Review Article

Systematic Review on Enhancing Science Process Skills through Virtual Reality in School Education

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Abstract

Developing science process skills (SPS) is fundamental to fostering scientific inquiry and problem-solving abilities among students. This article presents a systematic literature review (SLR) examining the utilisation of Virtual Reality (VR) technology to enhance SPS in school education settings. The study follows the PRISMA model, employing rigorous methodology to identify and analyse relevant research articles from 2012 to 2022. A comprehensive search across databases, including Scopus, Web of Science, Springer Link, and Google Scholar, initially yielded 933 articles, from which 28 were selected for detailed analysis. The review explores VR applications across elementary, middle, and high school levels, focussing on methodologies, theoretical frameworks, and input/output devices used in VR-based science education. The findings reveal that VR technology facilitates immersive and interactive learning experiences in various scientific disciplines, such as Botany, Biology, Physics, and Chemistry. Studies demonstrate the effectiveness of VR in enhancing student engagement, comprehension, and laboratory skills through simulations, games, and virtual field trips. The article highlights the potential of VR to transform science education by encouraging deeper understanding, critical thinking, and skill development among students. It recommends further research into optimal VR design, long-term learning outcomes, and issues of accessibility and equity in science education.

Keywords: Virtual Reality, Science Process Skills, Science Education, and School Students

Introduction

Scientific knowledge and the quality of science education determine a nation's level of development (Kaptan and Timurlenk, 2012). Driven by discoveries, innovations, and insights, science is always changing and progressing (NCF, 2005). The future generation has to be properly taught this scientific understanding through education. Science education encompasses various branches of the natural sciences, including biology, chemistry, physics, earth science, and environmental sciences.,. Science education, which is mandated in schools, aims to instill in students a positive attitude toward learning the subject, a scientific temperament, and an awareness of nature (Léna, 2012).

As a result, learners need to develop the ability to closely observe, examine, and control their physical and biological surroundings. Thus, science and scientific products—two crucial components of the process—can be used to gauge how well science is taught in schools. Studies, however, reveal that science is taught in schools in a highly mechanical manner, with little to no opportunity for creativity, problem-solving, or critical thinking. Students are also restricted to their textbooks. They are examination-oriented, and rote memorisation is the norm. Among the characteristics of science are method and outcome.

However, the majority of the science currently taught in classrooms emphasizes outcomes, which include learning ideas, rules, hypotheses, and facts. When teaching science, teachers tend to neglect the scientific method. Students are hardly encouraged to pay attention, investigate, quantify, categorise, and evaluate the ordinary occurrences going on around them (Ramesh, Patel, 2013). According to NCF (2005) and NCF(2023), a curriculum must include students in learning the procedures and techniques that produce and validate scientific knowledge, nature, and a child's innate scientific curiosity and creativity. Therefore, it is crucial to build process skills in order to understand science effectively.

Science Process Skills are a set of skills that are crucial for all human beings, not just in scientific investigations but also in situations associated with daily living. Learners engage in observation, inquiry, hypothesis, prediction, investigation, interpretation, and communication as they engage with the world in a scientific way. These are sometimes referred to as science's "process skills". When it comes to assisting kids in developing scientific concepts, process skills are essential. Primary and integrated skills are the two categories into which the process skills are classified. Processing in basic science includes observation, inquiry, measurement, communication, classification, prediction, and inference. Controlling variables, establishing operational terms, developing hypotheses, analysing data, and creating models are all necessary components of integrated science process abilities. Thinking and reasoning skills are enhanced when primary and integrated skills are combined.

Science Process Skills (SPS) are essential for scientific inquiry and problem-solving and are developed through science education (Kurniawati, 2021). However, the development of SPS can be hindered by traditional teaching methods and time constraints (Ya and Jun-Li, 2012). This is particularly evident in non-science undergraduate students, who only sometimes apply SPS to problem-solving (Fugarasti et al., 2019). Therefore, there is a need for innovative teaching methods and training to enhance the development of SPS in students.

