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Immersive Learning through Virtual Reality: A New Paradigm in Chemical Engineering Education

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Abstract

Traditional chemical engineering education faces persistent challenges, as lecture-based instruction and limited laboratory access restrict students' engagement, practical skill development, and comprehension of complex engineering concepts. In overcoming these challenges, immersive virtual reality (VR) learning environments are increasingly being adopted to enhance students' visualization, interactivity, and experiential learning. Therefore, this study aims to explore how VR can transform chemical engineering education by enhancing student engagement, conceptual understanding, and practical learning experiences. This review also analyzed and mapped research trends in the application of VR for immersive learning in chemical engineering education using keywords like "Immersive Learning", "Virtual Reality", "Chemical Engineering" and "Chemical Engineering Education". Accordingly, the keyword co-occurrence analysis revealed four thematic clusters linked to immersive visualisation, collaborative VR learning, VR–AI integration, and safety-oriented training. Based on these findings, a four-stage curriculum integration model is proposed (pre-conceptual familiarisation → immersive experimentation → hybrid transfer → real-lab validation). A comparative cost analysis indicates that although VR-based learning demands a higher upfront investment, it achieves cost parity within approximately 1.5 years and reduces total training expenses by about 40–45% in the third year, offering greater economic advantage for larger student cohorts. Finally, the synthesis indicates that VR can enhance conceptual understanding, hazard-awareness, and systems-level reasoning while improving utilisation efficiency in laboratory-intensive programmes. Future research should prioritise controlled cohort comparisons and longitudinal verification of transferability to physical plant behaviour.

Keywords: Chemical Engineering Education; Curriculum Integration; Experiential Simulation; Immersive Learning; Virtual Reality

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INTRODUCTION

In recent years, advancements in technology, which gave rise to digitalization and industrialization 4.0, have taken centre stage in shaping the global educational landscape, offering educators more effective, inclusive, and viable teaching and learning models. These emerging technologies, such as virtual and augmented environments, have long been applied in training contexts; however, their adoption in education has only gained traction in recent years due to earlier technical limitations (Chen et al., 2024; Kumar et al., 2021). Unlike traditional teaching resources, which are often confined to specific physical locations or limited to a few elite institutions, virtual environments eliminate these spatial and institutional barriers, offering broader accessibility. A key advantage of virtual environments is that the platforms can be easily replicated and accessed by anyone with compatible devices (Kumar et al., 2021). Moreover, advancements in technology, particularly the availability of affordable head-mounted displays (HMDs) and mobile devices, have further enhanced the accessibility and adoption of virtual learning platforms (Udugama et al., 2023). Studies reported by Cevikbas et al., (2023), Garzón et al., (2019), and Garzón & Acevedo, (2019) highlighted the significant improvements in students' learning experiences using virtual environment applications.

However, the need for dedicated hardware has continued to limit accessibility and drive-up initial capital costs. As digital technologies continue to mature, advancements in computing power, graphics processing, and immersive interface design have led to the development of VR, enabling realistic simulations and interactive environments for enhanced learning and experimentation in chemical engineering education (Udugama et al., 2023). VR refers to an immersive, interactive three-dimensional (3D) computer-generated environment that allows users to experience and engage with a simulated setting as if they were physically present within it (Hamad & Jia, 2022). Through the use of specialized hardware such as HMDs and sensory input systems, VR creates convincing perceptions of real-world presence and interaction (Bamodu & Ye, 2013). As part of the broader spectrum of mixed reality technologies, VR provides an innovative platform for teaching and learning, enabling the visualization and exploration of concepts that are difficult to demonstrate through conventional lecture methods (Radianti et al., 2020). Its versatility has led to widespread adoption in diverse sectors, including the development of virtual flight simulators, surgical training systems, and driving simulation programs (Schofield, 2012).

Beyond its benefits for advancing education and bringing students closer to interactive and engaging learning experiences, VR fosters deeper understanding through experiential learning. They enable learners to visualize complex concepts, explore simulated environments safely, and collaborate in real time regardless of physical location (Analyti et al., 2024; Crogman et al., 2025). Yet, their widespread adoption still depends on overcoming certain shared challenges. For instance, the substantial computational power needed to run VR environments further constrains their accessibility. Moreover, VR use can induce motion sickness in certain individuals, posing challenges for its adoption in educational settings that prioritize inclusivity (Di Lanzo et al., 2020; Weech et al., 2020). In the same vein, AR technologies face comparable limitations, such as the absence of tactile feedback, potential distractions from conventional learning tasks, and a steeper learning curve (Crogman et al., 2025; Mohammadhossein et al., 2025). These challenges, however, can be alleviated through effective classroom management, such as active supervision, and by integrating AR applications with hands-on, experiential learning activities.

In the chemical engineering discipline, industrial plant visits are occasionally offered as part of learning modules designed to bridge the gap between practical industrial experiences. However, their frequency is often restricted by logistical and financial constraints (Kumar et al., 2021). Virtual environments provide an effective alternative or complement to these traditional teaching methods by delivering content in a more immersive and interactive manner. Furthermore, in sub-domains of chemical engineering, such as process engineering and safety, biochemical engineering, and industrial process engineering, where many operations involve hazardous substances or potentially dangerous conditions, virtual environments provide a powerful tool for realistic simulation. They allow students to experience and understand complex industrial processes while ensuring safety through controlled, risk-free learning environments (Gani et al., 2020; Udugama et al., 2023). The advent of the COVID-19 pandemic, which resulted in a global shutdown, served as a major catalyst for the widespread adoption of virtual learning modules. During and after the pandemic, the ability to access learning resources remotely without relying on specialized hardware became increasingly important in selecting new teaching media.

However, despite this potential, VR adoption in chemical engineering education remains fragmented. Most existing work prioritises platform development rather than evaluating curriculum integration, learning assessment structures, or institutional economic justification. Only a few broader engineering reviews exist such as (Chan et al., 2021) surveyed VR across engineering domains, and (Udugama et al., 2023) analysed immersive technologies in STEM but neither offered chemical-engineering-specific bibliometric mapping, nor did they examine VR through a combined pedagogical integration and cost-benefit lens. This constitutes the novelty space of the present contribution. Accordingly, this review (i) maps VR-related research outputs relevant to chemical engineering using a Scopus bibliometric dataset retrieved through an Engineering education–proximal query (not strictly ChemE-only due to cross-domain inheritance of VR modules), (ii) proposes a four-stage curriculum integration model for VR as a scaffold within chemical engineering learning sequences, and (iii) evaluates the cost–benefit justification of VR relative to conventional laboratory expenditure profiles. The scope is therefore confined to VR for teaching/learning in chemical engineering, and not VR for plant design or industrial XR deployment. This analytical framing positions VR not as a novelty simulation, but as a potential pedagogically aligned and economically rational teaching innovation within laboratory-intensive engineering programmes.

The objective of this review is to generate a consolidated and evidence-informed understanding of how VR is currently positioned within chemical engineering education by systematically mapping research output patterns, disciplinary contribution profiles, and thematic evolution based on a Scopus-indexed bibliometric dataset. Beyond enumerating publication activity, this review seeks to interpret how VR may be pedagogically sequenced within chemical engineering curricula by proposing a four-stage instructional integration model that transitions VR from a pre-conceptual familiarisation tool toward a scaffold for higher-order laboratory reasoning and process-systems cognition. In parallel, this study evaluates VR feasibility from an institutional perspective by synthesising comparative cost information to characterise the breakeven conditions, marginal repetition cost, and resource utilisation profiles that differentiate VR from conventional laboratory expenditure patterns. Collectively, the intention is to clarify the conceptual, pedagogical, and economic rationale that would enable VR to progress from experimental demonstration toward scalable and sustainable institutional deployment in chemical engineering education.

METHOD

Study design and reporting

This work is a bibliometric study of research on virtual reality (VR) in chemical engineering education. The workflow followed the identification–screening–eligibility–inclusion logic commonly reported with PRISMA flow diagrams, and comprised database searching, screening against prespecified criteria, data extraction and cleaning, descriptive bibliometrics, and network analysis.

