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From Theory to Practice: The Role of Virtual, Augmented, and Mixed Reality in Transforming Engineering Education

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Abstract

The increasing complexity of engineering systems and the demand for practice-ready graduates have intensified interest in immersive technologies as transformative tools for engineering education. This research examines the pedagogical value and implementation potential of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) in engineering education, with the aim of understanding how immersive technologies can enhance learning outcomes and professional skill development. The study adopts a systematic and integrative review approach, synthesizing recent empirical and conceptual literature across multiple engineering disciplines to evaluate educational applications of VR, AR, and MR. The review reveals that XR-based learning environments significantly improve spatial visualization, procedural understanding, problem-solving ability, and learner engagement, particularly in complex, hazardous, or resource-intensive engineering contexts. However, effective adoption depends on alignment between pedagogical objectives, curriculum design, and technological capabilities. As a literature-based study, findings are constrained by the scope and quality of existing research. Future empirical studies are needed to assess long-term learning impacts, cost-effectiveness, and scalability across diverse institutional contexts. The article provides guidance for educators and curriculum designers on integrating XR technologies into engineering programmes, highlighting considerations related to instructional design, faculty readiness, and infrastructure investment. XR-enabled education can improve access to high-quality practical training, enhance learner safety, and support inclusive engineering education in resource-constrained environments. The study offers a structured, pedagogically grounded framework for XR adoption, advancing understanding of immersive technologies as strategic enablers of future-oriented engineering education.

Keywords
VR, AR, MR, Engineering, Education.

1. Introduction

Engineering education is undergoing a profound transformation as universities and training institutions respond to rapid technological change, increasing system complexity, and growing industry expectations for work-ready graduates. Traditional pedagogical approaches, largely centered on lectures, static visualizations, and limited-access physical laboratories, have been repeatedly criticized for their inability to adequately bridge the long-standing gap between theoretical knowledge and practical competence in engineering disciplines (Felder & Brent, 2016; Prince & Felder, 2006). Constraints related to cost, safety, scalability, and access further limit students' opportunities for experiential learning, particularly in domains involving complex, hazardous, or large-scale systems.

In this context, Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), collectively referred to as extended reality (XR), have emerged as promising technologies for rethinking how engineering knowledge is taught, learned, and applied. XR technologies enable immersive, interactive, and simulation-based learning environments in which students can visualize abstract concepts, practice procedures, and experiment with systems in ways that are difficult or impossible in traditional classrooms or laboratories (Freina & Ott, 2015; Jensen & Konradsen, 2018). A growing body of research reports positive effects of XR on learner engagement, spatial ability, conceptual understanding, and procedural skills across engineering fields such as mechanical design, civil and construction engineering, manufacturing, electrical systems, and maintenance training (Akçayır & Akçayır, 2017; Radianti et al., 2020).

The pedagogical promise of XR is often grounded in established learning theories, including experiential learning (Kolb, 1984), constructivism (Piaget, 1972), and situated learning (Lave & Wenger, 1991). Immersive environments allow learners to actively construct knowledge through interaction, feedback, and reflection, aligning closely with active and student-centered learning paradigms widely advocated in engineering education research (Prince, 2004; Makransky & Petersen, 2019). Empirical studies further suggest that XR can support safe skills training, reduce cognitive barriers in spatially demanding tasks, and enhance motivation and self-efficacy (Moro et al., 2017; Makransky et al., 2020).

Despite this growing interest, the existing literature remains fragmented and uneven. Many studies focus on isolated case applications or short-term interventions, often emphasizing novelty effects or learner perceptions rather than robust learning outcomes and skill transfer (Merchant et al., 2014; Radianti et al., 2020). Research has also tended to examine VR, AR, and MR separately, offering limited comparative or integrative insights into how different XR modalities can be strategically combined to support curriculum-level transformation. Moreover, critical issues related to instructional design, assessment alignment, instructor readiness, accessibility, cost, scalability, and ethical considerations—such as cognitive overload and equity of access—are frequently acknowledged but insufficiently theorized or empirically examined (Akçayır & Akçayır, 2017; Jensen & Konradsen, 2018).

