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Immersive Virtual Reality in Higher Science Education: A Systematic Review of Pedagogical Design, Science Engagement, and Digital Competence

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Abstract. Immersive virtual reality (IVR) supports the teaching of abstract, spatial, and microscopic concepts in higher education, although previous research has focused primarily on devices, access, and technical constraints. This systematic review examined IVR from the perspective of pedagogical design, science engagement, and students' digital competence. Following PRISMA 2020 guidelines, 2,177 Scopus-indexed articles were screened through identification, duplicate removal, title and abstract screening, and eligibility assessment, resulting in 39 articles for bibliometric and thematic analysis. The findings revealed that IVR research in higher education was dominated by life sciences, quasi-experimental designs, and small samples of approximately 30 participants, with head-mounted displays (HMD) to cover the user's field of view and create the sensation of being inside a three-dimensional environment, used in 23 of the 39 studies. The most common pedagogical patterns were simulation-based learning and virtual laboratories. Among the four engagement dimensions, emotional engagement was most consistently enhanced by IVR. Digital competence was rarely defined or measured explicitly and was more often represented implicitly through learners' interaction behaviors in VR environments, with explicit measurements largely limited to pre-service teacher education studies. These findings indicate that IVR effectiveness does not result automatically from device quality but is mediated by pedagogical design, content alignment, formative debriefing, and users' digital readiness.

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Future research should adopt longitudinal designs, multimodal measurements of engagement and digital competence, and discipline-specific pedagogical frameworks to realize the transformative potential of IVR in higher science education.

Keywords: IVR; higher science education; science engagement; digital competence; pedagogical design

1. Introduction

Science learning in higher education faces challenges in conveying abstract, spatial, microscopic, and procedural concepts that are difficult to present through conventional approaches (Matovu et al., 2023; Mohd Saidi et al., 2025). IVR, using HMDs, head-tracked visual, and controller-based interactions created multisensory, interactive and immersive learning environments (Stracke et al., 2025; Tene et al., 2024). It enables students to explore and manipulate scientific phenomena, from cell structure and mitosis to hazardous laboratory instruments, transforming imagined concepts into experiential learning (Akdag et al., 2025; Reen et al., 2022).

Previous reviews confirmed IVR's potential for science learning but examined different aspects of the evidence. Pellas et al. (2020) mapped immersive STEM applications, Matovu et al. (2023) reviewed design, implementation, and evaluation, and Acevedo at al. (2024) synthesized learning and user-experience outcomes. Discipline-specific reviews separately addressed engineering and biological science (Hernandez et al., 2025; Xian et al., 2025). However, IVR research has often emphasized hardware, interactivity, or cognitive outcomes such as test scores and retention (Acevedo et al., 2024; Akdag et al., 2025), without integrating three important pillars in education: the learning theory, instructional models, and evaluation methods (Kamrozzaman et al., 2025; Radianti et al., 2020). Consequently, gaps remain regarding how and why particular IVR designs are effective in specific science context and which elements support sustainable implementation.

Radianti et al. (2020) mapped the design elements and research gaps in higher education IVR, Lui et al. (2023) synthesized theory-based learning design in science education, and Acevedo et al. (2024) summarizes its advantages and limitations in STEM education. These reviews emphasized learning performance, motivation, presence, usability, and user experience. However, they did not integrate pedagogical design with the behavioral, emotional, cognitive and agentic dimensions of science engagement and digital competence. Most studies treated technology acceptance, usability or interaction behavior as outcomes without explicitly defining or measuring digital competence.

Together, these reviews provided complementary but separate accounts of IVR design, learning outcomes, and user experience (Acevedo et al., 2024; Lui et al., 2023; Matovu et al., 2023; Radianti et al., 2020). They did not explain how pedagogical design shaped multidimensional science engagement or how IVR participation contributed to digital competence. This review addressed that gap by integrating pedagogical design, four dimensions of science engagement, and six dimensions of digital competence within a single analytical framework. The integration identifies not only whether IVR is effective, but also which designs, outcomes, and implementation conditions supported meaningful and sustainable science learning. It therefore addresses a central question: which IVR design can support deep science learning while sustainably developing students' digital competence?

Despite growing empirical evidence, a more comprehensive mapping is needed to synthesis of five key aspects: (1) research trends that have developed in the last decade; (2) pedagogical design and instructional strategies used in IVR interventions; (3) the impact of IVR on student engagement in science learning; (4) the impact of IVR on the development of students' digital competencies; and (5) key factors, remaining research gaps, and future research directions to guide the development of this field in a sustainable manner. A comprehensive and multidimensional literature study is needed to fill this gap, and to provide guidance for researchers and practitioners in optimizing the use of IVR in higher science education. Particular attention is needed to its long-term impact, the development of a standardised pedagogical framework, and future research directions that can support its transformative potential.

Specifically, the review was designed to answer the following five research questions:

- RQ1. What are the main characteristics and research trends of IVR studies in higher science education?
- RQ2. What pedagogical designs and instructional strategies are used in IVR interventions in higher science education?
- RQ3. How does IVR affect students' science engagement in higher science education?
- RQ4. How is digital competence conceptualized and measured in IVR studies, and what direct or indirect evidence exists regarding its development?
- RQ5. What future directions can be identified from the literature on IVR in higher science education?

2. Literature Review

2.1 Immersive virtual reality in higher education

Fundamentally, virtual reality (VR) is a hardware and software system designed to create an immersive sensory experience that gives users the feeling of being present in another environment (Biocca & Delaney, 1995). Within the spectrum of immersive technologies, VR is classified into three tiers based on the Reality-Virtuality Continuum (Milgram et al., 1995), namely, non-immersive VR (desktop), semi-immersive VR (large projection screen), and immersive VR (IVR).

This study focuses on IVR characterized by the use of a HMD that envelops the user's entire field of vision, continuous visual updates according to head movements, and interaction through controller or freehand gestures (Lui et al., 2023; Stracke et al., 2025). In a pedagogical context, immersion is closely linked to the sense of presence, which refers to the subjective feeling of being physically present in a virtual environment. This sense of presence includes two dimensions: place illusion (PI) and plausibility illusion (Psi) (Slater & Wilbur, 1997). It is this immersive presence that connects the features of IVR technology with cognitive and affective outputs, as described in the cognitive-affective model of immersive learning (CAMIL) (Makransky & Petersen, 2021). It is important to note that comparative studies show no significant difference in learning outcomes between high-end HMDs (such as the Oculus Rift) and low-cost smartphone VR headsets (Moro et al., 2017; Papachristos et al., 2017), which means the quality of immersion is determined not only by the device specifications but also by the quality of the learning design (Samsudin et al., 2026; Stracke et al., 2025).

2.2 Pedagogical designs for immersive science learning

The pedagogical interpretation of IVR in this review drew on constructivism, experiential learning and cognitive load theory (Mohsen & Alangari, 2024). Constructivism assumes that learners build meaning by exploring, manipulating and discussing representations rather than receiving information passively. Experiential learning views knowledge as developing through concrete experience, reflection, conceptualization, and further experimentation (Fromm et al., 2021). In practice, experiential learning, constructivism and game-based learning are recorded as the most dominant theoretical frameworks in VR research for education (Hernandez et al., 2025), with VR proven to be able to facilitate all four modes of experiential learning from concrete experience to active experimentation through design thinking. Cognitive load theory emphasizes the limited capacity of working memory and therefore requires segmentation, guidance, and the removal of distracting information.