Data source and coverage

All records were retrieved from Elsevier's Scopus database (https://www.scopus.com). The temporal window covered publications from 2015 through 2025 (inclusive). At the retrieval stage, all source types and all document types were permitted. Language was restricted to English. The search was executed on 10 October 2025 and the records were exported as comma-separated values (CSV) for analysis.

Search strategy

An advanced Scopus query targeted terms for immersive technologies and the disciplinary/educational focus, spanning titles, abstracts, and author keywords (TITLE-ABS-KEY), and was developed following established guidance for comprehensive, reproducible database searches (Bramer et al., 2018). The strategy centred on the phrases "immersive learning," "virtual reality," "chemical engineering," and "chemical engineering education." Exact query (Scopus Advanced Search): *TITLE-ABS-KEY(("virtual reality" OR "immersive learning") AND ("chemical engineering" OR "chemical engineering education"))*

Database filters applied after the query: publication years 2015–2025; language = English; all source types; all document types. The query was chosen to maximize recall for VR/immersive learning in chemical engineering education while retaining all indexed publication formats for subsequent descriptive analysis.

Eligibility criteria

The eligibility rules were as follows: inclusion required Scopus-indexed records (2015–2025, English) addressing VR or immersive learning within chemical engineering or chemical engineering education, with no restriction on document or source type; exclusion removed duplicates, off-topic items, records with insufficient bibliographic metadata for analysis, and papers flagged as retracted at screening. A detailed breakdown appears in Table 1.

Table 1. Eligibility criteria.

Category	Criteria
Inclusion	Scopus-indexed records (2015–2025, English) addressing VR or immersive learning within chemical engineering or chemical engineering education; any document type; any source type.
Exclusion	Duplicates; off-topic items; records with incomplete bibliographic data; and records marked as retracted at screening (excluded and counted in PRISMA removals).

Screening and PRISMA flow

All retrieved records were imported into Microsoft Excel for deduplication and two-stage screening (title/abstract followed by full-record checks for borderline cases). As illustrated in Figure 1, the PRISMA flow is summarized as follows: records extracted and screened n = 2,950; records removed n = 10; records included in the bibliometric analysis n = 2,940. At retrieval, the 2,950 records comprised 1,587 articles, 557 conference papers, 411 reviews, 190 book chapters, 187 books, 4 notes, 2 editorials, 1 short survey, and 1 data paper; five retracted records were flagged and excluded during screening.

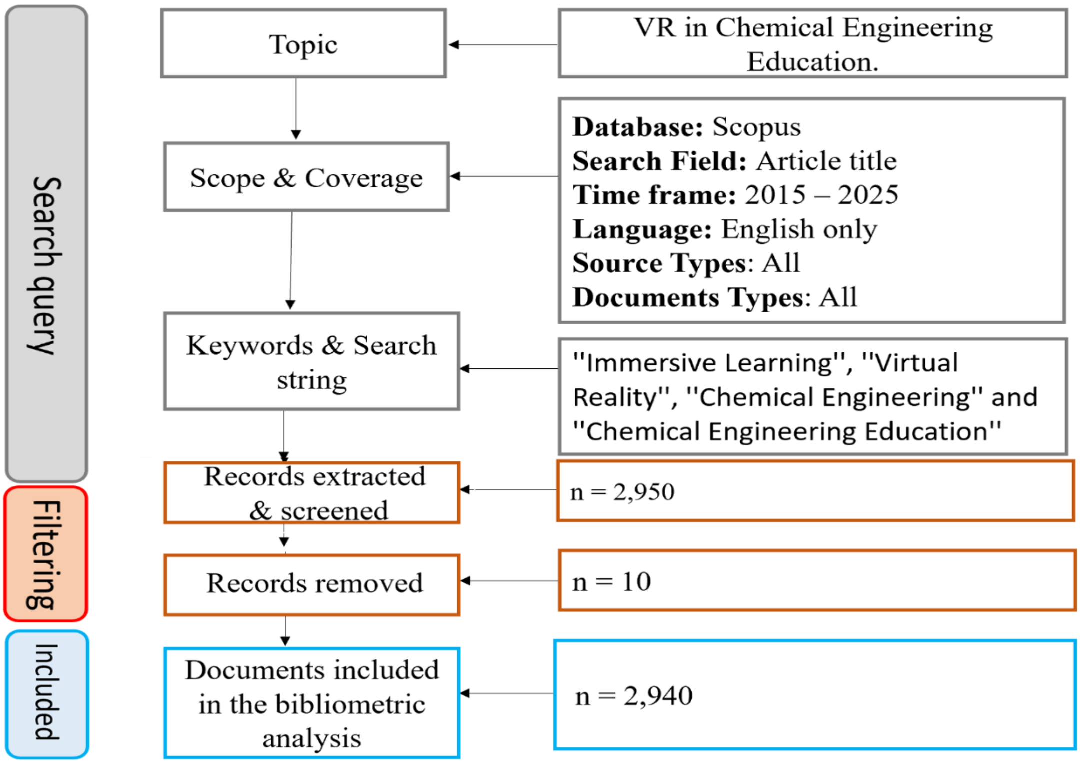

Figure 1. A PRISMA flow chart for the data processing and analysis

Data extraction and cleaning

From each included record, the following fields were extracted: publication year, document type, source type, authors, affiliations, countries/territories, author keywords and index terms, subject areas, citation counts, and funding data when available. Data cleaning involved (i) harmonizing author and institution names, (ii) standardizing country names, (iii) unifying spelling variants and singular/plural forms in keywords, and (iv) removing residual duplicates. Transformations were logged to maintain reproducibility.

Bibliometric indicators

Descriptive indicators computed on the final included set comprised: annual publication counts; distributions by document and source type; most prolific authors, institutions, and countries; and citation counts. Indicator tables and figures are presented in the Results section.

Network analysis and visualization

Keyword co-occurrence networks were constructed in VOSviewer v1.6.18. The unit of analysis was author and index keywords. The counting method was full counting. A minimum occurrence threshold of **10** was applied; out of the extracted keyword set, 111 keywords met this threshold and were mapped. Default VOSviewer normalization and clustering were used. Parameter choices were set a priori and reported for transparency and reproducibility (Majhi et al., 2023). Network maps report node sizes (occurrence frequencies), links (co-occurrences), and total link strengths, and are accompanied by ranked keyword tables.

Software

Screening and tabulation were performed in Microsoft Excel. Network mapping and visualizations were produced with VOSviewer v1.6.18; figures were exported directly from VOSviewer.

Reproducibility and data availability

The exact query string and search date are reported above. The raw Scopus CSV export and the cleaned dataset used for analysis can be shared as supplementary files upon request to facilitate replication.

Ethics

This study used bibliographic metadata only and did not involve human participants or confidential data; formal ethics approval was not required.

RESULTS AND DISCUSSION

Yearly research output patterns across document and source types

As a virgin technology, the use of VR in chemical engineering education is currently at the developmental and exploratory stage, where research efforts are primarily focused on proof-of-concept demonstrations, prototype simulations, and assessing its pedagogical value relative to traditional teaching approaches. However, this study's analysis of 2,950 documents and source types reveals significant insights into the publication landscape of the work carried out. Journal articles formed the majority, with 2,020 entries (68.47%), reaffirming the dominance of peer-reviewed journals as the primary medium for disseminating scientific knowledge. Conference Paper ranked second with 437 publications (14.8%), as shown in Table 2.

Book (331; 11.22%) and Book Series (161; 5.45%) made smaller yet meaningful contributions, often offering comprehensive, in-depth content tailored to both academic and professional audiences. However, other format, like Trade Journal (01), was sparsely represented, suggesting limited use of the research domain (Bramer et al., 2018). Overall, these findings emphasize the strong preference for journal-based outputs in academic publishing. The prevalence of peer-reviewed articles highlights their role in ensuring research visibility, credibility, and impact, an approach aligned with current trends in scholarly communication (Majhi et al., 2023).