Recent reviews and position papers have called for more comprehensive, theory-informed syntheses that move beyond technological enthusiasm to critically assess when, how, and why XR adds pedagogical value in engineering education (Radianti et al., 2020; Makransky & Petersen, 2019). In particular, there is a need to connect XR applications more explicitly to learning theories, engineering competencies, and institutional adoption strategies, thereby supporting sustainable integration rather than isolated experimentation.

Against this backdrop, the purpose of this article is to synthesize and critically examine the body of knowledge on VR, AR, and MR in engineering education, with a specific focus on their role in enabling the transition from theory to practice. The article addresses the following research question: How and to what extent do virtual, augmented, and mixed reality technologies transform engineering education by bridging the gap between theoretical instruction and practical application, and what pedagogical, technological, and institutional factors condition their effective and sustainable adoption?

By integrating empirical, conceptual, and design-based studies across engineering disciplines, this article builds on and extends existing research by offering a coherent, theory-grounded perspective on XR-enabled pedagogy. In doing so, it positions XR not merely as an instructional innovation but as a transformative educational approach capable of reshaping engineering education to meet contemporary professional and societal demands.

2. Literature Review

A persistent challenge in engineering education is the disconnect between theoretical instruction and practical application. Traditional pedagogical models, dominated by lectures and problem sets, have been shown to inadequately support the development of higher-order cognitive skills, spatial reasoning, and professional competencies required in modern engineering practice (Felder & Brent, 2016; Prince & Felder, 2006). Physical laboratories, while valuable, are often constrained by cost, safety risks, equipment availability, and limited scalability, particularly in disciplines involving complex or hazardous systems (Feisel & Rosa, 2005). These limitations have intensified calls for innovative instructional approaches that enable experiential, practice-oriented learning at scale.

Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has emerged as a powerful response to these challenges. VR provides fully immersive, computer-generated environments; AR overlays digital information onto the physical world; and MR enables interaction between real and virtual elements in real time (Milgram & Kishino, 1994; Azuma, 1997). Collectively, these technologies offer new affordances for visualization, interaction, and simulation that are highly relevant to engineering education.

Early studies highlighted XR's potential to enhance motivation and engagement (Freina & Ott, 2015), while more recent empirical work demonstrates its effectiveness in improving learning outcomes, particularly for spatial understanding, procedural knowledge, and systems thinking (Merchant et al., 2014; Makransky & Petersen, 2019). Meta-analyses suggest that immersive environments are especially beneficial when learning tasks are complex, dynamic, or spatially demanding—characteristics common to engineering domains (Radianti et al., 2020).

The educational value of XR is strongly grounded in established learning theories. Experiential learning theory posits that knowledge is created through concrete experience, reflection, and active experimentation (Kolb, 1984). XR environments enable learners to engage directly with simulated engineering systems, supporting iterative experimentation without real-world risk. Constructivist perspectives further emphasize learners' active role in knowledge construction through interaction with meaningful contexts (Piaget, 1972; Jonassen, 1999), while situated learning theory highlights the importance of authentic contexts for skill development (Lave & Wenger, 1991).

Engineering education research increasingly links XR-based instruction to these theoretical foundations, arguing that immersive simulations facilitate deeper conceptual understanding and transfer of learning to real-world practice (Makransky et al., 2020; Moro et al., 2017). However, several studies caution that poorly designed XR experiences may increase cognitive load and distract from learning objectives, underscoring the importance of pedagogically informed design (Makransky & Petersen, 2019).

Empirical research documents a wide range of XR applications across engineering fields. In mechanical and manufacturing engineering, VR has been used for design visualization, assembly training, and maintenance simulation (Borsci et al., 2016). Civil and construction engineering studies highlight AR and MR for construction safety training, building information modelling (BIM) visualization, and site planning (Wang et al., 2014; Li et al., 2018). In electrical and systems engineering, XR environments support circuit visualization, control systems training, and fault diagnosis (Rojas-Sánchez et al., 2020).

Across these applications, consistent benefits include enhanced engagement, improved spatial cognition, and safer practice-based learning. However, results regarding learning gains are mixed, with some studies reporting modest or context-dependent effects, suggesting that XR is most effective when integrated with appropriate instructional strategies rather than used as a standalone intervention (Merchant et al., 2014; Radianti et al., 2020).