In IVR, these perspectives imply that students should manipulate meaningful scientific objects, receive structured prompts, and reflect on the virtual experience through debriefing. Virtual simulations allow students to gain real-world skills and experience in a safe and controlled environment (Adnan et al., 2025). Given the high sensory and cognitive demands in IVR environments, scaffolding is a critical pedagogical element because adaptive metacognitive scaffolding in a collaborative VR environment has been proven to help students organize the learning process and collaborate more effectively (Pflieger et al., 2026).

2.3 Science engagement

Science engagement is a multidimensional construct that functions as both a predictor of academic achievement and an indicator of student readiness to participate in the STEM field for life. In the midst of declining interest in science and the gap between graduates and labor needs, engagement is seen not as only as a learning output, but also as a mechanism that connects instructional design to in-depth learning outcomes. Science engagement is treated as a four-dimensional construct.

Behavioral engagement refers to participation, persistence, task completion and direct interaction with virtual objects (Fredricks et al., 2004; Fredricks & McColskey, 2012). Emotional engagement includes interest, enjoyment, enthusiasm, boredom, and anxiety (Pekrun, 2006; Pekrun et al., 2011) which in a VR environment, this dimension can be triggered by realistic graphic quality, access to previously unattainable phenomena, and awe (Chirico et al., 2018). Cognitive engagement involves explaining phenomena, connecting evidence with claims, evaluating information, and regulating understanding; well-scaffolded simulations could support these processes (Hmelo-Silver et al., 2007; Makransky & Petersen, 2021; Pedaste et al., 2015). Agentic engagement describes students' initiatives to shape or enrich instruction, for example by selecting experimental parameters or choosing learning pathways (Reeve, 2013; Reeve & Tseng, 2011). In the context of IVR, this dimension can be facilitated through virtual labs that allow students to choose experimental parameters independently or simulations that offer different learning paths according to interests and objectives (de Jong et al., 2014). These dimensions provide the framework for examining how IVR supported participation, affect, reasoning and learner control in higher science education.

2.4 Digital competence

Digital competence in higher education extends beyond basic technical skill. Drawing on the DigComp framework and related scholarship, this review uses six dimensions (Ferrari et al., 2013). Operational and technical use concerns the ability to operate hardware and software, while navigation concerns locating and filtering digital information (van Deursen & van Dijk, 2011).

Information processing involves evaluating, storing, and retrieving information critically (Zhao et al., 2021). Communication and collaboration address productive interaction through digital tools (Guðmundsdóttir & Hatlevik, 2013). Digital problem-solving concerns the use of technology to resolve technical or conceptual challenges, and confidence or self-efficacy refers to learners' belief that they can use technology effectively (Compeau & Higgins, 1995; Makransky & Petersen, 2021). In IVR-based science learning, these dimensions are reflected in operating headsets, navigating virtual spaces, manipulating scientific objects, collaborating, and solving simulated experimental problems.

The four constructs form a hierarchical analytical sequence. Pedagogical design structures the use of IVR, which supports students' technology-related skills and digital competence while clarifying complex scientific concepts and, in turn, strengthening their engagement with science.

3. Methodology

The process of identifying, filtering, eligibility, and inclusion of articles in this systematic literature review was done by referring to the PRISMA 2020 guidelines. The PRISMA 2020 flowchart helps researchers report on the review process in a systematic and replicable manner (Page et al., 2021). Based on the purpose of the research, the articles were screened and selected according to the following PRISMA stages.

3.1 Data Collection and Analysis Using PRISMA

Figure 1 presents the PRISMA flow diagram used in this study. The search was conducted in the Scopus database using a combination of the terms "immersive virtual reality," "science education," "science engagement," and "digital competence" for the period from 2020 to April 2026. The reconstructed Scopus syntax, based on the search terms and filters documented in the review record, was: (TITLE-ABS-KEY (immersive VR) AND TITLE-ABS-KEY (higher education) OR TITLE-ABS-KEY (science education) OR TITLE-ABS-KEY (science engagement) OR TITLE-ABS-KEY (digital competence)) AND PUBYEAR > 2019 AND PUBYEAR < 2027 AND (LIMIT-TO (OA , "all")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (SUBJAREA , "SOCI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re")).

The search yielded 2,177 initial records. These records were then filtered; 943 after subject-area filtering, 838 after document, source and language filters, 797 final publications, and open access, resulting in 428 reports for further review. After title and abstract screening, 191 articles were excluded. The eligibility assessment further excluded studies outside science education, secondary studies, non-immersive technology studies, health training studies, and studies without specific science learning content. Finally, 39 studies met the inclusion criteria and were analyzed in depth in this systematic review.

The open-access filter was applied to permit consistent full-text verification and transparent extraction within the review workflow. This decision may have excluded relevant subscription-only evidence and introduced availability bias; it was therefore treated as a methodological constraint rather than as a quality criterion. The 2026 search endpoint represented a partial publication year, so annual-trend interpretations were limited to the analyzed corpus. Studies were included if they were empirical, addressed higher-education science learning, implemented immersive or headset-based VR, and reported sufficient information about pedagogy, learning engagement, digital competence, or closely related outcomes.

Secondary reviews were excluded because the synthesis focused on primary evidence. Non-immersive technologies were excluded to maintain conceptual consistency with the study's IVR definition. Studies outside science education, professional health training or wellness, technology-adoption studies without instructional implementation, non-STEM teacher education, and general metaverse applications without specific science content were excluded because they did not address the review questions. These criteria balanced topical relevance, methodological comparability, and the feasibility of full-text verification.

Bibliometric analyses were generated from the Scopus metadata using the Bibliometrix package in R through the Biblioshiny interface. These outputs included annual production, cumulative growth, the three-fields plot, word-frequency trends, reference publication year spectroscopy, and the thematic map.

