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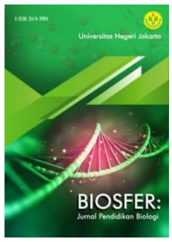

Implementation of virtual reality in biology education: Systematic literature review

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ABSTRACT

This study aims to investigate how virtual laboratories, cloud-based laboratory platforms, interactive molecular modelling, and serious educational games influence student engagement, conceptual understanding, and motivation. A systematic literature review was conducted on Scopus-indexed studies reporting empirical evaluations or pedagogical implementations of immersive technologies. Eligible studies were screened, coded, and analyzed thematically, emphasizing learning outcomes, instructional scaffolding, user interface design, scalability, and assessment practices. The review found that immersive technologies integrated with inquiry-based pedagogy consistently enhance student engagement and motivation, producing measurable short-term gains in conceptual understanding when supported by explicit scaffolding, timely feedback, and active instructor facilitation. Virtual and cloud-based laboratories expand access to authentic experimental experiences and enable scalable delivery through real-time data integration, while interactive molecular modeling strengthens spatial reasoning and procedural competence. Furthermore, serious educational games effectively promote conceptual transfer when their mechanics are explicitly aligned with instructional objectives.

INTRODUCTION

The twenty-first century is defined by rapid advances in digital technology that enable unprecedented levels of global connectivity. Often framed as a continuation of the industrial revolutions, these developments, particularly in information technology, have propelled societies from agrarian and industrial phases into what is commonly called an information society. In such a society, digitalization is not merely an add-on but a pervasive element of daily life, shaping how people communicate, work, and learn. Furthermore, digitalisation places greater emphasis on core skills, including critical thinking, communication, collaboration, and creativity, where communication is no longer simply the exchange of information but also involves digital literacy, thinking skills, and collaboration to build understanding and innovation in a complex and ever-changing global environment (Nurjanah, 2019). Communication skills in this era have become essential because they not only serve as a means of exchanging information but also as a foundation for building mutual understanding, cross-cultural collaboration, and sustainable innovation (Putri et al., 2020).

Over recent decades, digital innovations have transformed many sectors, and education is no exception (Bonfield et al., 2020). For Indonesia's education system, this transformation represents both a challenge and an opportunity, as institutions must adapt teaching practices and curricula to a landscape where information is abundant, and learning pathways are increasingly mediated by technology (Alenezi, 2023). Contemporary education, therefore, emphasizes skills beyond disciplinary knowledge, critical thinking, creativity, collaboration, and communication that prepare learners for an interconnected and rapidly changing world. Integrating innovative technologies and instructional media helps make learning more engaging, relevant, and accessible; for example, video projects or interactive presentations can foster creativity and teamwork, while online platforms build students' digital literacy (Bereczki & Kárpáti, 2021).

One widespread use of information technology in schools is the development and deployment of instructional media to support classroom activities (Shoraevna et al., 2021). Appropriately designed media can enhance student motivation and produce favourable psychological effects that facilitate learning (Kareem, 2018; Kuswanto et al., 2021; Ziadat, 2019). Conversely, a lack of adequate learning tools often hinders students' comprehension of complex material and undermines their interest, an issue that is particularly pronounced in biology. The effectiveness of biology instruction thus depends heavily on the selection and implementation of suitable media, which over time have evolved from print and simple audiovisuals to computer-based and hybrid formats.

In line with this, biology education in various countries shows a trend of increasingly structured and diverse development, where biology education research has become an international field of study that continues to evolve in order to understand the practices, challenges, and innovations in biology teaching and learning. Various international studies map the focus of research on topics such as the environment and ecology, genetics, teaching and learning, and students' attitudes towards biology, with a predominance of publications in indexed journals reflecting global attention to improving the quality of biology education and evaluation(Gul & Sozbilir, 2016). The increased use of educational technology in various contexts, including mobile learning and other digital media, further emphasises the direction of technology integration as a response to contemporary pedagogical needs in biology education in many countries(Sangur & Zubaidah, 2025).