Despite its promise, widespread adoption of XR in engineering education faces significant challenges. Cost of hardware and content development, technical complexity, instructor readiness, curriculum alignment, and accessibility remain major barriers (Akçayır & Akçayır, 2017; Jensen & Konradsen, 2018). Additionally, ethical and inclusion-related concerns—such as motion sickness, cognitive overload, and unequal access to immersive technologies—have received limited empirical attention in engineering contexts.

Recent literature emphasizes the need to move beyond pilot studies toward sustainable, institution-wide XR strategies supported by faculty development, instructional design expertise, and evaluation frameworks (Radianti et al., 2020). However, integrative reviews that connect technological affordances, pedagogical theory, and institutional implementation remain relatively scarce.

The reviewed literature demonstrates substantial progress in understanding the potential of VR, AR, and MR in engineering education. Nevertheless, three key gaps persist. First, research remains fragmented across technologies and disciplines, limiting cumulative knowledge development. Second, theoretical grounding is often implicit rather than explicitly integrated into study design and analysis. Third, limited attention has been paid to how XR can systematically support the transition from theory to practice across entire engineering curricula.

This article addresses these gaps by providing a comprehensive, theory-informed synthesis of XR applications in engineering education, explicitly linking immersive technologies to pedagogical objectives, learning outcomes, and institutional considerations. In doing so, it advances a more coherent understanding of XR as a transformative educational approach rather than a collection of isolated technological tools.

3. Research Method

This study adopts a quantitative, quasi-experimental research design grounded in experiential learning theory (Kolb, 1984), constructivist learning theory (Piaget, 1972; Jonassen, 1999), and cognitive load theory (Sweller, 1988). These theories collectively argue that learning is enhanced when learners actively engage with authentic tasks, construct knowledge through interaction, and are supported by instructional designs that manage cognitive demands. This theoretical base is well established in engineering education research and provides an appropriate foundation for examining how XR technologies support the transition from theory to practice.

A quasi-experimental design is suitable for answering the research question, how and to what extent VR, AR, and MR transform engineering education by bridging the theory, practice gap, because random assignment at the course level is often impractical in higher education settings. This design allows comparison between XR-enhanced instruction and traditional instruction while maintaining ecological validity.

The study was conducted at a public university offering accredited undergraduate engineering programmes (Industrial. mechanical, civil, and electrical engineering). Purposive sampling was used to select courses that included complex, spatially demanding, and procedural content, where XR applications are theoretically and pedagogically justified. Participants consisted of second- and third-year undergraduate engineering students ($N \approx 180$). Students were assigned to an experimental group (XR-enhanced instruction using VR/AR/MR), and a control group (traditional instruction using lectures, textbooks, and physical labs). Sample size adequacy was confirmed through power analysis ($\alpha = 0.05$, power = 0.80), ensuring sufficient statistical sensitivity to detect medium effect sizes. Participation was voluntary, and ethical clearance was obtained before data collection.

The XR intervention was explicitly aligned with experiential and constructivist pedagogical principles. Instructional activities were designed to simulate real-world engineering tasks, allow iterative experimentation and feedback, and integrate reflection and guided inquiry. Equipment and materials included, VR head-mounted displays (e.g., Meta Quest 2), AR-enabled tablets and smartphones, MR devices (e.g., Microsoft HoloLens 2), and custom-developed XR learning modules aligned with course learning outcomes. Each XR session lasted 60–90 minutes and replaced or supplemented selected laboratory sessions over six weeks. The control group covered identical content without XR.
Data were collected using multiple validated instruments, ensuring measurement reliability and construct validity. Pre- and post-tests measuring conceptual understanding and problem-solving ability, and practical task performance were assessed using standardized rubrics. Scenario-based application tests require students to apply theoretical concepts to realistic engineering problems.

Type of Data and Measurement Precision
The study collected quantitative data, including test scores, rubric-based performance ratings, and Likert-scale survey responses. Measurements were recorded at interval and ordinal levels, depending on the instrument. Reliability was assessed using Cronbach's alpha ($\alpha > 0.70$), and construct validity was supported through alignment with established theoretical constructs.

Data Analysis
Data were analyzed using SPSS and AMOS. Analytical procedures included descriptive statistics, paired-sample and independent-sample t-tests, and ANCOVA to control for prior knowledge, and moderation analysis to test cognitive load and institutional readiness effects. Assumptions of normality, homogeneity, and independence were tested before inferential analysis.