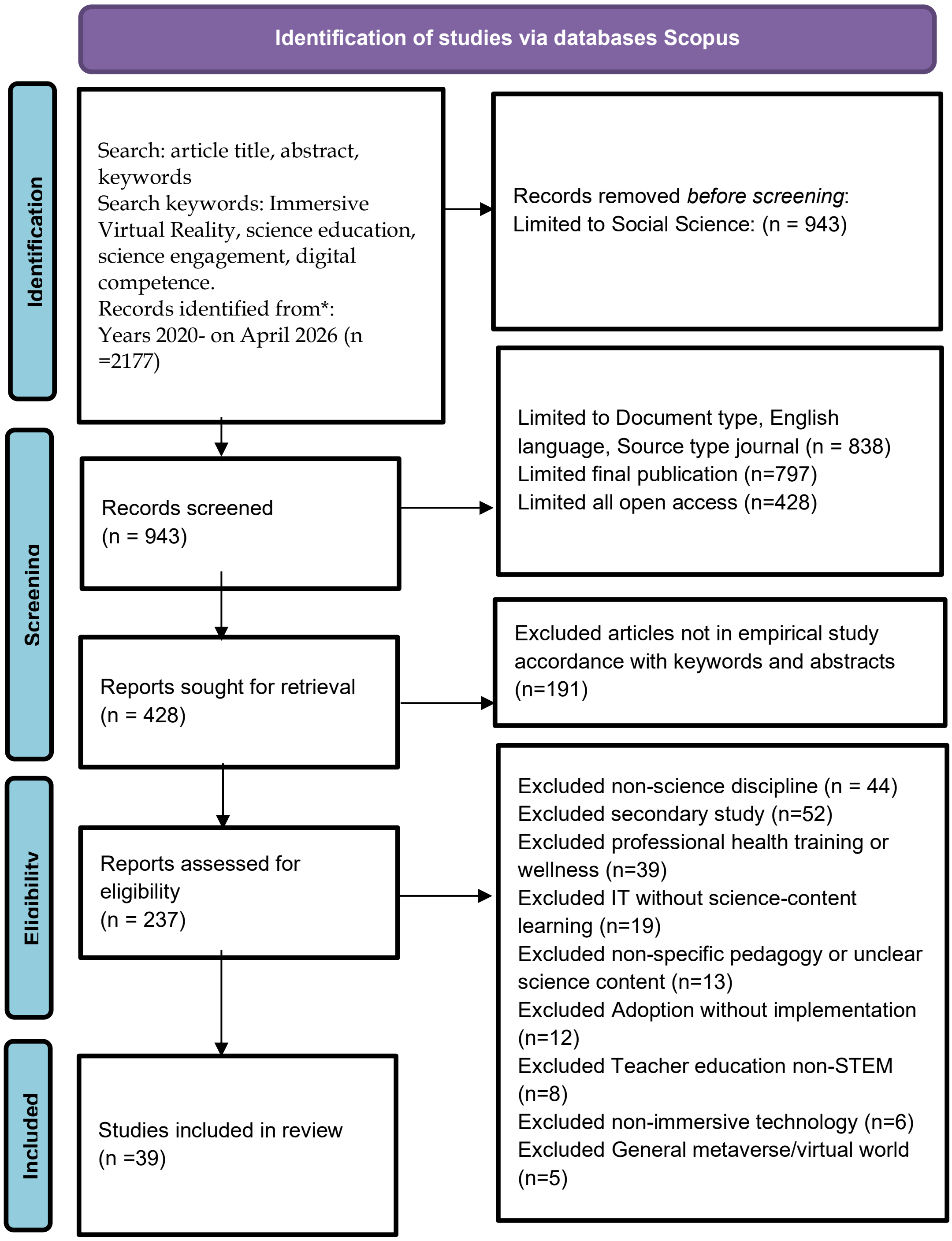

Figure 1: PRISMA Flow Diagram

3.2 Analytical Framework

The 39 studies were analyzed using RQ-based extraction framework, where each article systematically review by title, abstract, keyword, and full-text. RQ1 mapped research characteristics and trends (year, country, discipline, sample, design, and VR technology). RQ2 identified pedagogical designs and instructional strategies (simulation, virtual laboratory, inquiry, PBL, gamification, scaffolding).

RQ3 examined behavioral, emotional, cognitive and agentic engagement, while RQ4 assessed digital competence, including operational skills, navigation, information processing, collaboration, digital problem-solving, and confidence. These findings were synthesized into a trend table, a strategy map, an engagement matrix and a digital competency matrix, which formed the basis for RQ5 to identify factors influencing IVR effectiveness, methodological limitations and future research agendas.

4. Results and Discussion

4.1 Characteristics and research trends of immersive VR studies in higher Science education

The cumulative growth curve in **Figure 2** shows that publications on *immersive VR* in higher science education increased rapidly during the observation period. The 50%, 90% and 99% thresholds indicate that most studies were published in recent years, particularly after 2024. As the curve approached 99%, it began to flatten, suggesting that article corpus had reached maximum cumulative coverage within the analyzed data; it did not, however, indicate that global research activity had ceased.

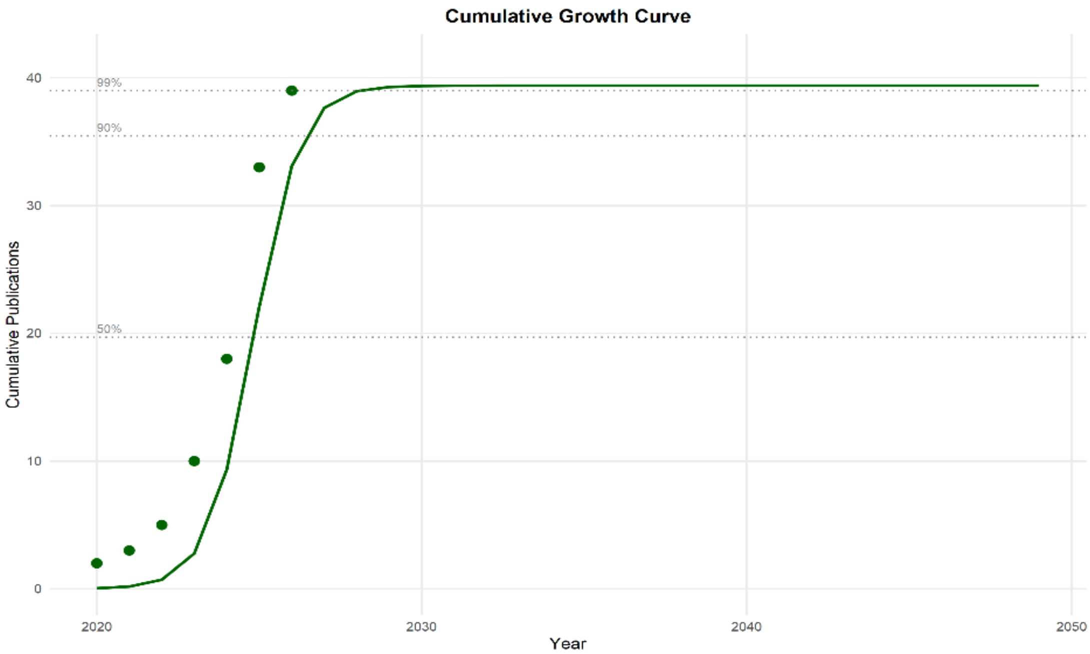

Figure 2: Cumulative Growth Curve

The annual publication related to *immersive VR* in higher science education in Figure 3 followed a strong research lifecycle pattern, which marks a period of academic attention to this topic being at its maximum intensity. After the peak phase, the curve shows a sharp decline, which indicates a reduction in publications in the corpus of analyzed data. An R^2 value of 0.892 shows that the model has a strong suitability in describing the development pattern of annual publications. This topic can be categorized as a fast-growing area of research in recent years, but it is starting to show a tendency toward a stabilization phase after the peak of growth.