Digital tools carry substantial potential to improve conceptual understanding and to cultivate twenty-first-century competencies in biology education (Ramaila & Molwele, 2022). Yet many existing animated resources remain essentially passive, because students can view content but rarely interact with it in meaningful ways (Amelia et al., 2021; Serin, 2020). Limited infrastructure and insufficient teacher training frequently underpin this shortfall. Moreover, despite growing adoption, relatively few studies have qualitatively examined how students and teachers experience and perceive the use of digital technologies in biology classrooms. Combining animation with immersive technologies such as Virtual Reality (VR) therefore, emerges as a promising strategy to address these gaps.

Virtual Reality (VR) refers to computer-generated environments that afford real-time user interaction, typically mediated by head-mounted displays, motion trackers, and sensory peripherals. In biology education, VR enables interactive visualization of three-dimensional structures ranging from cellular models to anatomical systems, making abstract concepts more tangible and easier to grasp. Beyond cognitive benefits, VR's immersive quality tends to increase student engagement and motivation by transforming learners from passive recipients into active explorers.

In recent years, VR has become one of the most influential technological innovations across multiple sectors, including education (Elmqaddem, 2019). By simulating 360-degree environments that resemble real-world contexts, VR and related technologies (such as Augmented Reality and interactive simulations) enhance learners' ability to visualize processes that are difficult to convey through conventional methods (Childs et al., 2023; Rashid et al., 2021). Empirical work, for instance, Chen's study, suggests that AR and VR can significantly boost immersion and motivation in learning tasks (Chen et al., 2024). However, much of the existing literature emphasizes quantitative outcomes, indicating a need for richer qualitative insight into how these technologies are perceived and integrated in practice.

Core characteristics of VR presence (immersion), multimodal sensory feedback (vision, hearing, potentially touch), and interactivity to support improved retention, comprehension, and attentional focus (Çoban & Göksu, 2022; Mariscal et al., 2020; Serin, 2020). These affordances help counteract the passive tendencies of traditional classroom formats (lecture, rote memorization), fostering a more meaningful and active learning experience (Kamińska et al., 2019; Molina-carmona, 2018; Sattar et al., 2019; Vergara et al., 2019). Given that many students today are digital natives, technology-mediated learning often better aligns with their preferences and habits, which can translate into higher enjoyment and improved learning outcomes (Paszkiewicz et al., 2021; Raja & Priya, 2021; Shin, 2017). The purpose of this study is to identify and analyze the use of Virtual Reality (VR) in biology learning and to explore its potential in improving conceptual understanding, engagement, and student achievement in the digital era.

METHODS

Research Design

This study employed a Systematic Literature Review (SLR) by selecting relevant articles from the Scopus database. The SLR approach enables a systematic and transparent synthesis of existing knowledge on a defined topic, which in this case is the use of Virtual Reality in biology learning (Maghfiroh et al., 2023). Using SLR helps ensure that the findings address specific research questions in a reproducible manner. The review procedure followed the framework proposed by Arksey & O'Malley (2005), which offers a clear and structured approach for conducting comprehensive literature reviews. This framework guides the review through key stages, namely identifying the research questions, searching for relevant studies, selecting eligible records, charting the data, and collating, summarizing, and reporting the results. Adopting this framework supports rigor, transparency, and reproducibility, and it has been widely used across disciplines.

Identifying the Research Question

The initial stage involved identifying the research question to determine the scope and develop a clear focus for this study. The guiding research question for this systematic literature review is:

"How is Virtual Reality implemented in biology learning?"

This research question provides the foundation for systematically exploring existing studies, ensuring that the review remains focused, coherent, and aligned with the study's objectives.

Identifying Relevant Studies

In the stage of identifying relevant studies, we selected the appropriate database and defined the search keywords. A comprehensive search was conducted in the Scopus database to capture high-quality, peer-reviewed articles. The search strategy employed the following combination of keywords and Boolean operators: ("virtual reality" OR "VR" OR ("immersive" AND "technology") OR ("simulator" OR "simulation")) AND ("biology" OR "biological" OR "life science" OR "bio") AND ("education" OR "learning" OR "teaching" OR "instruction") AND ("engagement" OR "interaction" OR "experience" OR "understanding") AND ("cur-riculum" OR "program" OR "method" OR "approach"). This keyword structure was designed to capture a comprehensive set of studies on the use of Virtual Reality in biology education, with particular emphasis on learner engagement, conceptual understanding, and instructional approaches.