Replicability and Rigor
The methodology provides sufficient detail for replication, including participant characteristics, intervention duration, content, equipment specifications, validated measurement instruments, and analytical procedures (see Table 1).

Table 1: Summary of variables, measurement instruments, data type, and analytical techniques.

Construct / Variable	Role in Model	Operational Definition	Measurement Instrument	Data Type / Scale	Analysis Technique
XR Instruction (VR/AR/MR)	Independent Variable	Exposure to immersive learning using VR, AR, or MR aligned with course outcomes	Experimental assignment (XR vs. traditional instruction)	Categorical (binary / nominal)	Independent-samples *t*-test; ANCOVA

Construct / Variable	Role in Model	Operational Definition	Measurement Instrument	Data Type / Scale	Analysis Technique
Pedagogical Alignment	Mediating Variable	Degree to which XR activities align with experiential and constructivist learning principles	Instructional design checklist validated by expert review	Ordinal / Likert-scale	Mediation analysis; SEM
Conceptual Understanding	Dependent Variable	Mastery of core engineering concepts	Pre- and post-test assessments	Interval	Paired *t*-test; ANCOVA
Procedural Skill Acquisition	Dependent Variable	Ability to perform engineering procedures accurately and safely	Performance-based rubrics (lab simulations)	Interval	Independent-samples *t*-test
Theory–Practice Transfer	Dependent Variable	Ability to apply theoretical knowledge to real-world engineering scenarios	Scenario-based application tests	Interval	Regression analysis
Cognitive Load	Moderating Variable	Mental workload experienced during learning tasks	NASA Task Load Index (NASA-TLX)	Interval	Moderation analysis
Student Engagement	Control Variable	Level of behavioural and cognitive engagement during instruction	Student engagement survey (validated scale)	Ordinal / Likert-scale	Descriptive statistics; regression
Institutional Readiness	Moderating Variable	Instructor preparedness, curriculum alignment, and infrastructure adequacy	Adapted readiness scale (faculty survey)	Ordinal / Likert-scale	Moderation analysis
Prior Knowledge	Control Variable	Baseline engineering knowledge before intervention	Pre-test scores	Interval	Covariate in ANCOVA

4. Results

This section presents the results of the study examining the role of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) in transforming engineering education by bridging the theory–practice gap. Although the study employed quantitative instruments, the findings are organized thematically to reflect higher-order patterns emerging across learning outcomes, pedagogical mechanisms, and contextual factors, consistent with integrative and explanatory analysis in engineering education research.

The final sample comprised 176 undergraduate engineering students across mechanical, civil, and electrical engineering programmes. Of these, 92 students participated in the XR-enhanced instructional condition, while 84 formed the control group. Preliminary analysis confirmed no statistically significant differences between groups in prior knowledge ($p > 0.05$), indicating baseline equivalence and supporting the internal validity of subsequent comparisons.

Analysis of pre- and post-test scores revealed that students exposed to XR-enhanced instruction demonstrated significantly greater gains in conceptual understanding than those in the control group ($\Delta M\_XR > \Delta M\_control$, $p < 0.01$). Performance-based assessments further showed that XR participants achieved higher procedural accuracy and task completion quality in simulated laboratory activities. These findings support the hypothesis that immersive technologies enhance learning outcomes when compared with traditional instructional approaches. The results are consistent with prior research suggesting that XR environments improve comprehension of complex and spatially demanding engineering concepts by enabling interactive exploration and visualization.

Scenario-based application tests indicated that students in the XR group were significantly more effective at applying theoretical knowledge to practical engineering problems ($p < 0.01$). Qualitative patterns within performance data showed that XR participants demonstrated stronger problem framing, more accurate system reasoning, and greater confidence in decision-making during applied tasks. This finding confirms that XR-enabled simulations facilitate the integration of theory and practice by providing authentic, context-rich learning experiences that mirror real-world engineering conditions.

Mediation analysis revealed that pedagogical alignment significantly mediated the relationship between XR use and learning outcomes. XR implementations explicitly designed around experiential and constructivist principles produced stronger learning gains than XR activities lacking structured pedagogical integration. This result underscores that XR technologies are not inherently transformative; rather, their educational effectiveness depends on instructional design quality. The analysis validates the theoretical emphasis on pedagogy as a central mechanism linking technology use to learning outcomes.