The analysis of publication trends in the last decade reveals a significant increase in research output, evident in both the yearly contributions and the variety of document types. The data presented in **Fig. 2** shows a clear upward trend in the number of publications related to the use of VR in chemical engineering between 2015 and 2025. From 2015 to 2018, the research output remained relatively low, with only a modest increase from 24 publications in 2015 to 61 in 2018, reflecting the nascent stage of VR adoption in engineering education during this period. This slow growth can be attributed to limited technological maturity, high equipment costs, and a lack of awareness of VR's pedagogical potential.

Table 2. Document and source types

		Frequency	Percentage (%)
Document	Articles	1587	53.79
	Conference paper	557	18.88
	Reviews	411	13.93
	Book chapters	190	6.44
	Book	187	6.23
	Retracted	10	0.33
	Note	04	0.13
	Editorial	02	0.068
	Short Survey	01	0.033
	Data paper	01	0.033
	Total	**2,950**	**100**
Source	Journal	2,020	68.47
	Conference proceedings	437	14.8
	Book	331	11.22
	Book Series	161	5.45
	Trade Journal	01	0.033
	Total	**2950**	**100**

A noticeable acceleration begins around 2019, with publications rising sharply from 86 in 2019 to 233 in 2021, indicating a growing research interest and technological advancement in immersive learning tools. This period coincides with increased accessibility of affordable VR devices and the growing recognition of digital learning technologies, particularly during the COVID-19 pandemic, which spurred global adoption of virtual learning environments. Between 2022 and 2025, the data show a substantial surge, with publications increasing from 356 in 2022 to a peak of 767 in 2024, before slightly decreasing to 728 in 2025. This pattern suggests that VR has transitioned from an emerging to a maturing research domain within chemical engineering education.

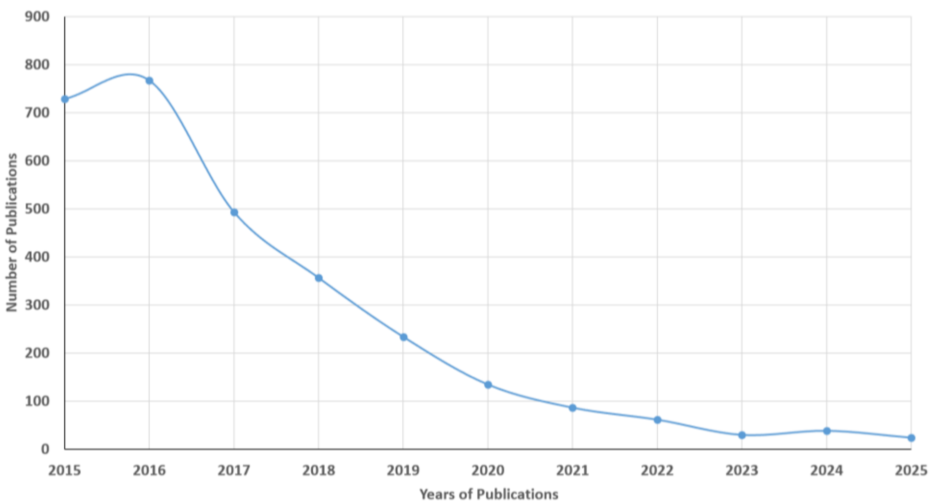

Figure 2. Research output dynamics (2015–2025), for VR in chemical engineering education based on the Scopus Database

The high publication volume during this period reflects intensified exploration of VR applications in laboratory simulations, process visualization, and safety training. Overall, the trend indicates a progressive and sustained growth in scholarly attention toward VR, with the slight decline in 2025 possibly signalling stabilization or saturation as research begins to consolidate around practical implementation, evaluation of learning outcomes, and integration into curricula rather than exploratory development.

Keywords co-occurrence analysis and visualization map

VOSviewer was employed to perform a keyword co-occurrence analysis aimed at identifying the core research themes and emerging trends related to the use of VR in chemical engineering education. In the visualization (Fig. 3), keywords appear as colored circles where the size represents their frequency of occurrence and are grouped into distinct thematic clusters that illustrate the conceptual structure of the field. Full counting was adopted to treats each keyword co-occurrence equally, making it useful for smaller datasets or highlighting frequently occurring terms. A minimum occurrence threshold of 10 was applied, and out of 5,137 extracted keywords, 111 met the inclusion criteria (Bukar et al., 2023). These clusters collectively map the interrelationships among key research terms, providing a comprehensive overview of the intellectual and thematic landscape of VR applications in chemical engineering education. Notably, the top-fifteen keywords with the corresponding total link strengths are presented in Table 3.

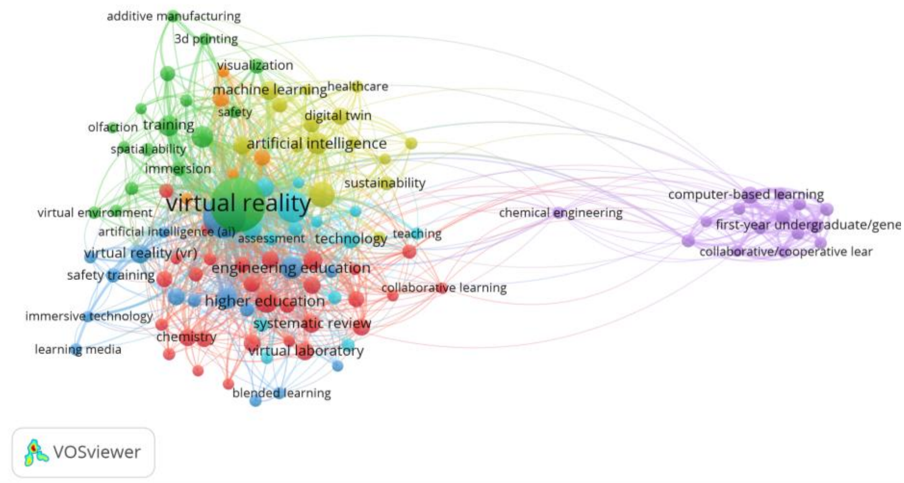

Figure 3. Visualization map of keyword clusters and linkages

The Green Cluster in the VOSviewer keyword analysis highlights the central role of VR in enhancing immersive and visualization-based learning in chemical engineering education. Keywords such as *spatial ability*, *immersion*, *3D printing*, and *virtual environment* emphasize how VR strengthens students' spatial reasoning, conceptual understanding, and engagement through interactive 3D simulations. The cluster reflects a growing pedagogical shift toward experiential, visualization-driven learning, where VR bridges theoretical concepts with practical, hands-on comprehension in engineering contexts

The Purple Cluster emphasizes the role of VR as a computer-based and collaborative learning tool in chemical engineering education. It highlights how VR technologies support interactive, team-oriented learning environments, enabling students to engage in shared virtual experiments and problem-solving tasks. This cluster reflects the shift from traditional individual learning toward digital, cooperative approaches, where VR enhances communication, teamwork, and applied understanding of chemical engineering concepts.

Table 3. Top-fifteen keywords and their occurrences with total link strengths

Rankings	Keywords	Occurrences	Total link strengths
1.	Virtual reality	507	707
2.	Augmented Reality	269	448
3.	Education	123	255
4.	Training	45	89
5.	Engineering education	53	82
6.	Higher education	54	90
7.	Artificial intelligence	53	83
8.	Machine learning	36	57
9.	Virtual Reality (Vr)	36	52
10.	Systematic review	32	54
11.	Digital twin	28	51
12.	visualization	21	32
13.	Computer-based learning	27	79
14.	First year undergraduate	22	79
15.	sustainability	17	25

The Yellow Cluster reflects the integration of emerging digital technologies such as *Artificial Intelligence (AI), Machine Learning (ML), and Digital Twin* systems with VR applications in chemical engineering education. In this context, the cluster represents a movement toward intelligent and data-driven immersive learning environments that simulate real-time process operations, optimize safety training, and promote sustainability awareness. It highlights how combining VR with AI and digital twins can create smart virtual laboratories that replicate complex industrial systems, allowing students to analyze performance, predict risks, and design more sustainable chemical processes within a safe and controlled virtual space.