Eligibility Criteria

The eligibility stage aimed to identify studies that met the review's inclusion criteria. The inclusion criteria were defined as follows: (1) articles published between 2016 and 2025; (2) articles written in English; and (3) studies published in open-access journals. These criteria were chosen to ensure that the selected literature is current, accessible, and directly relevant to the research question.

Study Selection

The study selection process was guided by the research question and the relevance of each article to the review objectives. The screening procedure followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Moher et al., 2010). The selection process was carried out in several stages. The initial search in the Scopus database yielded 284 documents. These records were then filtered according to the open-access criterion, resulting in a smaller pool of eligible studies. A further refinement based on publication year (2016–2025) and language (English) reduced the dataset to 163 articles. Each article was then examined for its alignment with the research objectives, and a total of ten studies were identified as meeting all inclusion criteria for the final analysis. The document search process is illustrated in Figure 1.

Data Extraction, synthesis, and Reporting

The reporting phase focused on analyzing the implementation of Virtual Reality in biology education as presented in the eligible studies. Data analysis was carried out through four main procedures adapted from Trilling and Jonkman (Trilling & Jonkman, 2018). First, definitions and conceptual frameworks from the selected studies were coded and summarized. Second, each article was synthesized to extract key components, including the author and publication year, subject area, core concepts, targeted skills, type of learning object, key findings, and supplementary information. The synthesized results provided the foundation for identifying patterns, trends, and research gaps related to the integration of Virtual Reality in biology learning.