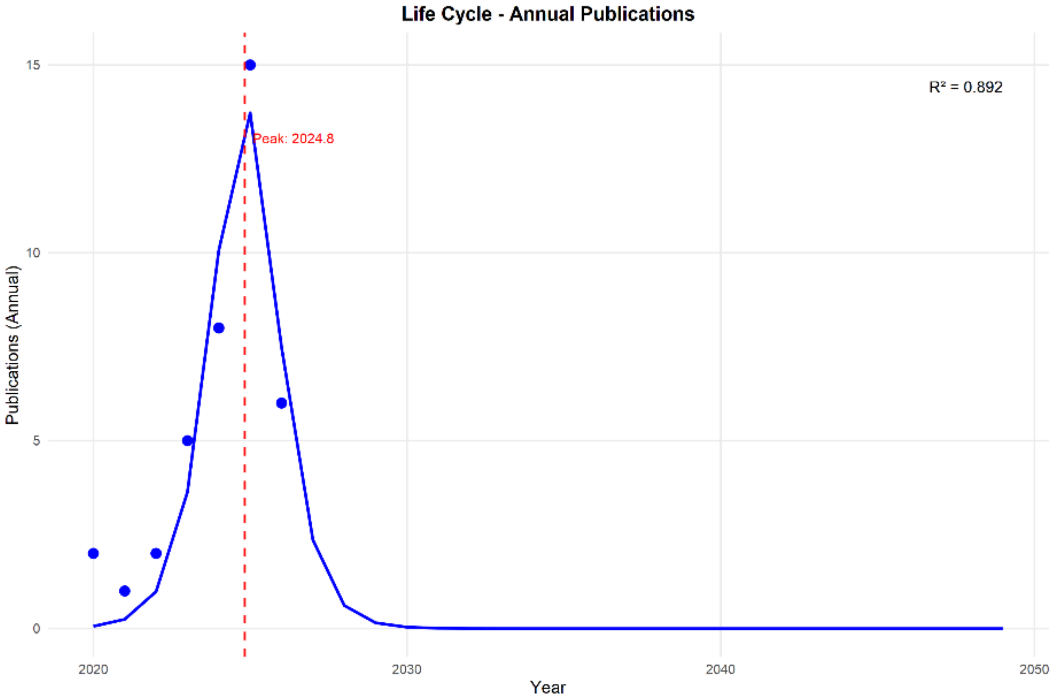

Figure 3: Life Cycle – Annual Publications

Figure 4 shows that *learning*, *students*, *VR*, *immersive*, *engagement*, *science*, and *education* were the dominant themes in the bibliometric network. This confirms that the research mainly focused on learning experiences and the integration of immersive technology in education. Geographically, China and the United States are the leading contributors, followed by Mexico, Malaysia, India and France. Indonesia appeared in the network, although its contribution remains limited. The interconnectedness of these keywords indicates that IVR in higher science education has developed into a multidisciplinary research area that combines technology, pedagogy and higher education.

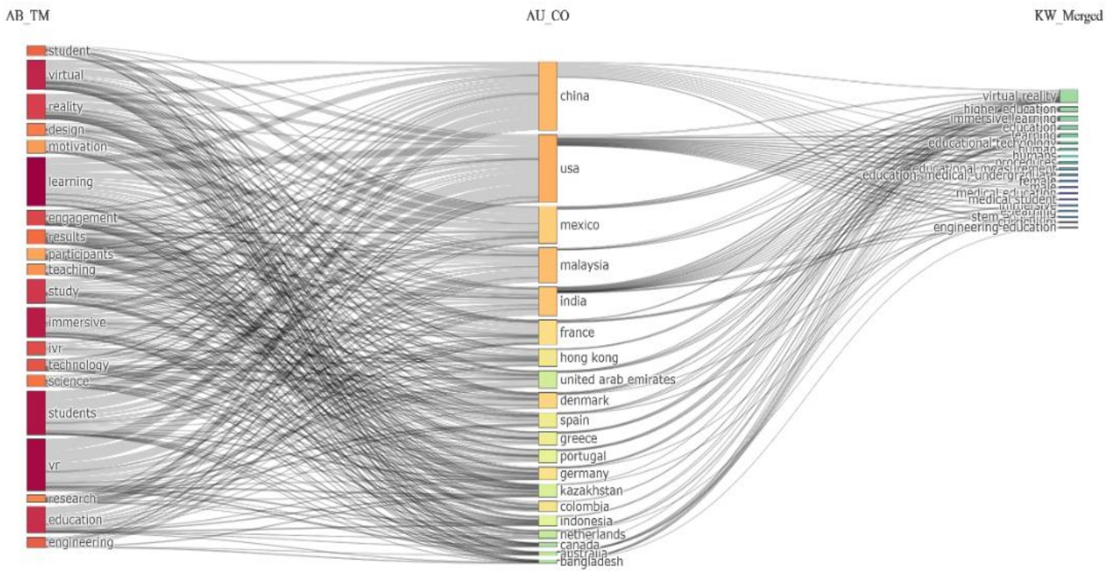

Figure 4: Three-fields plot

The analysis of the keyword trends in Figure 5 shows that virtual reality was the most dominant term with the sharpest growth, especially since 2024, indicating the increasing concentration of research on VR as the main technology in learning. The use of the words 'higher education' increased consistently, affirming higher education as the main application context. Meanwhile, the growth in use of the terms 'immersive learning', educational technology' and 'pedagogical design' after 2023 reflects a shift in research orientation from mere technology adoption to designing immersive learning experiences that are pedagogical and structured.

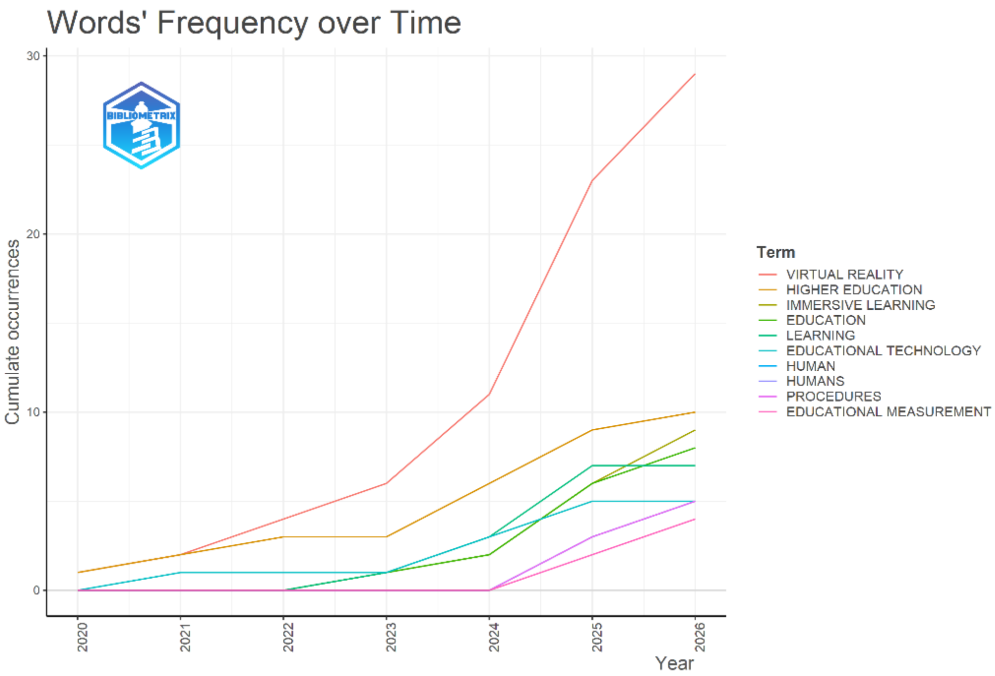

Figure 5: Words' Frequency over time

Figure 6 shows that the reference base was concentrated in contemporary literature, especially publications from 2016 to 2020. The strongest deviation occurred in 2018, indicating that several influential works from that year shaped later conceptual and methodological developments. Earlier peaks in 1956, 1992, 1997, and 2014 represent foundational theories and methods. The pattern confirms that the field combines classical theoretical foundations with a predominantly post-2014 empirical literature base.