SPS can be developed through two categories: with technology integration, which involves allowing students to interact with simulations and utilising technological tools like data loggers, sensors, and educational apps to enhance engagement and learning, and without technology integration, which includes hands-on experiments, scientific inquiry activities, collaborative projects, and field trips. Research has shown that science process skills can be developed through both traditional methods and technology integration. Fan (2014) found that a virtual experiment environment can effectively diagnose students' science process skills. Campbell (2016) further emphasised the potential of immersive visualisation, particularly virtual reality, to enhance scientific insight. Connolly (2005) highlighted the increasing capabilities of virtual applications in science and technology, suggesting their potential to support and enhance the learning process. These studies collectively underscore the potential of technology, particularly virtual simulations, in developing science process skills. When it comes to technology integration, utilising simulations is particularly important. A virtual simulation is a category of simulation that uses simulation equipment to create a simulated world for the user. It allows users to interact with a virtual world. Virtual simulations utilise a range of input and output hardware to create immersive experiences for users. Input hardware includes body tracking systems that capture movements, eye trackers for detecting eye movements, physical controllers for direct manipulation, and voice and sound recognition for interaction. Advanced research explores brain-computer interfaces (BCIs) to enhance immersion. For output, virtual simulations employ various hardware such as visual displays (including desktop and wrap-around screens and head-mounted displays), aural displays (using speakers or headphones for spatial audio), haptic displays (providing tactile feedback), and vestibular displays (motion simulators for sensations of motion and acceleration).

These technologies combine to simulate rich and engaging virtual environments (Ray and Deb, 2016). Simulations are often called Virtual Reality (*Virtual Reality Headset*,, 2024). Virtual Reality (VR) technology enhances science process skills by engaging students actively. VR offers interactive and hands-on learning experiences, visualises abstract concepts, and motivates students with immersive environments. The multisensory feedback in VR fosters engagement facilitates collaborative learning and connects classroom concepts to real-world applications. VR's accessibility and inclusivity make it a promising tool for developing critical thinking and process skills in science education.

It is essential to systematically analyse research articles to conduct future research using VR technology to enhance science process skills. Specifically, this research investigates the types of VR technological input and output utilised, the learning outcomes observed, the specific virtual environments employed, and the science process skills developed through VR technology. This analysis will provide valuable insights into how VR can be effectively integrated into science education to promote active learning and skill development. The research objectives include:

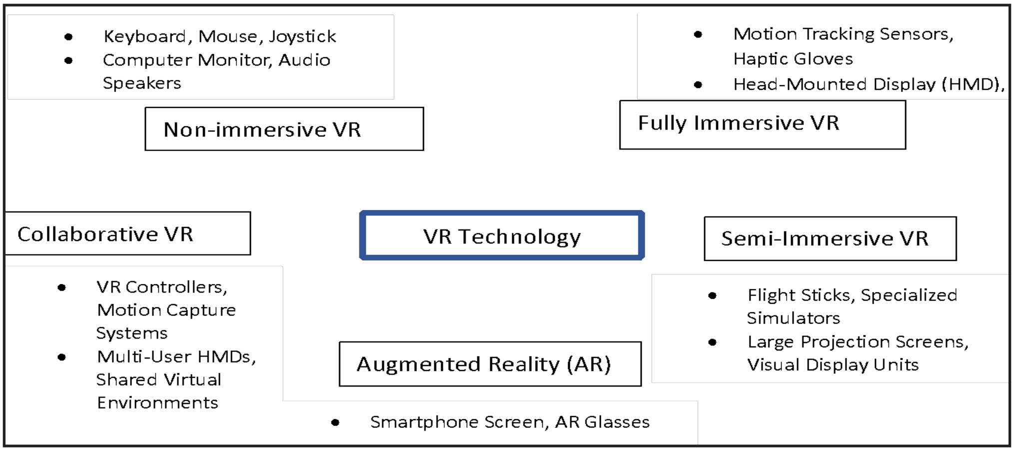
- identifying the specific VR technological inputs and outputs used in science education,
- examining the learning outcomes associated with VR-based science learning,
- investigating the types of virtual environments utilised for teaching science concepts,
- identifying the particular science process skills that are enhanced through VR technology.