The Red Cluster centres on the educational application and institutional adoption of VR within engineering and higher education. Its keywords such as *engineering education*, *higher education*, *virtual learning*, and *safety* emphasize the growing recognition of VR as a transformative teaching and learning tool that enhances engagement, improves safety awareness, and complements traditional laboratory training. The key takeaway is that VR is increasingly being integrated into formal engineering curricula to provide safe, flexible, and immersive learning experiences, preparing students for real-world industrial environments while reducing the risks and costs associated with physical experiments.

Most active institutional research contributors on VR

The bibliometric mapping of institutional outputs, presented in Fig. 4, provides a visual representation of the global research landscape on VR in chemical engineering education. A minimum document threshold of five publications per institution was applied, and out of 4,171 organizations, only 59 met the criteria, reflecting the selective distribution of research productivity within this emerging field. The analysis offers valuable insights into the key institutional contributors and their geographical spread (Table 4), highlighting active centres of research excellence across multiple continents. Prominent institutions identified in the network visualization include Curtin University (Australia), KU Leuven (Belgium), Kryvyi Rih National University (Ukraine), Consiglio Nazionale delle Ricerche (Italy), Tambov State University (Russia), Beijing Normal University (China), Harvard University (USA), Universitas Negeri Padang (Indonesia), University of Glasgow (UK), Virginia Tech College (USA), Universitas Negeri Jakarta (Indonesia), Amity University (India), Purdue Polytechnic Institute (USA), Chitkara University (India), and Universitas Pendidikan Indonesia.

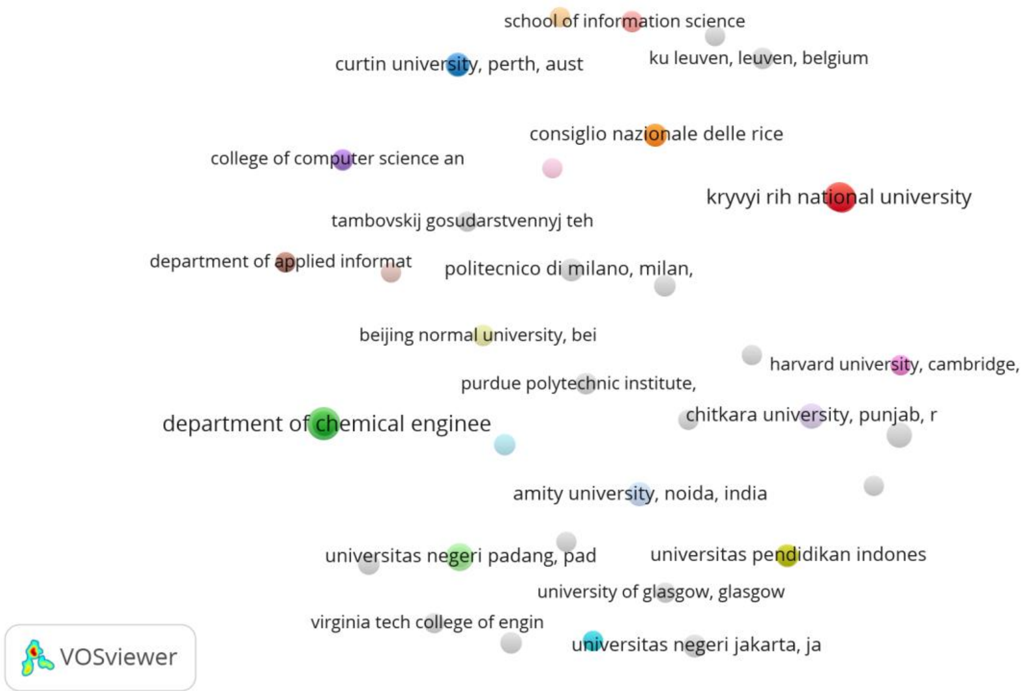

Figure 4. Visualization map of institutional clusters and linkages

The distribution and visibility of these institutions on the map demonstrate a diverse international engagement, suggesting that research on VR applications in chemical engineering is globally dispersed yet thematically interconnected (Bello et al., 2025). However, the weak correlation and sparse linkages observed across clusters indicate a lack of robust global collaboration, implying that institutional efforts are largely independent rather than synergistic. This fragmentation underscores the need for stronger international partnerships and cross-institutional research networks to advance the field more cohesively. For example, the introduction of joint VR-based curriculum initiatives between leading universities or international chemical engineering education consortia would serve as a gateway for promoting collaborative engagement and further opens avenue for growing the visibility of the technology's adoption (Abbas Shah et al., 2024). Furthermore, the variation in circle size and citation link density among institutions reflects differences in research output, visibility, and influence, offering a practical lens through which scholars can identify potential collaborators and high-impact institutions for future research endeavours (Thakkar et al., 2025). Overall, the bibliometric mapping underscores both the growing global interest and the existing collaboration gap in leveraging VR technologies to transform chemical engineering education.

Table 4. The top fifteen institutions, with the highest number of documents, citation counts, and total link strengths

Rankings	Name of Institution	Country	Documents	Citations	Total link strength
1.	KU Leuven	Belgium	17	331	8
2.	Kryvyi Rih National University	Ukraine	12	101	49
3.	Universitas Negeri Padang	Indonesia	11	213	3
4.	Chitkara University, Punjab	India	9	130	0
5.	Curtin University	Australia	8	239	1
6.	Amity University	India	8	14	0
7.	Consiglio Nazionale delle Ricerche	Italy	7	45	4
8.	Universitas Negeri Jakarta	Indonesia	7	67	0
9.	Universitas Pendidikan Indonesia.	Indonesia	7	115	3
10.	Purdue Polytechnic Institute	USA	6	459	0
11.	Beijing Normal University	China	6	658	0
12.	Harvard University	USA	5	814	1
13.	Stanford University, Stanford,	USA	5	564	1
14.	University of Glasgow	UK	5	63	0
15.	Virginia Tech College	USA	5	44	0

Vr-Assisted Laboratory Work Demonstrations in Chemical Engineering Education

In recent years, VR has gained significant attention as a transformative educational tool in chemical engineering, particularly for enhancing laboratory work demonstrations. Traditional chemical engineering laboratories often demand considerable investment in physical infrastructure, reagents, and safety measures (Oveissi & Ebrahimi Ghadi, 2022; Zhou et al., 2024). Additionally, the inherent risks associated with experiments involving hazardous chemicals, elevated pressures, or extreme temperatures frequently restrict student participation and practical exposure. VR technology, whose classification comprises immersive and non-immersive types (Fig. 5), provides innovative solutions to these limitations by offering immersive, interactive, and risk-free environments that replicate real laboratory conditions. The platform creates a completely digital workspace in which learners can perform simulated experiments using virtual instruments and materials, supported by tools and devices for channelising education. For instance, a VR-based distillation column simulator enables students to adjust parameters such as feed composition or reflux ratio and immediately visualize the effects on separation efficiency (Gao et al., 2023). Such digital experimentation deepens conceptual understanding, strengthens process intuition, and builds confidence prior to handling actual laboratory setups.