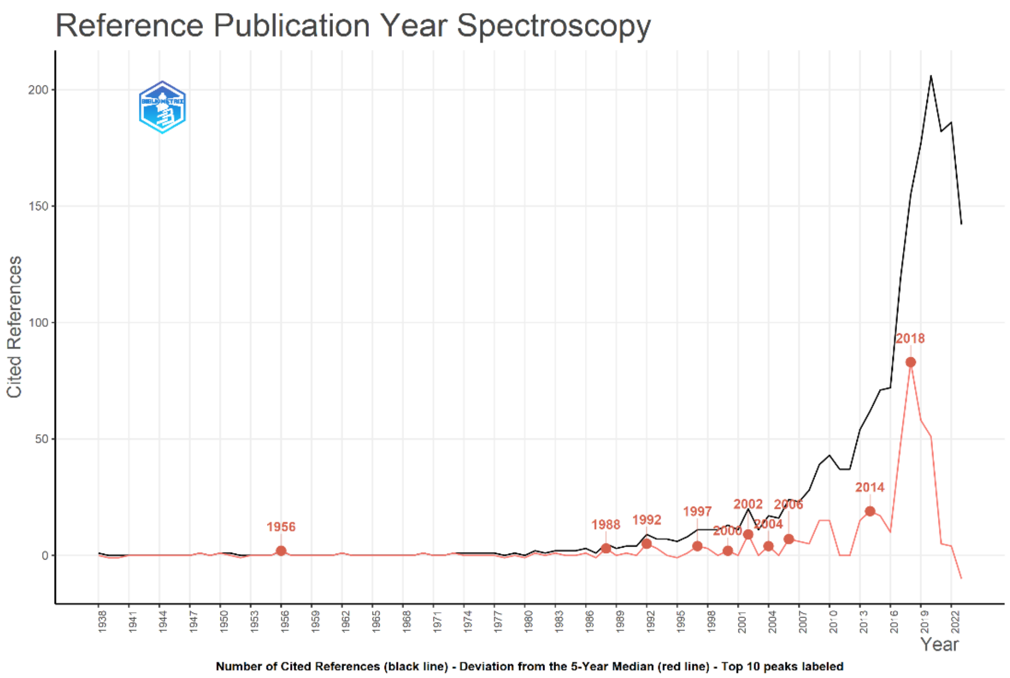

Figure 6: Reference Publication Year Spectroscopy

Figure 7 shows three main clusters in the co-citation network. The red cluster dominates the network and represents technology-based learning in STEM education. The green cluster focuses on students' learning experiences and educational contexts and the blue cluster connects VR technology with pedagogical practice. Dense links among the nodes suggest that IVR research has gradually shifted from technological exploration toward more specific pedagogical integration in higher science education. However, the limited number of strong bridging concepts between the technology and learning clusters indicates conceptual fragmentation, as device and user-experience research is not consistently linked to explicit pedagogical theory or competence measurement. This pattern supports the integrative synthesis developed later in the review.

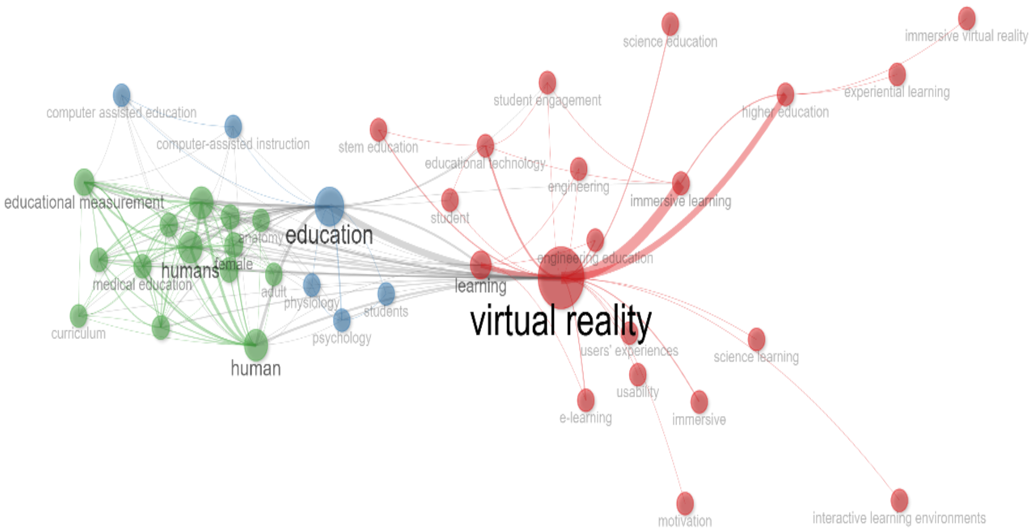

Figure 7: Co-Occurrence Network

The thematic map in Figure 8 identifies education, human, virtual reality, higher education, and immersive learning as major themes with high centrality and density, confirming their dominant and mature role in IVR research. On the other hand, the themes of teaching, science learning, motivation, and usability are identified in the emerging or declining themes quadrant, indicating that pedagogical aspects, student motivation, and evaluation of technological usability have not been fully empirically established. This pattern confirms that although the foundations of IVR research in higher education have been firmly established, significant development space is still open to pedagogical effectiveness and measurement of deeper learning experiences.

Figure 8: Thematic Map

Table 1 shows that IVR research in higher science education remains focused on demonstrating effectiveness, as reflected in the dominance of experimental and quasi-experimental designs and HMD use. Small to medium samples indicate a contextual, evidence base, limiting cross institutional generalizability. Its use across applied sciences, biology, education, and STEM confirms VR's development as an interdisciplinary learning medium. However, the limited use of mixed-methods, qualitative and design-based research means that little is known about how and under which pedagogical conditions IVR can sustainably improve science engagement and digital competence. This highlights the urgent need for longitudinal research.

Table 1: IVR Trend Domain in education

Study Focus	Research Trend (count)	Characteristic
Domains Sains	Life-science (14), applied science (7), chemistry (4), physics (4), teacher education (3), environment (3), general science education (2), lab safety (2)	The most dominant science domains are life sciences; the characteristics of materials require 3D representation, spatial visuals, and simulations that are difficult to achieve through text or 2D images.
Device/Platform	HMD/headset-based IVR (23), VR-AR mixed platform (5), WebVR-Metaverse browser platform (2), mixed IVR-nVR (7), CAVE-based VR (1), and VR simulation (3)	The dominant platforms include Oculus/Meta Quest, HTC Vive, VR headsets, and HMDs with controllers. The combination of VR and AR, often appearing in the metaverse, is STEM teacher training. Other types of WebVR/wearables, metaverse Spatial.io, desktop VR, tablets, notebooks, Zygote Body, Unity simulations, VR modules, and immersive software.
Research design	Quasi-experiment (15), randomized experiment or media comparison (5), mixed method or action research (5), survey (5), psychometric validation (2), qualitative case (7)	The most dominant research compared the before and after scores between the VR and non-VR groups, compared HMD VR with desktop, video, or conventional methods, and examined motivation, perception, usability, technology acceptance or preference. The research model used RASH, SEM, and PLS-SEM.
Sample size	<30 participants (14), 30-60 participants (8), 61-100 participants (6), 101-150 participants (6), >150 participants (4)	The dominance of the study was under 30 participants because VR implementation required devices, space, onboarding, technical assistance, and operational time. Qualitative and in-depth research tends to involve few participants.