Conceptual Framework

Virtual Reality in Science Education

Virtual Reality (VR) creates a sense of presence in a digital space, evolving from 19th-century panoramic art, like Roubaud's "Battle of Borodino", to today's immersive, sensory-stimulating computer simulations. Tracing back to Heilig's 1956 Sensorama, VR's history showcases its transformative journey (Evenden, 2016). VR technology has evolved significantly, and several types of VR experiences are available today. Virtual reality technology encompasses a spectrum from non-immersive experiences, akin to video games, to fully immersive simulations with head-mounted displays and body suits. Semi-immersive VR blends virtual elements with the physical world, often for training purposes, while augmented reality enhances real-world environments with digital overlays. Collaborative VR connects users in a shared virtual space for interaction and teamwork.

Figure-1: Types of VR Technology and their input/output devices



Even with the help of words and two-dimensional representations, young learners sometimes struggle to comprehend the number of abstract and complicated concepts included in scientific knowledge (Parker and Heywood, 1998). Additionally, laboratory experiments play a crucial part in science teaching. However, there is a risk of excessive material waste from tests, thus safety precautions need to be implemented. Because of the educational opportunities provided by information and communication technology, virtual labs and simulations have emerged as a useful and efficient substitute for physical, hands-on laboratories (Naz et al., 2024). Students need to be interested in order to learn science in virtual reality, in addition to feeling present in the environment. Scholars (Mikropoulos and Strouboulis, 2004) have proposed a number of strategies to use VR's technical advantages for science teaching.

Examples include embodying a distinct person or object, presenting incredibly little or massive items that are not easily visible, and providing first-order feelings of being able to move and interact with objects in novel environments (Durukan et al., 2020). These suggestions emphasise virtual reality's technological potential for scientific education. To guarantee the significance of the way the learning materials are organised and the advantages of social interactions in VR research, these guidelines must be updated (Matovu et al., 2023).

Virtual reality on enhancing Science Process Skills

Numerous recommendations exist about the science process skills that students have to acquire and engage effectively. The most significant set of guidelines, however, was produced in 1967 by a team of scientists and science educators at the American Association for the Advancement of Science (McComas, 2014). They had observed scientists at work and created a list of competencies that were commonly utilised by all scientists. Essential Science Process Skills, which are the cornerstones of scientific inquiry, are identified by the National Curriculum Framework (NCF), 2005. These abilities include seeing, categorising, inferring, measuring, predicting, and communicating. It also includes integrated skills like controlling variables, formulating hypotheses, conducting experiments, and interpreting data, which are crucial for advanced scientific understanding. The framework encourages experiential learning through direct interaction with the environment and practical activities that foster conceptual clarity. Moving to the NCF 2023 builds upon the previous framework by emphasising hands-on learning through projects, experiments, and investigative activities. It stresses the importance of applying scientific knowledge to real-life scenarios, enhancing students' problem-solving and critical-thinking abilities. The NCF 2023 also recommends regular assessments evaluating knowledge acquisition and applying Science Process Skills in diverse contexts. Science process skills evolve as students' progress through different educational levels, building a solid foundation for scientific thinking and inquiry. Basic SPS typically begin to be developed at the elementary level of education. (Ahsani and Rusilowati, 2022). Usually presented in middle and high school, integrated SPS involves more complicated activities including controlling variables, defining concepts, generating hypotheses, and analysing results (Roth and Roychoudhury, 1993). Virtual reality technology can potentially lead to a new milestone in acquiring Science Process Skills (Artun et al., 2020). The diversity inherent in VR's application is evident in the varied content areas, educational levels, and contexts explored. (Dede et al., 2017)

Illuminated VR's potential to impart ecological concepts to middle school students. This underscores VR's adaptability to bridge gaps in understanding complex scientific concepts among younger learners. Simultaneously, studies such as those by Mikropoulos and Natsis (2011) extend VR's reach to tertiary education, indicating its efficacy in cultivating higher-order thinking skills. This versatility suggests the potential for VR to be integrated across diverse educational levels and settings. Bailenson et al. (2008) exemplify the integration of the Experiential Learning Theory in designing a VR-based science curriculum. This theoretical foundation underscores the immersive experiences that VR environments can facilitate, aligning with Kolb's assertion that learning is inherently experiential. Moreover, the infusion of gaming elements within VR applications is notable (Konak et al., 2014)

Methodology

To gain a comprehensive and concrete understanding of how virtual reality can enhance Science Process Skills, we carried out a systematic literature review (SLR) using a strict and well-defined process. The process included finding, choosing, and evaluating all pertinent research material associated with certain research problems (Radianti et al., 2020).