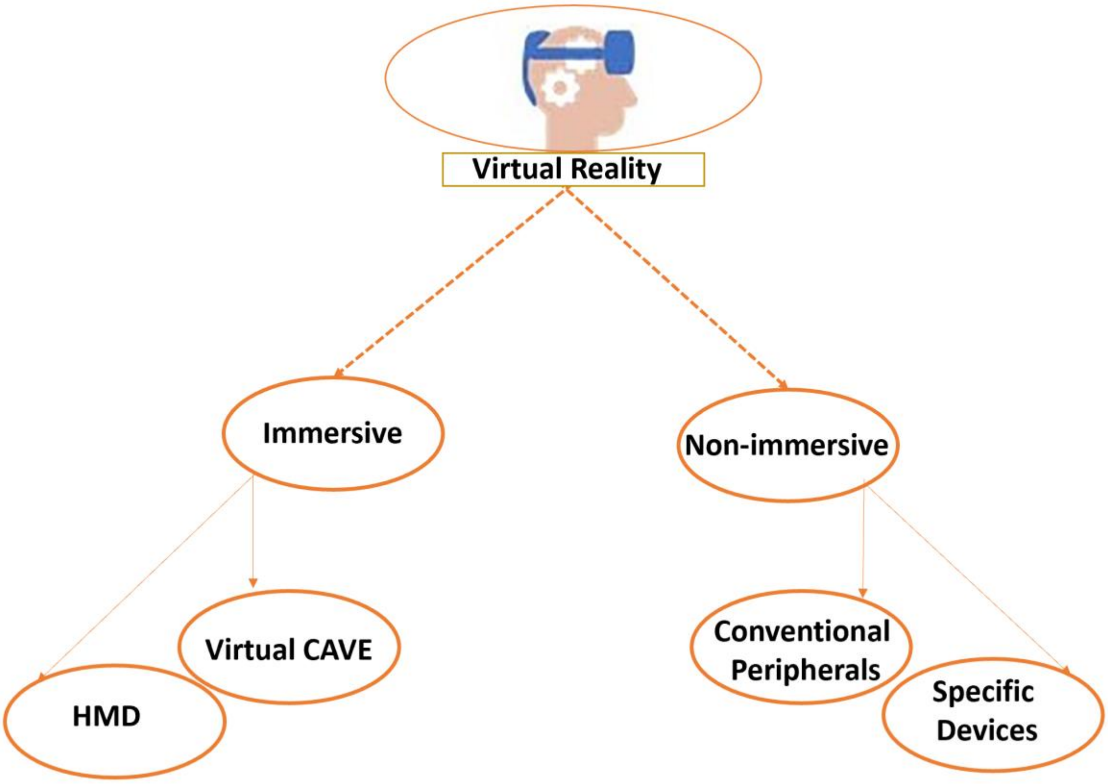

Figure 5. The Taxonomy of VR classification

While VR creates a fully virtual world is ideal for simulating hazardous or complex large-scale processes and subsequently enables students to explore and interact with virtual laboratory systems safely and cost-effectively. An AR overlays digital information onto real laboratory settings to enhance visualization, data interpretation, and procedural accuracy during actual experiments (Lastrucci et al., 2024; Singh & Ahmad, 2024). Therefore, VR and AR represent two distinct yet complementary immersive technologies in chemical engineering education. Unlike VR, AR enriches physical laboratory experiences by superimposing digital information onto real-world apparatus. Through AR-enabled devices such as tablets, smartphones, or smart glasses where students can interact with enhanced visual overlays that display molecular structures, process data, or dynamic system responses. For example, during a heat exchanger experiment, AR can project live temperature profiles, flow rates, and efficiency metrics directly onto the equipment surface, thereby improving comprehension of thermodynamic and transport principles (Kasumu et al., 2017). Collectively, VR and AR facilitate active, experiential, and student-centred learning, enabling visualization of microscopic and abstract phenomena such as reaction kinetics, heat and mass transfer, and fluid dynamics in ways traditional methods cannot achieve. Furthermore, VR/AR-assisted laboratories support remote and flexible learning, providing access to laboratory simulations anytime and anywhere. This broadens educational accessibility, minimizes dependence on costly infrastructure, and represents a paradigm shift toward digitally enhanced chemical engineering education.

Therefore, Fig. 6, shows a conceptual figure illustrating how VR and AR enhance chemical engineering education. The figure shows two parallel flows: one for VR-assisted lab work, depicting students wearing VR headsets performing simulated experiments in a fully virtual lab; and one for AR-assisted lab work, showing students using AR glasses overlaying digital data and molecular structures onto real laboratory setups. Arrows indicate stages such as design of interactive modules, simulation validation, instructor training, and curriculum integration.

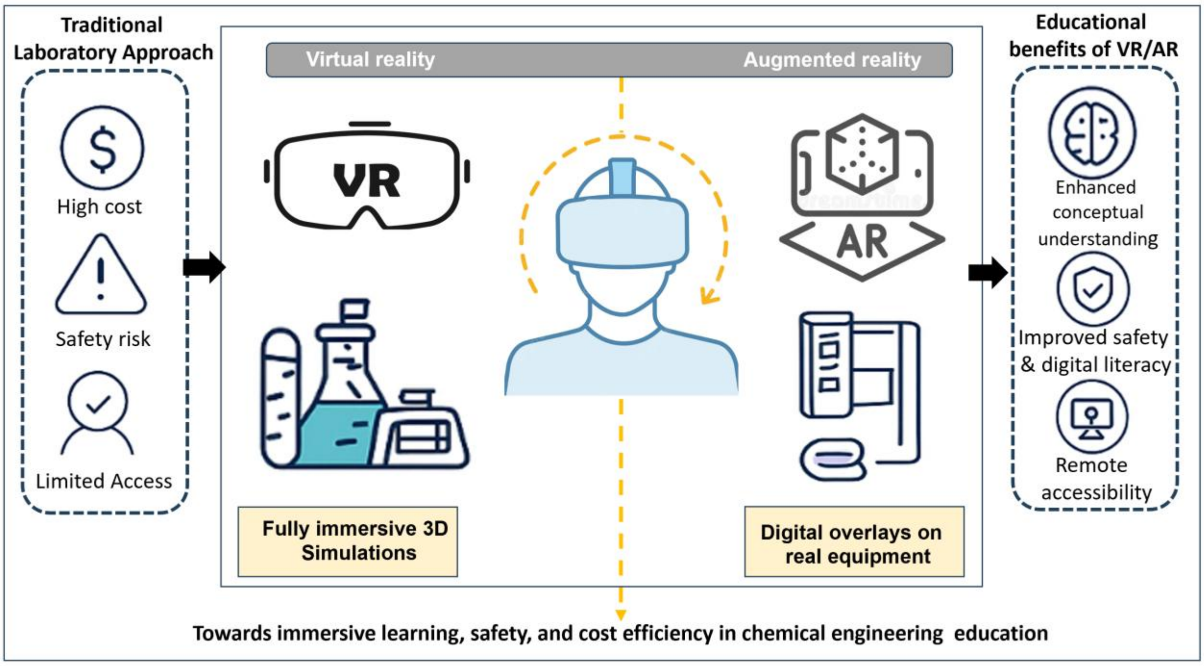

Figure 6. A conceptual figure illustrating how (VR) and (AR) enhance chemical engineering education

Technological Barriers and Educational Implications of VR in Chemical Engineering Education

The application of VR in chemical engineering education has emerged as a promising innovation for enhancing experiential and interactive learning. However, despite its growing relevance, VR integration within engineering curricula remains at an early developmental stage, facing numerous technological and pedagogical challenges that constrain its large-scale adoption (Al-Ansi et al., 2023; Jackson et al., 2025). From a technological standpoint, the implementation of VR-based learning environments requires substantial infrastructural investment and technical expertise. High-performance computing systems, HMDs, motion sensors, and immersive simulation software are essential to deliver realistic and responsive environments that accurately replicate chemical processes. The development of such environments also demands interdisciplinary collaboration, particularly between educators, computer scientists, and VR developers, to ensure the fidelity of simulations and their pedagogical relevance (Faculty of Law, Universiti Kebangsaan Malaysia, Selangor, Malaysia. et al., 2020). Furthermore, limitations such as motion sickness, reduced tactile feedback, and system calibration issues have been reported to affect user comfort and continuity of learning (Bamodu & Ye, 2013).

Sustained implementation also necessitates continuous hardware maintenance, software upgrades, and user support to maintain system reliability and functionality. Pedagogically, the integration of VR into chemical engineering education implies a significant shift from traditional lecture-based instruction to interactive, student-centred learning paradigms. Instructors are required not only to acquire technical competence in VR operation but also to redesign course structures that align with immersive and experiential learning outcomes. Studies have demonstrated that interactive VR environments enhance student engagement and conceptual understanding by providing hands-on virtual experiences and dynamic visualizations of abstract phenomena (Di Lanzo et al., 2020; Quintero et al., 2019). Within chemical engineering, VR allows learners to visualize internal operations of process equipment such as reactors, heat exchangers, and distillation columns that are often inaccessible in real laboratories due to insulation or safety restrictions (Wolfartsberger et al., 2023). Additionally, VR supports safe experimentation and exploration of hazardous or complex scenarios, including plant shutdowns, emergency responses, and process optimization exercises (Ouyang et al., 2018; Passos et al., 2016).