4.2 Pedagogical designs and instructional strategies used in immersive VR interventions

The reviewed corpus shows three prominent pedagogical patterns: simulation-based learning, virtual laboratories, and experiential learning (Table 2). The learning theories underlying VR design in these studies are dominated by the cognitive theory of multimedia learning (CTML), CAMIL, and experiential learning theory. CTML and CAMIL are the main foundations, as they provide guidance on the principles of multimedia design and explain specific cognitive-affective mechanisms in immersive environments. CAMIL outlines how presence and agency affect interest, intrinsic motivation, self-efficacy, cognitive load and self-regulation (Makransky & Petersen, 2021). The implementation of this framework is seen in the principles of CTML (segmentation, modality, and redundancy) to reduce the cognitive load in the learning object (Cabero-Almenara et al., 2025). It is also used to interpret the relationship between immersive experience and science-related thinking (Neiroukh & Ayyoub, 2025). The experiential learning approach is also dominant, especially in studies that emphasize the learning cycle through concrete experiences, reflective observation, abstract conceptualization and active experimentation such as in the development of VR teaching systems for Automated Guided Vehicle (AGV) operations (Ou et al., 2021) and a collaborative VR environment such as the CAVE Automatic Virtual Environment (CAVE) (de Back et al., 2021).

Table 2: Synthesis of Pedagogical Design and IVR Instructional Strategies

Pedagogical design	Characteristic	Instructional strategies	Interpretation
Simulation-based learning (Iqbal & Campbell, 2023 ; López-Sánchez et al., 2026 ; Pande et al., 2021 ; Pande & Jepsen, 2025 ; Poupard et al., 2026)	VR is used to simulate science phenomena that are abstract, microscopic, spatial, risky, or difficult to access directly.	3D visualization, virtual object manipulation, first-person experience, pre-test/post-test, directional exploration.	This is the most dominant pattern. VR is positioned as a medium to transform abstract concepts into visual and interactive experiences.
Virtual laboratory (Costabile et al., 2025; Giussani et al., 2025; Kurbanbekov et al., 2025; Li et al., 2023)	Students interact with instruments, tools, procedures, technical components, or virtual laboratory environments.	Lab briefing, procedural simulation, virtual experiment, quiz, midterm assessment, satisfaction survey.	Very dominant in engineering, biotechnology, chemistry, laboratory medicine, physiology, and lab safety. VR more often acts as a limited complement or replacement for expensive, risky, or unavailable laboratory conditions.
Experiential learning (Kee & Zhang, 2022)	Learning is built through hands-on experience, reflection, and practice in a virtual environment.	Kolb's experiential learning, active experimentation, reflective observation, and team-based hybrid learning.	This design is quite powerful, especially in horticulture, field-based science, and engineering. However, the reflection stage has not always been explicitly designed.
Constructivist learning (Azzam et al., 2024)	Students build understanding through manipulation, practice, exploration, and problem-solving.	Hands-on interaction, assembly–disassembly, testing, virtual practice, task-based learning.	Many studies use constructivist principles, especially in engineering and applied science, but are often stronger on the activity aspect than on the theoretical arguments of learning.
Embodied/ kinesthetic learning	Learning involves	Hand-tracking, wearable sensor,	It is still evolving, but it has great potential

Pedagogical design	Characteristic	Instructional strategies	Interpretation
(Acevedo, Magana, Walsh, et al., 2024; Bagher et al., 2023)	gestures, gestures, hand interactions, haptic cues, or motion sensors.	haptic/visual cue, movement-based analytics.	for spatial, mechanistic, and phenomenal concepts that require a sense of agency.
Collaborative learning (S. Y. Chen et al., 2025; de Back et al., 2020, 2021)	Students learn in a shared space through CAVEs, avatars, teams, or group activities.	Cooperative learning, team-based learning, avatar-mediated collaboration, peer interaction, gamification.	The potential is huge, but it is not mainstream yet. Most studies are still oriented toward individual experiences with headsets.
Gamification/challenge-based learning (Bhatt et al., 2025; de Back et al., 2020)	Some studies add competitions, games, missions, or challenges to VR experience.	Competition games, quiz games, problem scenarios, task completion.	Gamification is often used to increase engagement, but it has not always been associated with long-term cognitive assessment design.
Blended/supplementary VR (Shine et al., 2025)	VR is combined with lectures, textbooks, discussions, physical models, field trips, real labs, and other learning platforms.	Lecture–VR–assessment, theory–simulation–quiz, lab physical–virtual integration.	This is the most realistic implementation pattern. Literature is more supportive of VR as a learning supporter, rather than a total replacement for conventional approaches.
Teacher training/digital competence design (Rodríguez & García López, 2026; Sumardani & Lin, 2024)	VR is used to train prospective teachers or develop technology integration competencies.	TPACK, collaborative teaching sequence design, peer feedback, final presentation.	The number is smaller, but it is important to explain that the success of VR depends on the pedagogical and digital competence of educators.

IVR learning in this corpus is dominated by simulation-based learning and virtual laboratories, that replicated scenarios that are difficult, dangerous, or impossible to present conventionally. Applications include mobile-scale phenomena (Yu & Tarng, 2025); metal and crystal structures using the VeRidium platform (Thiele et al., 2025), and laboratory safety simulations (Mariscal et al., 2020). Virtual laboratories also enable safer, more accessible procedural practice in biology learning (Sunday et al., 2023); risky chemical reactions using POE approach (K.F. Chen et al., 2025); hydraulic-gripper assembly and testing (Azzam et al., 2024); and infrared spectroscopy integrated quizzes and assessment (Sánchez-López et al., 2024). These designs provide situated, repeatable, and manipulable experiences for content that is difficult to observe directly.

The dominant instructional pattern follows a theory-VR-assessment sequence, positioning IVR not as substitute for theory but as a space for application and conceptual elaboration. This pattern appears in the integration of theoretical frameworks, IR spectrum exercises, individual quizzes and competition games (Sánchez-López et al., 2024), as well as in pre-test, experience and post-test designs comparing VR and clay-model experience (Thiele et al., 2025). Other strategies include guided exploration, blended or supplementary VR alongside lectures, physical laboratories, plastic models, field trips, and team-based learning, and more complex designs involving collaboration, embodiment, and gamification (de Back et al., 2020, 2021).

Effectiveness depends on IVR's position in the learning sequence and the quality of visual design, curriculum alignment, guidance and assessment (Samsudin et al., 2026). Overall, simulation and virtual laboratories are the strongest patterns, where structured inquiry, embedded formative assessment, long-term evaluation, conceptual scaffolding, and teachers' digital-pedagogical competence remained underdeveloped.

4.3 Effects of immersive VR on students' science engagement

The effects of IVR on science engagement were mapped into four dimensions as follows, namely behavioral engagement, emotional engagement, cognitive engagement, and agentic engagement. The 39-study corpus did not measure these dimensions equally. Emotional engagement was the most consistently reported outcome, and cognitive engagement was examined relatively often. Objective behavioral measures were less common, while agentic engagement was rarely operationalized directly (Table 3).