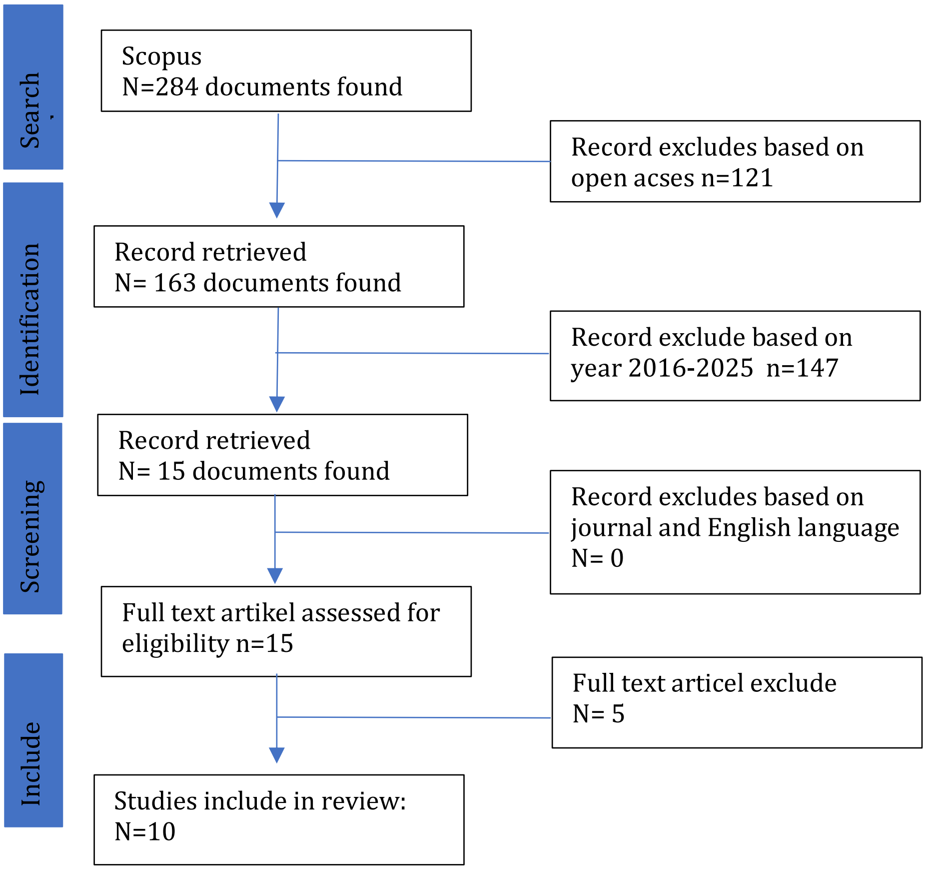

Figure 1. Study selection stage flow

RESULTS AND DISCUSSION

The analysis of ten articles retrieved from the Scopus database indicates that the implementation of immersive technologies and inquiry-based learning approaches has a significant impact on improving students' conceptual understanding, scientific process skills, and learning motivation across various educational levels. Based on a systematic review of studies involving Virtual Reality (VR) laboratories, cloud-based biology laboratories, serious educational games, and interactive molecular modeling environments, several key themes were identified. These themes highlight the developmental trends and educational effectiveness of these innovations within the broader context of modern science education. The results of the analysis are summarized in Table 1.

Table 1.
Summary of Key Research Findings

Author(s)	Country	Main Findings
Jarrett et al. (2016)	Alabama (AS)	The development of an inquiry-based genetics laboratory enhanced students' conceptual understanding and scientific process skills.
Hossain et al. (2017)	Stanford (California)	Cloud laboratories expanded access to biology experiments and supported large-scale authentic learning experiences.
Blikstein & Fuhrmann (2016)	Stanford (California)	The integration of physical and virtual models promoted deep conceptual change in learners' understanding.
Petrizzo et al. (2019)	Hofstra/Northwell (New York)	Digital clinical simulations improved diagnostic reasoning and knowledge relevance among students.
Low & Ellefson (2024)	California	Serious games increased motivation and facilitated conceptual transfer in genetics learning.
Magni dkk. (2019)	Malaysia & Singapure	The international forensic science program enhances authentic learning experiences, cross-cultural competencies, and student employability through a combination of lectures, workshops, and crime scene simulations.
Reen (2024)	Ireland	The use of virtual reality simulations can emphasize the importance of active learning in understanding complex concepts.
Wang (2024)	Taiwan	The use of virtual reality (VR) in K-12 education, particularly through a program called "Escape from the Material Room," can enhance the learning experience and outcomes for students.
Liu (2022)	Taiwan	The integration of virtual reality (VR) in education highlights its positive effects on student engagement and problem-solving skills.
Zaatar (2024)	Dubai	Immersive VR experiences significantly improve student understanding and engagement compared to traditional teaching methods, highlighting VR's potential as a transformative educational tool.

Based on the research findings in Table 1, it can be seen that optimising the use of digital technology through various simulations, namely digital laboratories, serious games, and virtual reality (VR), can be used as a means of improving the quality of science learning. The above studies state that virtual reality has been widely used in the field of biology, thereby supporting effective learning.

Research conducted by Jarrett et al., (2016) shows the effect of developing inquiry-based genetics learning laboratories on conceptual understanding and scientific process skills. In this activity, students carry out complex scientific processes such as DNA analysis and cell observation using restriction digestion, gel electrophoresis, and microscopy techniques. The results showed that students better understood the relationship between genotype and phenotype by actively participating in experiments. The inquiry-based laboratory model also helped transform concepts and improve students' scientific reasoning skills. This is in line with inquiry-based learning theory, which emphasizes that active exploration, problem solving, and reflection are important components in the formation of meaningful scientific knowledge. This method allows students to develop hypotheses, conduct experiments, and interpret empirical data in a flexible but controlled environment (Ikhsan et al., 2016). However, this study also implies the implicit assumption that improved conceptual understanding automatically reflects the depth of students' scientific thinking. A relevant criticism is the lack of exploration of the sustainability of the impact of such learning, especially in relation to the transfer of knowledge to non-laboratory contexts.