Pedagogically, VR requires instructors to shift from procedural demonstration toward diagnostic facilitation. Several ChemE classroom trials such as reactor start-up simulations (Ouyang et al., 2018), distillation column emergency response (Passos et al., 2016) and compressor surge troubleshooting modules (Quintero et al., 2019) demonstrated that VR can enhance conceptual reasoning, hazard awareness, and operational decision-making. However, these trials are typically short, single-cohort implementations and rarely evaluate long-term retention, post-transfer competence, or Accreditation Board for Engineering and Technology (ABET)-aligned outcome attainment (Kazdin, 2019; Liang et al., 2025). The empirical base therefore remains fragmented, with high heterogeneity in platforms, tasks, and assessment artefacts (Putrama & Martinek, 2024). This limits cross-study comparability and makes it difficult to infer stable pedagogical effect sizes. In sum, while VR offers high pedagogical value, particularly for visualising internal equipment internals that are physically inaccessible, such as tray hydrodynamics, heat exchanger fouling progression is widespread adoption is constrained by cost, technical support capacity, and the absence of validated integration frameworks (Javaid et al., 2024). Sustained progress will require co-development models in which instructional designers and ChemE subject matter experts co-specify tasks, outcomes, and assessment strategies.

Beyond safety and visualization benefits, VR has significant potential to promote collaboration and higher-order learning. Virtual environments enable students to engage in peer-based evaluations, teamwork simulations, and collaborative design activities that foster skills aligned with advanced levels of Bloom's taxonomy (Balalle, 2024). Nevertheless, despite its pedagogical promise, empirical evidence assessing the long-term impact of VR on knowledge retention, critical thinking, and practical competence remains limited. While VR represents a transformative tool for advancing chemical engineering education, its widespread adoption is hindered by technological costs, system limitations, and a lack of pedagogically validated frameworks. Addressing these challenges requires sustained multidisciplinary collaboration between educators, software engineers, and instructional designers to ensure that VR evolves from a technological novelty into a pedagogically integrated and sustainable educational practice. Table 5 summarises representative ChemE VR application domains, along with their advantages and implementation challenges.

Table 5. Areas of application for VR in chemical engineering education

Area of Application	Description	Advantages	Challenges
Process Simulation and Reactor Design	Students interactively explore chemical reactors, distillation columns, and heat exchangers in a 3D virtual plant.	Enhances understanding of scale, process flow, and safety systems; allows experimentation without real risks.	High development cost; limited tactile feedback; requires accurate process data.
Thermodynamics and Fluid Flow Experiments	Visualization of fluid dynamics, heat transfer, and phase changes in virtual systems.	Improves conceptual grasp of abstract phenomena; enables real-time visualization of molecular or bulk behaviours.	Requires high computational resources; potential motion sickness in long sessions.
Safety and Hazard Management Training	Simulated environments for learning emergency response, chemical spills, and fire safety.	Risk-free exposure to hazardous scenarios, improves decision-making and hazard perception.	May not fully replicate real pressure or panic conditions; periodic updates needed for realism.
Unit Operations and Equipment Handling	Virtual labs for pumps, compressors, separators, and filtration systems.	Reduces wear and tear on physical equipment; allows repeated practice.	Lacks the tactile sense of real equipment operation; initial software setup may be complex.
Analytical Instrumentation Training	Virtual handling of instruments like GC, HPLC, or spectrophotometers.	Enables familiarization before real lab exposure; reduces reagent costs and instrument downtime.	May oversimplify maintenance procedures or instrument calibration.
Plant Start-up and Shutdown Procedures	Students engage in VR-based control room simulations for operating processes.	Builds operational confidence; reinforces teamwork and communication.	Needs synchronization with actual control systems; risk of over-reliance on virtual cues.

Area of Application	Description	Advantages	Challenges
Environmental and Waste Treatment Simulations	Virtual representation of effluent treatment or CO_2 capture units.	Promotes understanding of sustainability processes and emission control.	Real-world variability may be hard to simulate accurately.

Pedagogical Integration Framework for Embedding VR into Chemical Engineering Curricula

Effective adoption of VR in chemical engineering education requires instructional alignment grounded in established learning theory rather than technological enthusiasm. Drawing upon principles from experiential learning (Saggar et al., 2023), cognitive load theory (Sweller, 2011), and ABET outcome categories (knowledge application, design, experimentation, teamwork, and lifelong learning) (Abo El-Nasr, 2022), a four-stage curriculum integration framework is proposed to embed VR as a scaffolded learning instrument: (i) pre-conceptual familiarisation, (ii) VR-based experiential visualisation, (iii) hybrid VR–physical laboratory transition, and (iv) real-laboratory validation and reflective consolidation as summarized in Fig. 7 based on (El-Metwally et al., 2013).

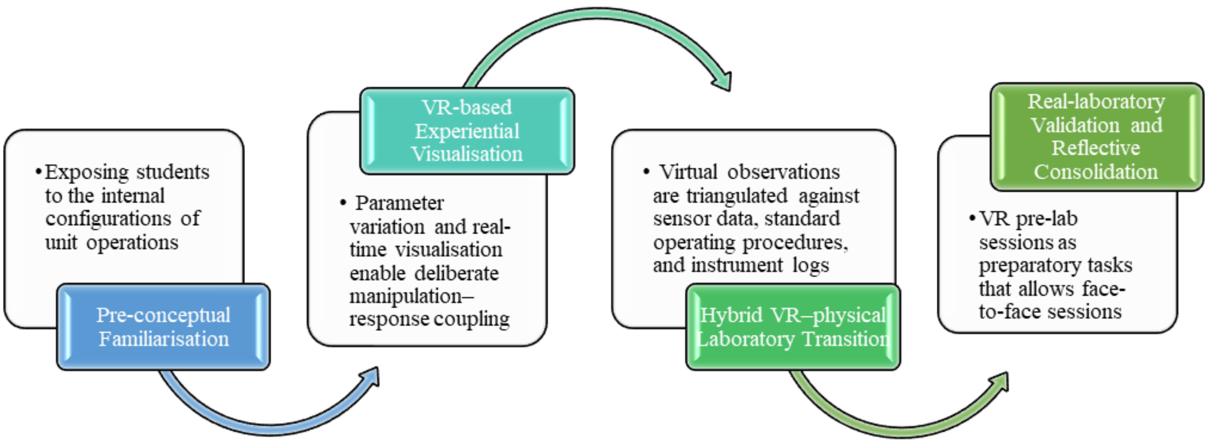

Figure 7. Structured four-stage sequencing to position VR as a scaffolded pedagogical instrument.

In the first stage, VR modules are deployed prior to conventional lectures to reduce abstraction and cognitive load by exposing students to the internal configurations of unit operations normally inaccessible during real laboratory work. In the second stage, VR becomes the active experimental environment where parameter variation and real-time visualisation enable deliberate manipulation–response coupling, thereby accelerating conceptual acquisition and procedural fluency. The third stage operationalises VR as a bridge to physical laboratory work, where virtual observations are triangulated against sensor data, standard operating procedures, and instrument logs to strengthen transferability from simulated to real contexts. The fourth stage deploys VR pre-lab sessions as preparatory tasks that reduce low-level familiarisation time in physical laboratories, allowing face-to-face sessions to prioritise higher-order tasks such as optimisation, troubleshooting, and scenario-based deviation analysis.

To illustrate how the proposed sequencing can be operationalised in real teaching contexts, Table 6 provides representative examples drawn from core chemical engineering courses. It links each stage of the VR integration framework with the corresponding course topic, immersive task design, assessment artefact, and the mechanism of transfer to the physical laboratory (Saggar et al., 2023; Sweller, 2011). This mapping demonstrates how VR activities can be systematically aligned with ABET learning outcomes and used to evaluate higher-order cognitive and practical competencies (Abo El-Nasr, 2022).

Table 6. operationalises this sequence within typical chemical engineering course contexts, linking learning outcomes, representative VR tasks, and assessment artefacts.