Table 3: Effects of immersive VR on students' science engagement

Engagement Dimensions	Indicators Reported	Pattern of Finding	Synthesis
Behavioral engagement	Active participation, object exploration, gesture use, interaction with virtual tools, task completion, attendance/attrition, platform use.	Increases when VR provides space for direct interaction, object manipulation (Azzam et al., 2024), or virtual practice. However, most of it is still measured through student perception, not direct behavioral observation (Du et al., 2020; Poupard et al., 2026).	Behavioral engagement appears to be strong in virtual lab and simulation-based learning, but objective evidence is still limited. Sensor-based studies and movement analytics are starting to fill this gap.
Emotional engagement	Motivation, enjoyment, interest, satisfaction, excitement,	The most consistent dimensions increase. Many	Emotional engagement is the most stable outcome in the

Engagement Dimensions	Indicators Reported	Pattern of Finding	Synthesis
	comfort, curiosity, situational interest, positive attitude.	studies report that college students are more motivated, interested, satisfied, and enjoy the VR experience (Azzam et al., 2024; Zaatar et al., 2024).	corpus, but it is mostly self-report based so it needs to be complemented by behavioral and longitudinal measures.
Cognitive engagement	Conceptual understanding, learning gain, reflective thinking, germane cognitive load, deeper processing, knowledge retention, comprehension.	It is quite often increased, especially in abstract, spatial, microscopic, or procedural material (Makransky & Petersen, 2021). However, the results are not always consistent when compared to VR desktops (Majewska & Vereen, 2023), physical models, textbooks, or traditional learning (Kurbanbekov et al., 2025; Supurwoko et al., 2025).	Cognitive engagement relies more on the quality of instructional design, scaffolding, and material suitability. VR does not automatically lead to better understanding if it relies only on novelty or visual immersion.
Agentic engagement	Sense of agency, perceived interaction control, autonomy, self-directed exploration, ability to manipulate and control virtual objects.	It is beginning to emerge as an important dimension, but it is still rarely explicitly tested. Studies that measured perceived interaction control showed a positive relationship (Thadani et al., 2025) with motivation (Bhatt et al., 2025) and engagement (Pande & Jepsen, 2025) .	Agentic engagement is the most prospective but least empirical, dimension. More studies are needed that measure how students initiate actions, control the learning process, and make decisions in VR.

Behavioral engagement in IVR is reflected in exploratory and manipulative activities including moving, observing, rotating models, operating instruments, and assembling virtual components. This dimension was most evident in virtual laboratories, where students performed actions resembling real laboratory practice, with 97% reported excitement, over 90% greater engagement, and 87% viewed VR laboratories as realistic and practical (Azzam et al., 2024). Sensor-based studies support these findings by combining WebVR with wearable inertial sensors to capture physical interactions in engineering learning (Bhatt et al., 2025) and analyzing head and hand movements and movement entropy as behavioral metrics (Poupard et al., 2026). However, behavioral engagement is still measured mainly through self-reports rather than direct observation, activity logs, or learning analytics.

Emotional engagement is the most consistent finding. Across science discipline, IVR increases motivation, interest, enjoyment, curiosity, satisfaction and excitement. Thadani et al. (2025) report positive responses in anatomy and physiology, although not all motivational improved equally. Biology students also showed high engagement and satisfaction while exploring three-dimensional body models (Zaatar et al., 2024), while virtual dissection preparation reduced discomfort for some learners (Shine et al., 2025). However, these findings should be interpretated cautiously because most measures were collected immediately after the intervention and may reflect novelty effects.

Cognitive engagement was reflected in conceptual understanding, learning gains, retention, and links between theory and practice. IVR was particularly effective for content requiring spatial understanding, 3D visualization, or simulation of processes that are difficult to observe directly, such as complex biological structures (Zaatar et al., 2024). Students with more varied movements also reported greater cognitive effort in processing and integrating information (Poupard et al., 2026). However, cognitive outcomes are not always significant when instructional design is weak, adaptation time was insufficient, or assessments were misaligned with learning objectives. Thus, cognitive engagement depends on pedagogical quality rather than immersion alone.

Agentic engagement, in which students initiate, control and modify their learning experiences, was strongly supported by IVR affordances but rarely measured explicitly. Real-time manipulation of virtual walves strengthens meaningful links between actions and learning outcomes (Bhatt et al., 2025), However, behavioral indicators do not always correlate with autonomy and competence, showing that movement alone does not represent pedagogically meaningful agency (Poupard et al., 2026).

Across the 39 studies, IVR most consistently enhanced emotional engagement, particularly motivation, enjoyment, curiosity, and satisfaction (Thadani et al., 2025; Zaatar et al., 2024). Cognitive benefits were more conditional and strongest for spatial, microscopic, and procedural content supported by appropriate scaffolding (Makransky & Petersen, 2021; Thiele et al., 2025). Behavioral engagement appeared through evidence remained largely self-reported rather than directly observed (Azzam et al., 2024; Poupard et al., 2026). Agentic engagement was supported by learner control and object manipulation, but rarely measured explicitly (Bhatt et al., 2025; Pande & Jepsen, 2025). Future studies should combine self-reports with cognitive tests, observations, interaction logs, sensor data and longitudinal assessment.

4.4 Effects of immersive VR on students' digital competence

Digital competence was not the primary outcome in most studies. Typical outcome measures include learning achievement and retention (Kurbanbekov et al., 2025; Sánchez-López et al., 2024), motivation and engagement (Azzam et al., 2024; Thadani et al., 2025), and usability, perceived usefulness, ease of use or behavioral intention (Sumardani & Lin, 2024; Zamli et al., 2025). These outcomes are related to technology use but do not constitute direct measures of digital competence. The synthesis therefore distinguishes four categories: explicitly measured competence; technology acceptance as a related construct; implicitly indicated learner competence; and digital feasibility or implementation readiness (Table 4).

Table 4: Effect of immersive VR on Digital Competence

Category	Emerging Forms Indicators	Interpretative Synthesis
Explicitly measured digital competence	Technology integration competencies, TPACK (Rodríguez & García López, 2026), perception of technological competence (Sumardani & Lin, 2024), critical thinking toward digital content (Rico et al., 2024), the use of VR/AR for learning and teaching.	Explicit evidence mainly appears in prospective teachers/pre-service teachers. Digital competence is understood as a pedagogical-technological ability, not just the ability to use a headset.
Technology acceptance as related construct	Perceived usefulness, perceived ease of use, perceived enjoyment, intention to use (Sumardani & Lin, 2024), absence of cybersickness (Wagner et al., 2025), behavioral intention (Zamli et al., 2025).	This construct is not the same as digital competence but is a prerequisite for technology adoption and readiness to use VR in a sustainable manner.
Implicitly indicated learner digital competence	Navigasi VR, manipulasi objek 3D (de Back et al., 2020), penggunaan HMD/desktop VR (Zamli et al., 2025), hand interaction (Iqbal & Campbell, 2023), self-directed exploration, operation of virtual instruments, adaptation to platform (Thiele et al., 2025).	In regular science students, digital competence is more often indicated through interaction performance and user experience, rather than measured as a formal outcome.
Digital feasibility and implementation readiness	Technology stability, accessibility, compatibility, ease of integration, physical comfort (Amirbekova et al., 2023), procedural guidance.	Digital competence is not only inherent in students, but is also influenced by system design, infrastructure, lecturer readiness, and technical support.