Blikstein et al., (2016) proposed a bifocal modelling method that combines direct experiments with virtual simulations. Their study showed that students experienced different events when comparing real experimental results with digital models, which led to cognitive restructuring. This means that engaging learning experiences can help students understand cause-and-effect relationships in complex biological systems. Other research also states that virtual reality can increase student engagement, conceptual understanding, and desire(Amelia et al., 2021; Mariscal et al., 2020; Molina-carmona, 2018; Serin, 2020). Although these findings are consistent with multimedia learning and dual representation theories, this study implicitly assumes that all learners are able to manage the cognitive load generated by multi-representation. In this context, the absence of an analysis of student ability differentiation is a significant gap, given that physical-virtual integration has the potential to increase cognitive overload for learners with low digital literacy.

Research Hossain et al., (2018) shows that innovative cloud-based biology laboratories enable students to conduct remote experiments on Euglena plants to study the phenomenon of phototaxis. This system collaborates with Massive Open Online Courses (MOOCs), which allow thousands of students to conduct online experiments simultaneously. This study shows that cloud-based labs have great potential to increase access to real science learning without the constraints of place or time. The study also emphasizes that the use of well-designed digital technologies is essential to help students engage effectively in scientific research in virtual learning environments. These tools enable access to large-scale experiments while reducing financial and logistical challenges(Mariscal et al., 2020). This finding reinforces the argument that technology can democratise science education. However, from a critical perspective, it is questionable whether cloud-based laboratory experiences truly replicate the complexity of real scientific practice or whether they simplify it. Reliance on simulations has the potential to reduce the uncertainty and experimental error that are essential to authentic science learning.

Several researchers above stated that, a virtual laboratory is a simulated environment that mimics real laboratory experiments using mathematical models, animations, and interactive interfaces. Virtual laboratories are designed to provide a learning experience similar to physical laboratories, but with the flexibility of remote access and reduced risk (Byukusenge et al., 2022). They differ from physical laboratories in that they do not involve the consumption of materials or safety hazards, but still maintain the experimental aspect through digital interaction (Fadillah et al., 2024; Siyamsih, 2024). In addition, cloud-based laboratories enrich the learning experience by providing real-time data and allowing students to analyze biological variability directly. These findings are in line with the principles of authentic inquiry learning, which emphasize active interaction between students, empirical data, and experimental devices in building meaningful and evidence-based scientific understanding. This shows that students acquire better spatial reasoning skills, understand procedures better, and are better able to simulate learning systems in practical situations. This is in line with previous research investigating the readiness of higher education institutions to implement virtual reality (VR) laboratories, which shows that VR has significant potential to enhance learning experiences through three-dimensional visualization and exceptional interactivity (Lamb et al., 2020).

Zaatar et al., (2024) also conducted research the HTC VIVE Pro headset and the Sharecare YOU application to support this. The integration of Virtual Reality (VR) into undergraduate biology education at UEA can significantly enhance student learning experiences and engagement, marking a pioneering effort in educational innovation. These findings show a substantial increase in student assessment scores after the VR experience, indicating that VR effectively aids in understanding complex biological concepts. Previous studies have shown that the use of VR can increase student engagement with learning materials (Vola et al., 2023), which contributes positively to academic performance (George et al., 2018) and learning persistence (Fredricks et al., 2008). Therefore, the development of effective teaching strategies to increase engagement is an important issue to be researched in order to promote overall improvement in educational outcomes.

Low & Ellefson (2024) also developed Punnett Farms, an educational game based on the Unity platform designed to teach Mendelian inheritance principles. Students can predict the results of genetic crosses and learn phenotypic ratios through interactive games in a realistic virtual environment. The results of the trial showed a significant increase in scores and an increase in motivation and learning satisfaction. This study supports the idea that intrinsic motivation plays a crucial role in the success of technology-based learning. Game flow, progressive challenges, and direct feedback were identified as important components to balance fun with learning objectives. As a result, serious games are useful tools for improving conceptual understanding while maintaining high student engagement. Educational game design must explicitly align game mechanics with learning objectives and assessment strategies. Another study supporting this research is that the use of digital games can increase student engagement and learning outcomes (Situmorang et al., 2024).