Course Topic	VR Task	Assessment Artefact	Transfer to Physical Lab
Fluid Mechanics / Transport Phenomena	Visualise laminar–turbulent transition and valve pressure loss in virtual piping systems	Quantitative flow analysis report and concept quiz	Calibration of pressure-drop experiments and pump curve validation
Chemical Reaction Engineering	Manipulate virtual reactor temperature and feed composition to achieve target conversion	Design memo predicting reaction yield under variable conditions	Comparison with real reactor data and temperature-control performance
Process Control and Instrumentation	Operate a simulated control room to stabilise column temperature during disturbance	Control-loop tuning record and deviation-response log	Implementation of PID settings in physical distillation column
Process Safety and Hazard Management	Execute VR-based emergency shutdown after simulated compressor surge	Reflective safety debrief and team response rubric	Evaluation of the safety checklist and hazard-identification exercise

This sequencing has implications for assessment design and instructor readiness. Instructors must reposition from procedural demonstrators to evaluators of higher-order cognition, supported by VR-enabled formative metrics such as scenario-based emergency response performance, fault-diagnosis accuracy, time-to-stability in virtual plant control tasks, and variable-space exploration efficiency (El-Metwally et al., 2013). In parallel, instructor professional development must evolve beyond basic platform operation to include instructional design for immersive media, cognitive load regulation, accessibility considerations such as cybersickness mitigation, and multi-modal alignment of VR activities to curriculum-level learning outcomes (Uzorka et al., 2023). Through this alignment, VR functions not as a substitute for physical laboratories but as an optimisation layer that restructures physical contact time toward deep reasoning tasks (Zhou et al., 2024). Accordingly, VR is framed as a pedagogically integrated driver of competency development particularly in systems-thinking, hazard perception, dynamic decision-making, and process-systems reasoning, rather than as an isolated technological artefact (Zhou et al., 2024).

This structured mapping enables direct alignment between VR learning activities and ABET performance criteria. Instructors consequently shift from procedural demonstration toward evaluating higher-order cognition using metrics such as virtual emergency-response time, fault-diagnosis accuracy, and process-stability recovery (El-Metwally et al., 2013). Professional development must extend beyond technical proficiency to include immersive-media pedagogy, equitable design, and cybersickness mitigation strategies. When sequenced as an instructional scaffold, VR functions not as a replacement for physical laboratories but as a pedagogical accelerator in which to optimise contact hours, enrich systems-thinking, and strengthen students' readiness for real-world plant environments.

Economic Considerations and Cost–Benefit Justification for VR Integration in Chemical Engineering Education

Beyond its pedagogical value, the adoption of VR in chemical engineering curricula must be economically rationalized, particularly in resource-constrained institutions where investment decisions are scrutinized against infrastructure priorities, laboratory operation costs, and annual student throughput (Zhou et al., 2024). In this context, VR offers distinctive cost–benefit characteristics that contrast with conventional laboratory infrastructure. While the initial capital expenditure for VR hardware such as head-mounted displays, compatible computing units, and development licenses remains non-trivial, the recurring operational expenditure is significantly lower (Hamad & Jia, 2022). Physical laboratories demand continuous reagent procurement, hazardous waste disposal, preventive equipment maintenance, calibration, safety compliance, laboratory personnel, and periodic refurbishment (Wang et al., 2025), thus VR laboratories incur comparatively minimal marginal costs once digital modules are developed and deployed. More importantly, VR eliminates consumables and risk-linked costs such as chemical spillage, breakage of glassware, small-scale fires, and flooded columns (Scorgie et al., 2024), thereby reducing insurance exposure, hazard mitigation overhead, and the indirect costs associated with downtime when physical equipment becomes non-operational.

The economic leverage of VR becomes more pronounced when annual student volume is considered such as digital assets are infinitely replicable, allowing repeated practice, unlimited trial-and-error experimentation, and asynchronous access without incremental cost (Javaid et al., 2024). This enables a shift from "one-shot" physical demonstrations toward iterative problem-based simulation cycles which is an approach that would be unsustainable financially in a traditional wet laboratory. VR additionally increases utilization efficiency by de-coupling laboratory access from timetabled occupancy as the virtual modules can be scaled horizontally across cohorts without requiring expansion of physical floor space, thereby reducing capital intensity per student (Chan et al., 2021). While content development requires upfront investment in 3D modelling, programming, and scenario design, these costs amortize over successive semester deployments, often resulting in lower cost-per-learner after only two to three cycles of use. Cost accumulations associated with instrumentation wear, column fouling, pump seal replacement, catalyst degradation, or solvent-based experiments do not arise in virtual contexts (Jafari et al., 2021; Nthunya et al., 2022). Therefore, although VR does not eliminate the need for physical laboratories particularly for tactile skill development, calibration exposure, and sensory familiarity, it strategically reduces reliance on them for lower-order procedural familiarization and high-risk demonstration activities, thus optimizing the value extracted from physical infrastructure.

When total ownership cost is compared holistically, VR functions not as a substitute, but as a capital-efficiency multiplier. The greatest economic return is realized when VR is integrated structurally into curriculum design rather than implemented as an occasional accessory (Oje et al., 2025). Under this configuration, VR yields economic value through reduced marginal cost of practice, enhanced laboratory throughput, reduced consumables expenditure, improved utilization rates of physical labs, and improved student learning efficiency (Prajapati & Kumar, 2025). These cost-structuring benefits, when aligned with learning outcome improvements and reduced operational hazard exposure, collectively justify VR adoption on both pedagogical and institutional economic grounds.

The data in Table 7 highlights that while conventional laboratories incur recurring costs across multiple budget categories, VR laboratories exhibit a front-loaded cost profile with minimal long-term operating expenses. The shift from a resource-intensive to a digital asset-based infrastructure yields a steeper initial cost amortisation curve, with breakeven typically achieved after two to three deployment cycles depending on student enrolment size (Buck et al., 2023). Additionally, the scalability of VR reduces marginal cost per learner to near zero, allowing institutions to accommodate growing enrolments without proportional expansion of laboratory space or resources (Javaid et al., 2024). The removal of consumables, reagent disposal, and hazard mitigation expenses further compounds institutional savings while simultaneously supporting sustainability goals aligned with green campus initiatives. Therefore, the integration of VR not only strengthens pedagogical innovation but also advances financial sustainability and environmental responsibility within engineering education ecosystems.

Table 7. Comparative Cost Structure between Conventional and VR-Based Chemical Engineering Laboratories

Cost Component	Conventional Laboratory	VR-Based Laboratory	Economic Implications
Capital Investment (CAPEX)	Construction of laboratory spaces, purchase of experimental rigs, safety systems,	Procurement of HMDs, high-performance computers, and software development licences.	VR requires lower initial capital outlay and minimal physical infrastructure footprint.

Cost Component	Conventional Laboratory	VR-Based Laboratory	Economic Implications
	ventilation, and utilities.		
Operational Expenditure (OPEX)	Continuous purchase of reagents, solvents, catalysts, and consumables; energy usage; waste disposal; equipment maintenance.	Periodic software updates, hardware servicing, and occasional module upgrades.	VR incurs negligible recurring costs once modules are deployed, reducing annual expenditure.
Safety and Liability Costs	High insurance premiums, personal protective equipment, accident mitigation, and safety audits.	Minimal safety risk and liability; training occurs in controlled virtual environments.	Substantial long-term savings through reduced risk exposure and insurance costs.
Personnel and Training	Requires technical officers, safety supervisors, and laboratory demonstrators for every session.	Requires digital technicians and instructors trained in VR pedagogy.	Lower recurring staff hours; instructor-to-student ratio improves due to scalable digital access.
Consumable Waste Management	Hazardous waste disposal and environmental compliance costs.	No physical waste generated.	Eliminates recurring environmental management fees.
Student Throughput and Accessibility	Limited by physical space and equipment availability, fixed lab schedules.	Unlimited access; scalable use across cohorts and campuses.	Enhances capacity without additional infrastructure expansion.
Equipment Wear and Depreciation	High mechanical wear and periodic replacement of pumps, valves, sensors, and glassware.	Minimal physical wear; primarily digital depreciation through software obsolescence.	Extends the lifespan of existing physical assets by reducing usage frequency.
Learning Repetition Costs	Repeat experiments consume additional reagents and time.	Repetition is cost-free and can be conducted asynchronously.	Enables mastery learning at zero marginal cost.