The PRISMA approach, which stands for Preferred Reporting Items for Systematic Reviews and Meta-Analyses, was followed to ensure our review process's systematic and transparent conduct (Moher et al., 2009). The review process involved the following steps (Lan et al., 2023):

- specifying research questions
- searching relevant databases
- applying inclusion/exclusion criteria to select studies
- analysing and extracting data from the selected studies

- summarising and interpreting the findings
- writing the review report

The databases searched included *Scopus*, *Web of Science*, *Springer Link,* and Google Scholar. Various terms in the literature have referred to immersive virtual reality, including virtual reality, fully immersive virtual reality, 3D virtual reality, interactive virtual reality, immersive technology, and virtual environments. To ensure a comprehensive search of the relevant literature, we followed (Merchant et al., 2014) recommendation to consider alternative terms with equivalent meanings. We used Boolean operators (AND, OR) to mix alternative terms that we found in the database thesaurus. Key phrases such as "immersive virtual reality," "Science Process Skills," "application content," and "educational level," as well as synonyms, are listed in Table 1 and were pertinent to our research subject and concerns. By employing these substitute phrases, our objective was to optimize the data acquired during our methodical literature analysis and guarantee our study encompassed every relevant investigation.

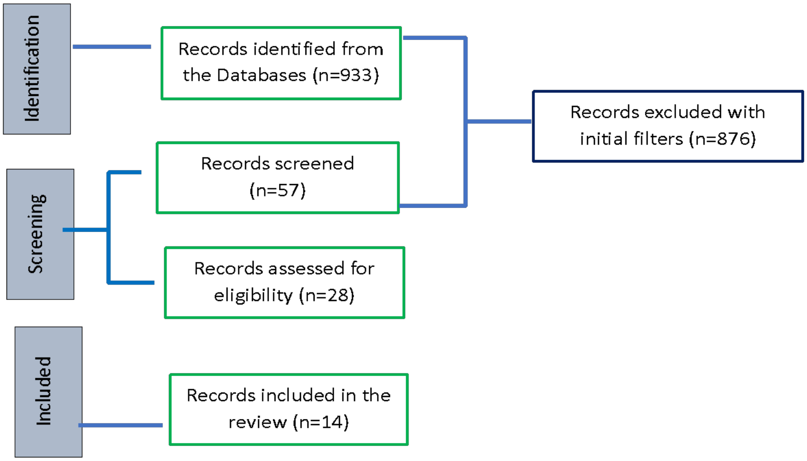
The primary search string used was "virtual reality" OR "immersive virtual reality" AND "Science Process Skills" AND "school students*". ("Immersive virtual reality" OR "Fully immersive virtual reality" OR "3D virtual reality" OR "interactive virtual reality" OR "immersive technology" OR "virtual environment" OR "synthetic reality" OR "augmented virtuality" OR "mixed reality" OR "extended reality") AND ("Scientific Process Skills" OR "scientific method" OR "scientific inquiry") AND ("School students" OR "K-12 students" OR "primary school students" OR "secondary school students" OR "middle school students") AND ("Engaging features" OR "Interactive components" OR "Realistic stimuli" OR "Sensory effects" OR "Participatory features")

To streamline the research, we set precise inclusion criteria for selecting empirical, peer-reviewed studies on virtual reality in science education from 2012 to 2022, conducted in school settings and focusing on SPS. Exclusion criteria excluded non English studies outside of school education or VR, opinion pieces, abstract-only publications, and irrelevant outcomes.

The initial search conducted across various academic and electronic databases yielded 933 items. After applying the initial filters to remove duplicates, considering publication dates, and assessing titles for relevance, 876 items were discarded. The abstract review process was used to examine the remaining 57 publications in further detail. Excluded were studies that did not address the particular subjects of interest in scientific education, leading to the removal of 29 more articles. The remaining 28 articles were subjected to a thorough review guided by the established inclusion and exclusion criteria. Upon closer examination, ten studies among the 14 articles were found to need more clear empirical evidence regarding immersive virtual reality technology. Consequently, these studies were removed from the final dataset. The remaining 18 articles, which met all the criteria and provided relevant empirical evidence, were included in the systematic review.

