonstrates that VR-based learning is theoretically grounded, empirically supported, and contextually relevant.

Despite these contributions, this study has limitations. The relatively small post-implementation sample and short intervention period constrain generalizability and preclude conclusions about long-term retention or transfer. Future research should employ larger samples, include controlled comparisons with non-immersive conditions, and adopt longitudinal designs. Further studies should also examine how specific design features, such as signaling density, interactivity level, and pretraining, mediate the relationships among presence, cognitive load, and learning performance in immersive environments (Albus et al., 2021; Makransky & Mayer, 2022; Skulmowski & Xu, 2022).

CONCLUSION

This study demonstrates that a Virtual Reality (VR)-based laboratory model, when developed through design-based research and aligned with Outcome-Based Education (OBE) principles, can enhance student engagement, learning motivation, operational confidence, and short-term conceptual understanding in undergraduate science learning, whereby the educational value of VR does not stem from immersion alone, but from its pedagogically structured integration into curriculum-aligned laboratory activities that support cognitive, psychomotor, and affective learning domains, thus supporting the use of VR as a complementary experiential learning infrastructure, particularly in contexts where access to physical laboratory facilities is limited. At the institutional level, the validated VR laboratory model shows potential as a pilot-ready digital learning infrastructure that aligns conceptually with SDG 4 (Quality Education) by supporting more inclusive access to laboratory-based learning experiences and with SDG 9 (Industry, Innovation, and Infrastructure) by contributing to the development of innovative educational technologies. However, these contributions should be interpreted as conceptual and exploratory rather than definitive indicators of systemic SDG attainment, and the scalability and long-term institutional impact of VR laboratories require further evaluation through longitudinal studies, cost-benefit analyses, policy alignment, and broader multi-institutional trials. Despite its contributions, this study is limited by a relatively small implementation sample, short intervention duration, and a primary focus on short-term and perceptual learning outcomes; therefore, future research should employ larger samples, controlled experimental comparisons with non-immersive conditions, and longitudinal designs to examine learning retention, transfer of learning, and sustainability of VR integration at the institutional level, with further inquiry also needed to investigate how specific instructional design features, such as signaling, scaffolding, and pretraining, mediate the relationships among presence, cognitive load, and learning performance in immersive learning environments.

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