Digital competence was more often inferred from technology use than measured as a dependent variable. Many studies required learners to operate devices, navigate virtual spaces, manipulate objects, and complete virtual tasks without assessing improvement through validated competence framework. Explicit evidence appears mainly in pre-service teacher education, where technology-integration competence and TPACK were examined, suggesting that IVR more strongly supports digital competence when combined with design-based learning and teacher preparation (Rodríguez-García et al., 2019; Silva-Díaz et al., 2021). Technology acceptance is also influenced by perceived usefulness, enjoyment, and absence of cybersickness (Sumardani & Lin, 2024). Thus, competence development is more evident when IVR involves design, reflection and professional preparation, while usefulness, enjoyment, intention to use and cybersickness reflect adoption rather than digital competence.

The relationship between IVR and digital competence also depends on system design, infrastructure, technical support, and curriculum alignment (Samsudin et al., 2026). Hands-on interaction and self-directed virtual exploration support technology use and learner autonomy, although these reflect design affordances rather than verified competence gains (Iqbal & Campbell, 2023), Comparative studies showed that most participants preferred HMDs despite usability comparable to desktop VR, with gender differences identified in usability perceptions (Zamli et al., 2025). These finding indicate uneven digital readiness related to prior experience, comfort, simulator sickness and interface preference. Limited bandwidth, device availability, onboarding and educator preparation further constrain implementation (Lee et al., 2020). Overall, no study formally defines, operationalizes, and measures digital competence as the primary IVR learning outcome, despite its potential important in higher science education.

4.5 Key factors and future directions

IVR is not merely a visualization device but a pedagogical ecosystem requiring coordination among technology, curriculum, users and institutional contexts. Its effectiveness depends not only on immersion but also on visual and technological design, aesthetic quality, curriculum alignment and digital feasibility (Samsudin et al., 2026). Thus, the key question is not whether VR is used, but how it is integrated into science learning. IVR is most valuable for content requiring three-dimensional representation, object manipulation, or procedural experience, such as crystal structures, metabolic processes and engineering components (Azzam et al., 2024; López-Sánchez et al., 2026; Thiele et al., 2025).

For content adequately taught through simple methods, however, VR may increase cognitive load without proportional pedagogical benefits. Comparisons with desktop VR and physical models show that familiarity, usability, onboarding, and comfort shape learning experience (Chen & Chu, 2024; G. Chen et al., 2025; Qin et al., 2025). Sustainable implementation therefore depends on familiarity, scaffolding, procedural guidance, physical comfort, and sensitivity to diverse learner characteristics (Pande et al., 2021; Pande & Jepsen, 2025; Samsudin et al., 2026). Effective design requires both procedural scaffolding for system use and conceptual scaffolding linking virtual activities to scientific reasoning, while addressing cybersickness, cost, accessibility and learner preferences.

Future IVR research should address five limitations. First, it should move beyond short-term effectiveness studies toward longitudinal and comparative designs examining retention, transfer and professional competence. Second, engagement should be assessed through multimodal evidence, including questionnaires, performance tasks, observations, eye tracking, movement data and interaction logs (Poupard et al., 2026). Third, digital competence should be defined before intervention and measured using validated, discipline-relevant indicators.

Fourth, because most studies not connected immersive experiences with question formulation, hypothesis testing and scientific argumentation, research should shift from immersive visualization to structured immersive inquiry supported by curriculum alignment, procedural guidance, and scaffolding (Samsudin et al., 2026). Fifth, studies should examine equity and inclusivity by investigating how access, spatial ability, gender, prior digital experience, disability and cybersickness interact with pedagogical design (de Back et al., 2020; 2021; Zamli et al., 2025). Current evidence remains insufficient to explain how, for whom, and under which pedagogical and institutional conditions IVR produces sustainable science learning. Research should therefore shift from asking whether VR is effective to identifying the designs, engagement forms, digital competencies and institutional conditions that enable effective, sustainable and inclusive implementation.

5. Implications

This SLR shifts immersive VR research from a technology-centered view to a pedagogy-centered perspective. IVR effectiveness depends not only on immersion, device type or visual quality, but also on pedagogical design, curriculum alignment, learning support and users' digital readiness. Engagement and digital competence are closely linked because active IVR participation can help students use, interpret and evaluate digital technology more critically.

In practice, IVR should be designed as a learning intervention, particularly for objectives requiring 3D visualization, object manipulation, laboratory simulation or procedural practice. Scaffolding, onboarding, debriefing and aligned assessment are essential for connecting virtual experiences with scientific concepts. Future research should move beyond perception-based measures by combining self-reports, observations, interaction logs, task performance and explicit rubrics for digital competence. Overall, IVR should be treated not as stand-alone technology but as a pedagogical platform that requires careful design, measurement, comparison and contextualization.

Practical implications also require stakeholder-specific decisions. Curriculum designers should align immersive affordances with learning objectives; faculty should provide structured guidance and disciplinary feedback; and administrators and IT units should ensure sustainable infrastructure, accessibility, privacy and technical support. Researchers and evaluators should use rigorous designs, valid multimodal measures, appropriate comparators and delayed or transfer assessments so that claims about IVR remain proportional to the quality of the evidence.

6. Limitations

This study has several limitations. Scopus was used because its standardized multidisciplinary metadata supports bibliometric and thematic analyses, but reliance on a single database may have excluded relevant studies indexed elsewhere. The search covered January 2020 to April 2026, so the 2026 publication counts represented only a partial year. Limiting the review to English-language, final, open-access journal articles improved comparability and full-text access but may have introduced language, publication-status and availability biases. Focusing on immersive VR in higher science education also limited generalizability to other educational levels and non-science disciplines.

7. Conclusion

This review indicates that IVR should be understood as a conditional pedagogical system rather than as a generally superior medium. Across the selected Scopus open-access evidence base, its most defensible uses involved spatial, microscopic, hazardous, inaccessible or procedural science content benefiting from immersive representation and manipulation. These benefits depended on onboarding, scaffolding, reflection, debriefing and assessment alignment. However, the evidence remained narrow, with frequent use of life-science applications, simulation, virtual laboratories, HMDs, quasi-experimental designs and small samples across the 39 studies. Simulation-based learning and virtual laboratories were the dominant pedagogical patterns, with IVR commonly integrated into instructional sequences for conceptual elaboration and assessment.

IVR effectiveness did not result automatically from immersion but depended on instructional quality, alignment between VR affordances and science content, and appropriate scaffolding, debriefing, and assessment. Conclusions about engagement were constrained by measurement quality: short-term emotional responses were common; cognitive outcomes varied by context and comparators; objective behavioral measures were rare; and agentic engagement was seldom operationalized. Heterogeneous constructs and reporting prevented meta-analysis and pooled causal claims.

Digital competence remained a major evidence gap because most studies assessed platform use, acceptance or implementation readiness rather than validated, transferable competence development. The review therefore contributes an integrative framework linking pedagogical design, mediating experiences, measurement quality, engagement, digital competence, learner characteristics and institutional conditions. Future research should test these relationships through preregistered, multisite, longitudinal, multimodal and transfer-oriented designs.

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