Cavuoto Petrizzo et al., (2019) revealed in their study that interactive simulations in preclinical immunology classes improve students' clinical reasoning skills. This combines basic and clinical knowledge. Simulations used as learning cases for Primary Immunodeficiency Diseases (PIDD) provide contextual experiences that effectively combine theoretical understanding with practical application. The results of the Objective Structured Clinical Examination (OSCE) showed that students had better diagnostic skills after participating in the simulation. These results confirm that immersive digital simulations can enhance the medical learning curriculum by improving clinical skills and increasing understanding of biomedical concepts. Therefore, simulation-based learning helps build a connection between theoretical knowledge and real-life practice in education.

Based on the above researchers, it can be concluded that educational games are interactive learning tools that integrate game elements such as challenges, scores, and rewards to convey scientific concepts. In biology education, these games are used to teach topics such as cell structure, ecosystems, evolution, and genetics through engaging simulations. With advances in digital technology, educational games have become an integral part of modern education, allowing students to learn while playing. Research shows that they can increase understanding of biological concepts by 25-30% compared to traditional methods, as they involve active learning and immediate feedback (Hamari, 2017). A study by (Rincon-Flores & Santos-Guevara, 2021) found that Foldit was effective for biology students in understanding biochemistry. This game increased high school students' engagement in the topic of evolution (Lin et al., 2025).

Research conducted by Magni et al., (2019) provides students with authentic, intercultural, and cross-jurisdictional learning experiences, enhancing their employability skills. This study discusses an international forensic science curriculum developed between Australia and Malaysia, which aims to improve students' skills through intercultural learning and collaboration. It highlights the importance of addressing contemporary forensic needs and preparing students for cross-jurisdictional investigations in a global context. The innovative curriculum developed will improve students' employability by equipping them with job-ready skills in a global context.

Reen et al., (2024) integrating virtual reality (VR) into life science education has the potential to significantly enhance the learning experience, especially in understanding abstract concepts in molecular and cellular science. The visual and kinesthetic elements of simulation provide a unique entry point to challenging molecular concepts, demonstrating the potential to transform life science education. The use of familiar visual elements can reduce the cognitive load on humans regarding functionality (Prochazkova et al., 2019).

Wang (2025) states that VR has great potential in driving educational innovation and enhancing learning experiences. By integrating unique VR features, such as immersion and interactivity, into the teaching and learning process, educators can create a more engaging and effective learning environment. Besides that, Liu (2024) states that interactive VR learning courses have a positive effect on course identity and students' behavioural intentions in problem solving. Through the interactive design of VR learning materials, students can improve their understanding of the impact of human behaviour on the environment. They can immerse themselves in the virtual world using virtual cameras to explore environmental pollution and record sources of pollution in their surroundings.

Interactive molecular modelling is a digital simulation technique that allows users to visualise, manipulate, and analyse molecular structures through an interactive computer interface. It is often used in biology, chemistry, and pharmacy to understand molecular interactions, such as in drug design or protein studies. With advances in technology, this modelling has become an important tool in education and research, allowing for more in-depth exploration without physical laboratory equipment. Interactive molecular modelling involves the use of software to create 3D models of molecules that can be rotated, enlarged, or modified in real time. This modelling enhances the understanding of abstract concepts by providing interactive visual representations, allowing students to learn through active exploration. Research Domingo & Bradley (2018) shows that interactive modelling increases motivation and knowledge retention in molecular biology learning by up to 25%, especially during distance learning. To provide a comprehensive overview of the patterns of interrelationships between concepts in the implementation of virtual reality in biology education in various countries, the results of the analysis are presented in the form of a concept network visualisation, as shown in Figure 2.