The paper uses PRISMA in Figure 1 to show the flow of study selection and inclusion and to demonstrate the review process. This graphic depiction helps to illustrate the transparency and rigour of the review procedure.

Figure-2: PRISMA Review Process



Findings

The 14 selected articles were comprehensively analysed to derive aggregated findings pertinent to the research questions. A triangulation approach was adopted to establish a robust foundation (Kern, 2016). The initial step involved meticulously examining and evaluating immersive virtual reality studies, encompassing trends, theoretical frameworks, methodologies, objectives, outcomes, and their intersections with science education.

Research	School Level	Methodology	Theories	Skill	Input/Output Devices
Lee et al. (2022)	Elementary School	Mixed method	Hypothesised learning model	Understanding	VR headsets (HMD)
Rasheed et al. (2021)	Secondary School	Quantitative research	Not mentioned	Observation, measurement, data analysis, and critical thinking.	Oculus Rift HMD
Tutwiler et al. (2012)	Secondary School	Quasi-experimental method	Constructivism	Observation, data collection, analysis, interpretation	Laptop
Webb et al. (2021)	Secondary School	Quantitative method	Learning and haptic feedback	Understanding	Computer and VR headset
Tsivitanidou et al. (2021)	High School	Quantitative method	Inquiry-based approach	Critical thinking, scientific reasoning	Oculus (HMD) and personal computers
Boda and Brown (2020)	Elementary School	Quantitative method	Situated learning theory	Communication skills	phones Google Cardboard
Jagodzinski and Wolski (2015)	Middle School and High School	Mixed method	Constructivist and experiential learning theories	Experimental design.	A Kinect sensor and a computer

Research	School Level	Methodology	Theories	Skill	Input/Output Devices
Anderson and Barnett (2013)	Middle School	Mixed method	Game-based learning theory	Does not explicitly state	computer
Chen et al. (2013)	Middle School	Quasi-experimental design	5E Instructional Model	Inquiry, problem-solving, and critical thinking	Computer
Chao et al. (2016)	High School	Quasi-experimental design	Knowledge integration assessment framework	Data collection, interpretation	motion sensors
Wilson et al. (2018)	High School	Mixed method	cognitive load	Collaborative knowledge construction	Computer
Hite et al. (2019)	Secondary School	Quantitative research	Piaget's theory of cognitive development	Not mentioned	3-D screen, haptic technology, eyeglasses
Georgiou et al. (2021)	High School	Mixed method	Learning Experience (LX)	Statement of problems, formulation of hypotheses, experimentation,	Oculus Rift head-mounted
Makransky and Mayer (2022)	Middle School	Quantitative method	Cognitive, affective model	Understand Scientific temper Interpret	Head-mounted display (HMD)