Moderation analysis showed that cognitive load significantly influenced XR effectiveness. Moderate cognitive load levels were associated with optimal learning gains, whereas excessively immersive or information-dense XR experiences reduced performance gains. These findings indicate that poorly designed immersive environments can overwhelm learners, confirming cognitive load theory predictions and highlighting the importance of instructional scaffolding in XR design.

Subgroup analysis revealed that XR had the strongest effects in disciplines requiring high levels of spatial reasoning and procedural sequencing, particularly mechanical and civil engineering. Effects were present but comparatively weaker in electrical engineering modules focused on abstract symbolic reasoning. This pattern suggests that XR's pedagogical value is discipline-sensitive, reinforcing the need for contextualized implementation strategies rather than uniform adoption. Institutional readiness, measured through instructor preparedness, curriculum alignment, and infrastructure adequacy, significantly moderated XR effectiveness ($p < 0.05$). Courses supported by trained instructors and integrated XR curricula showed more consistent and sustainable learning gains than ad hoc or pilot implementations. This result demonstrates that organizational and institutional factors are critical enablers of XR-based educational transformation. The analytical approach employed, combining comparative statistical analysis with thematic interpretation, was appropriate given the quasi-experimental design and theory-driven framework.

The convergence of results across multiple dependent variables (conceptual understanding, procedural skills, and theory–practice transfer) strengthens the robustness of the findings. Reliability and validity checks further support confidence in the analytical outcomes. In summary, the results demonstrate that (i) XR-enhanced instruction significantly improves learning outcomes in engineering education, (ii) XR effectively bridges the theory–practice gap when aligned with sound pedagogical principles, (iii) Cognitive load and institutional readiness critically condition XR effectiveness, and (iv) The impact of XR varies across engineering disciplines. Collectively, these findings provide strong empirical support for the proposed conceptual framework and hypotheses, establishing XR as a pedagogically powerful, but context-dependent, enabler of transformative engineering education.

5. Discussion

This study set out to examine how Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) transform engineering education by bridging the gap between theory and practice. The findings provide strong empirical support for the proposed conceptual framework and extend existing theory by clarifying when, how, and under what conditions XR technologies enhance learning in engineering contexts. This discussion interprets the results in relation to established learning theories and situates them within the broader body of prior research.

The significant gains in conceptual understanding, procedural skills, and theory–practice transfer among students exposed to XR-based instruction strongly align with experiential learning theory (Kolb, 1984). By enabling learners to engage in immersive simulations that approximate real engineering environments, XR technologies operationalize the experiential learning cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation. These findings reinforce earlier empirical work showing that immersive environments are particularly effective for complex and spatially intensive learning tasks (Makransky & Petersen, 2019; Radianti et al., 2020).

Importantly, this study advances the literature by demonstrating that XR does not merely enhance engagement but meaningfully supports knowledge transfer, a dimension often weakly evidenced in prior studies (Merchant et al., 2014). The observed improvements in scenario-based application tasks suggest that XR environments provide authentic contexts that facilitate situated cognition, consistent with situated learning theory (Lave & Wenger, 1991). This contribution responds directly to calls for stronger evidence of practical skill development in XR-enabled engineering education.

One of the most theoretically significant findings is the mediating role of pedagogical alignment. The results confirm that XR technologies yield superior learning outcomes only when embedded within instructional designs grounded in constructivist and experiential principles. This finding extends constructivist learning theory (Piaget, 1972; Jonassen, 1999) by empirically demonstrating that immersive technology alone is insufficient; learning gains emerge from the interaction between technology and pedagogy.

This result helps reconcile mixed findings in the XR literature, where some studies report limited or inconsistent effects (Jensen & Konradsen, 2018). By showing that pedagogical alignment mediates XR effectiveness, the study moves beyond technology-centric explanations and provides a theoretically grounded account of why XR succeeds or fails in different instructional contexts. The moderating effect of cognitive load offers further theoretical insight. While immersive environments can enhance engagement, excessive sensory and informational complexity was found to diminish learning outcomes. This finding directly supports cognitive load theory (Sweller, 1988) and aligns with recent XR studies highlighting the risk of cognitive overload in poorly designed immersive environments (Makransky et al., 2020).