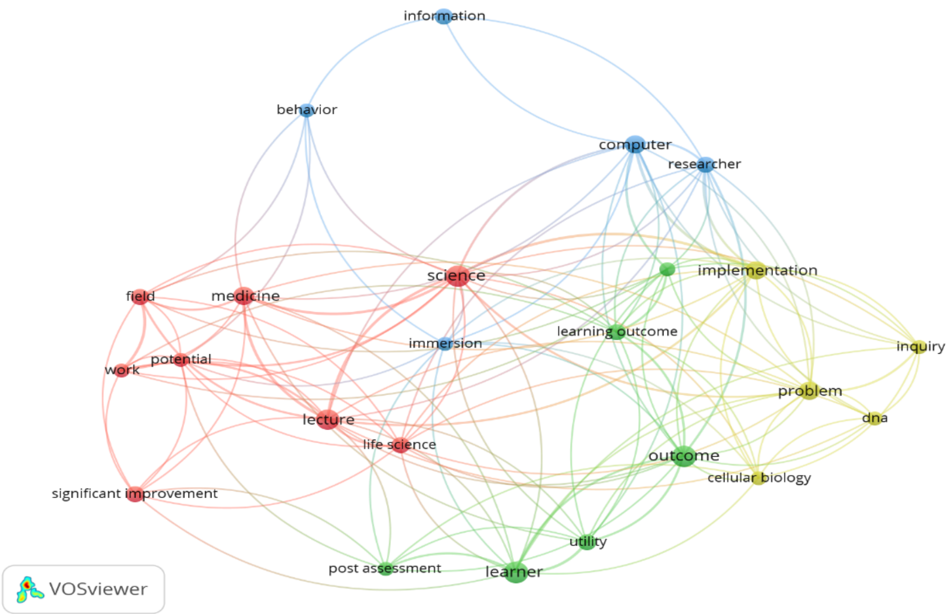

Figure 2. Network of Virtual Reality

Based on the results of the analysis of virtual reality implementation in several countries, visualised through the concept network in Figure 2, it is clear that science plays a central role in connecting various key clusters, ranging from the fields of computing and research (computers, researchers, publications), learning processes (learners, learning outcomes, post-assessment), to specific scientific contexts such as medicine, life sciences and cellular biology. The strong interconnection between nodes shows that biology learning is integrative and collaborative, connecting cognitive, technological, and scientific practice aspects (Byukusenge et al., 2022). The inquiry, problem, and outcome models emphasise the importance of inquiry and problem-solving approaches in producing meaningful learning outcomes, while the connection with implementation and utility reflects the learning orientation towards real-world application and student learning success. Overall, this network depicts a dynamic biology learning ecosystem, where interactions between researchers, technology, and students contribute to the continuous improvement of the quality of the learning process and outcomes(Kareem, 2018; Sattar et al., 2019).

Although the results are mostly positive, there are still some issues to be implemented. The main obstacles to large-scale adoption have been identified as infrastructure and technical issues such as high hardware costs, limited institutional readiness, and inadequate instructor training. Limitations in hardware interface design also need to be improved, such as the operation of VR handles and so on (Lamb et al., 2020; Moro & Gregory, 2019; Popa et al., 2023; Situmorang et al., 2024). For unfamiliar user interfaces, most users need a longer adaptation period. In addition, many institutions do not have adequate policy support and resources to incorporate immersive technologies such as virtual reality (VR) and cloud-based laboratories into their curricula. Basically, these challenges require strategic development and pedagogical innovation to ensure the sustainable integration of immersive technologies in science education, especially biology.

CONCLUSION

Based on the results of the analysis, it can be concluded that the integration of inquiry-based laboratories, digital simulations, cloud-based laboratories, educational games, and immersive technologies such as virtual reality (VR) consistently shows significant potential in improving conceptual understanding, scientific reasoning, engagement, and student motivation in biology and life science learning. These approaches enable students to actively engage in authentic scientific processes, facilitate cognitive restructuring through direct experience and complex visualisation, and bridge the gap between theory and practice in both local and global contexts. However, the successful implementation of these technologies is highly dependent on infrastructure readiness, institutional support, educator competence, and pedagogical design that is aligned with learning objectives. Therefore, the development of planned, sustainable, and evidence-based learning strategies is key to ensuring that the use of immersive and digital technologies not only enhances the learning experience but also has a real impact on the quality and relevance of science education, particularly biology, in the global and digital era.

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