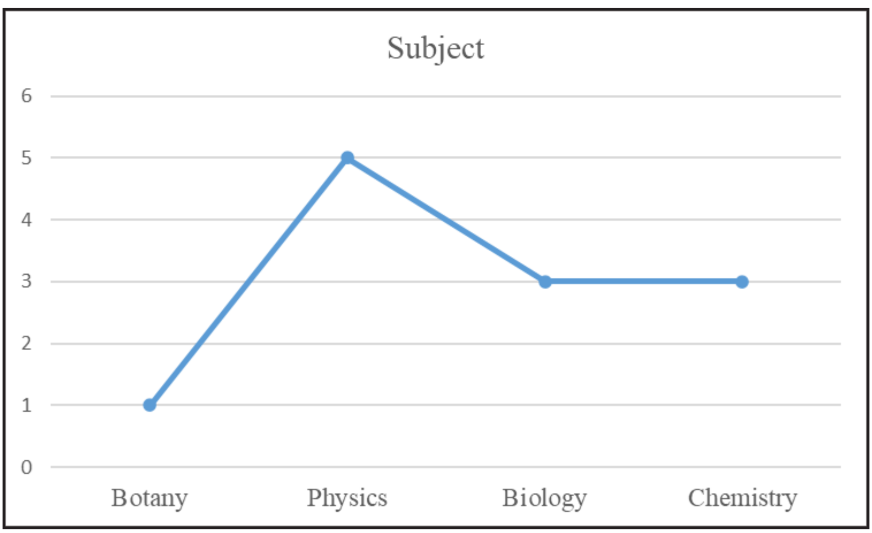
Lee et al. (2022) conducted a mixed method study at the elementary school level to develop a hypothesised learning model that incorporated epistemic curiosity, affective factors, and learning outcomes to enhance students' understanding of plant concepts. They utilised Samsung Gear VR headsets as input/output devices. Rasheed et al. (2021) employed quantitative research at the secondary school level, using Oculus Rift head-mounted displays (HMDs) to investigate observation, measurement, data analysis, and critical thinking skills. The specific theories guiding the study were not explicitly mentioned. Tutwiler et al. (2012) utilised a quasi-experimental methodology at the secondary school level with a constructivist approach. Their study focused on observation, data collection, analysis, interpretation, critical thinking, problem-solving, and decision-making skills using laptops as input/output devices.

Webb et al. (2021) employed a quantitative method at the secondary school level, integrating learning and haptic feedback to enhance understanding. They utilised computers and VR headsets as input/output devices. Tsivitanidou et al. (2021) conducted a quantitative study at the high school level, applying an inquiry-based approach to promote critical thinking, scientific reasoning, data analysis, and interpretation. They used Oculus Rift HMDs and personal computers as input/output devices. Boda and Brown (2020) utilised a quantitative method at the elementary school level, applying situated learning theory to enhance communication skills. They used Samsung Galaxy S6 phones and Google Cardboard as input/output devices. Jagodzinski and Wolski (2015) employed a mixed-methods approach with middle and high school students, guided by constructivist and experiential learning theories. They utilised a Kinect sensor and a computer for observation, measurement, data analysis, and experimental design. Anderson and Barnett (2013) used a mixed methodology at the middle school level, focusing on game-based learning theory using computers as input/output devices. However, explicit theories guiding the study were not mentioned. Chen et al. (2013) implemented a quasi-experimental design at the middle school level, employing the 5E Instructional Model to enhance inquiry, problem solving, and critical thinking skills. They used computers as input/output devices. Chao et al. (2016) conducted a quasi-experimental study at the high school level, employing a knowledge integration assessment framework using temperature, pressure, and motion sensors as input/output devices.

Wilson et al. (2018) conducted a mixed method study at the high school level, employing situated learning and cognitive load theories to foster collaborative knowledge construction and scientific argumentation using computers as input/output devices. At the secondary school level, Hite et al. (2019) used quantitative research under the direction of Piaget's theory of cognitive development. They used polarised eyeglasses with reflecting sensors for tracking cameras, a 3-button stylus with integrated haptic technology, and a liquid crystal 3-D stereoscopic display screen.

Georgiou et al. (2021) employed a mixed method approach at the high school level, utilising a Learning Experience (LX) design within an inquiry-based learning environment. They used Oculus Rift head-mounted displays (HMDs) as input/output devices. Makransky and Mayer (2022) conducted a quantitative study at the middle school level, applying a cognitive-affective model to understand scientific temper and interpretation. They used head-mounted displays (HMDs) as input/output devices.

Figure -3: Science subjects were explored using VR



Virtual Reality (VR) technology has been explored across various educational scientific disciplines, including Botany, Biology, Physics, and Chemistry. In

Botany, a study on elementary school students utilised a VR application ("Find the ROOT") to engage students in interactive exploration of botanical concepts, potentially encompassing plant structures and growth patterns. In Biology, VR has been employed extensively with four distinct educational concepts: the development of a haptic-enabled 3D VR model of the cell membrane for secondary school education, the creation of an immersive game ("Universe") for high school biology teaching, and conducting virtual field trips to Greenland using head-mounted displays (HMDs) for middle school biology education. In Physics, VR has facilitated hands-on learning through simulations and experiments across secondary and high school levels, including teaching complex concepts such as the Theory of Relativity through immersive experiences. Likewise, in Chemistry, VR applications have ranged from developing custom VR software and games for interactive learning to implementing sensor augmented virtual labs for high school students to explore gas behaviour. These educational initiatives highlight the innovative use of VR technology to enhance understanding, engagement, and practical learning experiences in diverse scientific disciplines within educational settings. Each study demonstrates the potential of VR to create immersive and interactive educational contexts that support deeper exploration and comprehension of complex scientific concepts across different grade levels.