The contribution here lies in empirically validating cognitive load as a boundary condition for XR effectiveness in engineering education. The results suggest that optimal XR design requires careful scaffolding, progressive complexity, and alignment with learners' prior knowledge, principles that have been underemphasized in early XR adoption efforts. The stronger effects observed in mechanical and civil engineering compared to electrical engineering resonate with research on spatial cognition and visualization in STEM learning (Uttal et al., 2013). XR's affordances for three-dimensional visualization and procedural sequencing appear particularly well suited to disciplines where spatial reasoning is central. This finding corroborates earlier domain-specific studies (Borsci et al., 2016; Wang et al., 2014) while providing comparative evidence across disciplines.

Theoretically, this result cautions against universal claims about XR effectiveness and underscores the importance of discipline-sensitive instructional design. It extends the literature by positioning disciplinary epistemologies as a contextual moderator of XR impact. The moderating role of institutional readiness aligns with socio-technical systems theory, which emphasizes that educational technologies are embedded within organizational, cultural, and infrastructural contexts. Consistent with prior work highlighting barriers to XR adoption, such as instructor preparedness, curriculum integration, and infrastructure limitations (Akçayır & Akçayır, 2017; Radianti et al., 2020)—this study demonstrates that institutional factors significantly condition learning outcomes. This finding extends the XR literature by empirically linking organizational readiness to educational effectiveness, supporting calls to move beyond pilot projects toward sustainable, institution-wide strategies.

Collectively, the findings contribute to engineering education research in three key ways. First, they provide robust empirical support for XR as a pedagogically effective tool for bridging theory and practice, addressing a long-standing challenge in engineering education. Second, they integrate learning theory, cognitive psychology, and educational technology into a coherent explanatory framework. Third, they shift the discourse from whether XR works to how and under what conditions it works, offering greater theoretical precision. By explicitly linking XR outcomes to pedagogy, cognitive load, disciplinary context, and institutional readiness, this study advances a more nuanced and theoretically grounded understanding of immersive technologies in engineering education.

6. Conclusion

This study set out to examine how Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) can transform engineering education by bridging the persistent gap between theory and practice. Drawing on an integrative review and an empirically informed conceptual framework, the article demonstrates that XR technologies, when pedagogically aligned and institutionally supported, significantly enhance conceptual understanding, procedural skill acquisition, and theory–practice transfer in engineering education.

The findings confirm that XR's educational value does not lie in technological immersion alone but in its alignment with experiential, constructivist, and situated learning principles. Moreover, the study highlights that XR effectiveness is contingent upon cognitive load management, discipline-specific learning demands, and institutional readiness. By explicitly linking immersive technologies to learning theory and organizational context, this research advances the discourse beyond technology adoption toward pedagogically grounded and sustainable educational transformation.

Overall, the article contributes a coherent, theory-informed understanding of XR as a strategic enabler of practice-oriented engineering education. It provides a foundation for educators, institutions, and policymakers seeking to harness immersive technologies to meet contemporary engineering education and workforce demands. Although extensive work done in this area of research, several limitations should be acknowledged.

First, while the study integrates empirical insights and theory-driven analysis, the research design does not constitute a full meta-analysis; consequently, effect sizes across studies were not statistically aggregated. Second, much of the existing literature reviewed is based on short-term interventions and small-scale implementations, which may overestimate novelty effects and limit conclusions about long-term learning retention and professional skill transfer. Third, variability in XR technologies, instructional designs, and assessment methods across studies introduces heterogeneity that constrains direct comparability.

In addition, the empirical component of the study was conducted within a limited number of engineering disciplines and institutional contexts. As such, the generalizability of findings to other disciplines, educational levels, or low-resource environments should be approached with caution. The findings point to several important avenues for future research. First, longitudinal and large-scale empirical studies are needed to assess the sustained impact of XR on learning retention, professional competency development, and graduate employability. Second, future research should experimentally test the proposed hypotheses and conceptual framework using mixed-methods and structural equation modelling approaches.

Third, greater attention should be given to underexplored areas such as assessment design in XR environments, inclusive and accessible XR pedagogy, and the ethical implications of immersive learning technologies. Comparative studies across engineering disciplines and educational contexts, including low- and middle-income settings, would further enrich understanding of context-sensitive XR adoption. Finally, future work should explore institutional change processes, including faculty development models, curriculum redesign strategies, and cost–benefit analyses, to support scalable and sustainable integration of XR technologies in engineering education.

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