To illustrate the economic claim empirically, Table 8 presents an illustrative worked scenario comparing cumulative costs for conventional wet laboratories and a VR-enabled laboratory over a three-year horizon for two cohort sizes (60 and 120 students) (Bhatia et al., 2019). Under the base assumptions (module development = $50,000; headsets/shared units; 6 lab modules per year), VR reaches cumulative cost parity with conventional labs in approximately 1.2–1.6 academic years, depending on cohort size and shared-use efficiency (Bhatia et al., 2019; Bridges et al., 2014). Sensitivity checks indicate breakeven is delayed if development costs double or module reuse is limited. Conversely, breakeven accelerates with larger cohorts, inter-departmental sharing, or lower headset costs. These numeric examples render the earlier qualitative statement explicit, and provide a transparent template that institutions can adapt by substituting local line-item costs. Larger enrolments or shared module reuse shorten the breakeven period, while higher development expenditure extends it (Nazareth & Rothenberger, 2004). Once initial costs are amortised, the marginal cost per additional learner approaches zero, validating the economic rationale for institutional VR adoption in laboratory-intensive programmes (Nazareth & Rothenberger, 2004).

Table 8. Worked cost–benefit scenario comparing conventional and VR-based chemical engineering laboratories over three academic years (Bhatia et al., 2019; Bridges et al., 2014)

Item / Year	Small Cohort (60 students)	Large Cohort (120 students)
Conventional – Annual Components		
Consumables (students × experiments × $15)	$ 5 400	$ 10 800
Equipment maintenance (per year)	$ 10 000	$ 15 000
Technical staff allocation (per year)	$ 30 000	$ 40 000
Waste / PPE / compliance (per year)	$ 2 000	$ 3 000
Conventional annual total	**$ 47 400**	**$ 68 800**
VR – Initial (Year 0, one-time)		
Headsets (20 @ $400 / 40 @ $400)	$ 8 000	$ 16 000
IT / Infrastructure setup	$ 5 000	$ 7 000
Module development (6 modules)	$ 50 000	$ 50 000
VR initial total (Year 0)	**$ 63 000**	**$ 73 000**
VR – Recurring (annual)		
Software licence	$ 5 000	$ 5 000
IT / support / training	$ 3 000	$ 7 000
VR annual recurring total	**$ 8 000**	**$ 12 000**
Cumulative Costs (End of Year)		
Conventional – Year 0	$ 0	$ 0
Conventional – End Year 1	$ 47 400	$ 68 800
Conventional – End Year 2	$ 94 800	$ 137 600
Conventional – End Year 3	$ 142 200	$ 206 400
VR – Year 0 (initial)	$ 63 000	$ 73 000
VR – End Year 1	$ 71 000	$ 85 000
VR – End Year 2	$ 79 000	$ 97 000
VR – End Year 3	$ 87 000	$ 109 000
Approximate breakeven (cumulative parity)	**≈ 1.6 years**	**≈ 1.2 years**

Notes:

1. Costs are indicative and reflect mid-range U.S. institutional estimates for six core laboratory modules.
2. "Breakeven" denotes the earliest academic year where cumulative VR expenditure ≤ cumulative conventional expenditure.
3. Development amortisation assumed over three years; sharing modules across departments or larger cohorts accelerates breakeven.
4. To localise the analysis, multiply USD values by the prevailing exchange rate (1 USD = RM 4.70).
5. Figures exclude indirect costs such as facility depreciation and electricity; including these would further favour VR due to lower recurring usage.

CONCLUSION

This review demonstrates that VR has progressed from early prototype demonstrations toward a credible instructional medium capable of strengthening conceptual understanding and operational reasoning within chemical engineering education. ChemE-focused bibliometric analysis indicates accelerated growth since 2019, driven by advances in hardware, rendering capabilities, and digitized learning infrastructure, although research remains fragmented with technological development outpacing pedagogical and curriculum-level work. This imbalance highlights the critical need to reposition VR from a purely technological artefact toward a curriculum-embedded learning architecture grounded in instructional theory and validated learning outcomes. Additionally, a four-stage integration sequence—pre-conceptual familiarisation → immersive experimentation → hybrid transfer → real-lab validation—positions VR as an instructional scaffold that complements, rather than replaces, physical laboratories, improving learning efficiency and competency development in systems thinking, troubleshooting, and dynamic decision-making.

The framework presented in this paper positions VR as an instructional scaffold rather than a laboratory replacement, optimizing physical laboratory contact time for higher-order analytical tasks. When correctly sequenced across pre-conceptual familiarization, immersive experimentation, hybrid transfer, and real-lab validation, VR enhances learning efficiency while enabling competency development in systems thinking, troubleshooting, and dynamic decision-making. The shift from procedural demonstration to deliberate cognitive challenge also imposes new demands on instructor capacity, particularly in assessment design, scenario development, student cognitive load modulation, and mitigation of cybersickness-related inclusivity constraints. Addressing these pedagogical barriers requires sustained cross-disciplinary collaboration between chemical engineers, simulation developers, and instructional designers.

Furthermore, an economic analysis reveals that VR yields significant cost-structuring advantages compared to conventional laboratories. Typically, the analysis shows that VR becomes cost-competitive after roughly 1.5 years and reduces training expenses by 40–45% by the third year for large cohorts. Collectively, these findings indicate that VR can transition from novelty to an essential component of chemical engineering curricula when strategically aligned with instructional and economic priorities. VR is capital-efficient beyond the second or third deployment cycle due to negligible marginal repetition cost, absence of consumables, and scalability independent of physical laboratory capacity. As such, VR functions as a multiplier for physical laboratory investment: extending asset lifespan, lowering operational expenditure, and increasing student throughput without proportional infrastructure growth. Collectively, these findings indicate that VR can transition from novelty to necessity provided its adoption is strategically aligned with curriculum-level learning outcomes, institutional economic priorities, and evidence-driven pedagogical practice. Future research must therefore progress beyond proof-of-concept simulations toward longitudinal validation of cognitive gains, transferability to real plant behaviour, and robust cost-performance modelling across diverse institutional contexts. Finally, the falsifiable research questions include: (1) whether VR familiarisation reduces time-to-stability in virtual control tasks; (2) whether VR safety training decreases first-time pilot-plant error rates; and (3) whether hybrid VR-to-lab sequencing enhances systems-level reasoning relative to traditional pathways. Such evidence is needed to validate long-term cognitive gains and confirm transferability to real plant behaviour.

RECOMMENDATION

Future research on VR in chemical engineering education should transition toward longitudinal, evidence-based evaluations that quantify how immersive exposure translates into real laboratory performance, industrial readiness, and post-graduation competency retention. Empirical studies should benchmark VR performance against physical laboratory data using controlled cohorts, integrating objective indicators such as task completion accuracy, plant-upset response time, and critical-fault detection behaviour. Further, VR–AI integration (e.g., adaptive difficulty, intelligent tutoring, predictive safety flags) represents a promising direction for personalised learning and automated feedback systems. Collaboration between universities and industrial VR developers is encouraged to support module co-creation, validation of process fidelity, and industry co-funding models that accelerate adoption.

However, several barriers may influence research outcomes and system scalability. High-resolution rendering and fluid dynamics visualisation continue to require substantial computational capacity, which may limit deployment in low-resource institutions. Cybersickness, inclusive design constraints, and variability in students' prior digital familiarity may distort learning outcome measurements if not controlled experimentally. Additionally, a lack of unified assessment frameworks across studies reduces cross-comparability and limits meta-analysis validity. Content development remains costly and labour-intensive unless reusable, modular VR content repositories are established. Addressing these barriers is essential to ensure that future VR implementation transitions from isolated pilots into standardised, scalable, and sustainable educational infrastructure within chemical engineering programmes.

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Author Contributions

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Wan Nur Aisyah Wan Osman	✓	✓				✓	✓	✓	✓	✓	✓			
Shafirah Samsuri	✓	✓		✓		✓	✓			✓	✓	✓	✓	✓

Conflict of interests
The authors declare no conflict of interest.

Data Availability
The authors confirm that the data supporting the findings of this study are available within the article.

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