Discussion and Suggestion

The review identified several factors that influenced the effectiveness of VR in developing Science Process Skills. These included the design and quality of the VR program, the level of student engagement, and the role of the teacher in facilitating the learning process. Studies also highlighted the importance of providing appropriate guidance and scaffolding to students to effectively use VR for learning science process skills. VR provides immersive experiences that enhance engagement and facilitate understanding complex scientific concepts like molecular structures or planetary systems. This technology improves student motivation by offering interactive learning experiences and hands-on experimentation, leading to increased knowledge acquisition and retention. VR simulations also foster specific skills such as experimentation, data analysis, problem-solving, and collaboration, which are essential for scientific inquiry and exploration. Overall, VR-based learning offers an innovative and practical approach to enhancing science education and developing critical Science Process Skills among students.

All the referenced studies were conducted outside India and are not specific to Indian contexts. Additionally, most of the above reviewed studies utilised already-developed VR applications and software. Therefore, countries like India can incorporate these developed VR applications to teach abstract science concepts. Conducting research with VR in science education can effectively enhance Science Process Skills. The following suggestions can address the issues and effectively propose ways to incorporate VR into science teaching.

- Infrastructure Development: Focus on advocating for network infrastructure development in educational institutions, especially in rural areas. This could involve government initiatives to enhance connectivity and access to digital technologies, which are essential for effectively integrating VR into science education.

- Digital Literacy Education: Emphasise the importance of education and training programs to improve students' digital literacy. This includes teaching students how to search for and utilise information effectively, which is crucial for leveraging VR technologies in learning.
- Inclusive Policies and Actions: Advocate for appropriate actions to ensure the sustainable integration of socially excluded groups, including those facing economic challenges or residing in remote areas. This could involve policy interventions that promote equitable access to educational resources, including VR technologies.
- Community Initiatives: Highlight the role of charitable organisations and community-driven initiatives in bridging the digital divide. For instance, providing recycled computers and establishing WiFi networks in low-income households can facilitate access to educational resources, including VR-based learning tools.

Various educational approaches have been developed to enhance the efficacy of virtual reality in scientific teaching. As a result, a few recent studies have demonstrated that using different scaffolding methodologies with VR can boost its effectiveness. Virtual reality technology encompasses a spectrum from non-immersive experiences, akin to video games, to fully immersive simulations with head-mounted displays and body suits. Semi-immersive VR blends virtual elements with the physical world, often for training purposes, while augmented reality enhances real-world environments with digital overlays. Collaborative VR connects users in a shared virtual space for interaction and teamwork.

Conclusion

Virtual Reality (VR) can revolutionise science education by enhancing student engagement, understanding of concepts, and laboratory skills (Potkonjak et al., 2016). It particularly promotes deeper learning, content mastery, and creative endeavour in high school science (Mikropoulos and Natsis, 2011). However, the design of VR software for teacher education should consider factors such as interactivity, feedback, and user control (Matsubara et al., 2002). Despite the potential of VR, there is a need for further research to explore its impact on learning outcomes in science education (Durukan et al., 2020).

The systematic analysis of VR technology in science education reveals significant insights. VR has demonstrated efficacy in enhancing Science Process Skills through immersive and interactive experiences, improving student engagement and knowledge retention. Future research should explore optimal VR design principles, assess long-term learning outcomes, and address accessibility and equity concerns. Educators and researchers should collaborate to develop standardised VR content aligned with curriculum objectives, ensuring inclusive and effective integration into science education. Integrating VR into science curricula holds immense potential to transform teaching and learning, fostering more profound understanding, critical thinking, and skill development among students. This technology can bridge gaps in traditional education by providing dynamic and experiential learning opportunities, paving the way for innovative and effective science education practices.

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