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Utilization of Virtual Reality (VR) in Enhancing Science Concept Understanding

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Abstract

The integration of Virtual Reality (VR) in science education has emerged as an innovative approach to address difficulties in understanding abstract and complex concepts. This study aims to analyze the effectiveness of VR in enhancing students' conceptual understanding and to identify the technological and pedagogical factors influencing its success. A quantitative approach with an explanatory design was employed, involving students who participated in VR-based science learning. Data were collected through structured questionnaires, as well as pre-test and post-test assessments, and analyzed using descriptive statistics, paired sample t-tests, and multiple regression analysis. The results indicate a significant improvement in students' conceptual understanding, as evidenced by higher post-test scores compared to pre-test results. Technological factors, particularly immersion and interactivity, show a more dominant influence, while pedagogical factors such as guided inquiry and instructional design also contribute significantly. The discussion highlights that VR is especially effective in facilitating visualization and comprehension of abstract scientific concepts. In conclusion, the effectiveness of VR depends on the integration of immersive technology with appropriate pedagogical strategies, making it a powerful tool for improving conceptual understanding in science learning.

Keywords:
Virtual Reality, Conceptual Understanding, Science Learning, Learning Outcomes, Immersive Technology
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1. INTRODUCTION

The rapid advancement of digital technology has significantly transformed the landscape of science education, particularly through the integration of immersive technologies such as Virtual Reality (VR). As an emerging instructional tool, VR offers a highly interactive and three-dimensional (3D) learning environment that enables students to visualize and manipulate complex scientific phenomena that are otherwise difficult to observe directly. In science education, many concepts such as atomic structures, molecular interactions, astronomical systems, and thermodynamic processes are inherently abstract and often challenging for students to comprehend through conventional teaching methods. VR addresses this limitation by providing immersive simulations that allow learners to experience these phenomena in a realistic and engaging manner. Consequently, VR has gained increasing attention as a promising technology for enhancing science learning outcomes, particularly in fostering deeper conceptual understanding (Matovu et al., 2022; Mallek et al., 2024; Wong et al., 2024; Ka et al., 2025; Cabrera-Duffaut et al., 2024).

The integration of VR into science education aligns with contemporary pedagogical paradigms that emphasize experiential and constructivist learning. Through immersive environments, students are not merely passive recipients of information but active participants in the learning process. VR enables learners to explore, experiment, and interact with virtual objects, thereby facilitating meaningful learning experiences that support knowledge construction. For instance, students can observe molecular structures in three dimensions, simulate physical experiments without safety risks, and engage in virtual field trips that enhance contextual understanding. These capabilities make VR particularly relevant for science education, where understanding often depends on the ability to visualize and conceptualize complex systems (Mallek et al., 2024; Marougkas et al., 2023). Furthermore, VR-based learning environments have been shown to increase student motivation and engagement, which are critical factors in achieving effective learning outcomes.

Despite these advantages, the growing body of research on VR in education reveals a critical limitation: the majority of studies tend to focus on affective outcomes such as motivation, engagement, and user experience, rather than on cognitive outcomes, particularly conceptual understanding. A comprehensive review of immersive VR (IVR) in science education, encompassing 64 studies conducted between 2016 and 2020, found that while VR consistently enhances students' interest and engagement, its impact on learning outcomes—especially conceptual understanding—remains inconclusive and insufficiently explored (Matovu et al., 2022). This indicates that although VR is widely recognized as an engaging educational tool, there is still limited empirical evidence demonstrating its effectiveness in improving students' deep understanding of scientific concepts.

Further reinforcing this issue, recent systematic literature reviews and bibliometric analyses highlight that many VR studies in education are characterized by short-term interventions, diverse research contexts, and a lack of strong theoretical grounding. As a result, it becomes difficult to draw definitive conclusions about the specific impact of VR on conceptual understanding in science. Many studies do not adequately integrate established learning theories, such as constructivism or experiential learning, into the design and implementation of VR-based instruction. This lack of theoretical alignment may limit the effectiveness of VR as a learning tool and hinder its potential to support meaningful conceptual change (Mallek et al., 2024; Rojas-Sánchez et al., 2022; Dhanil & Mufit, 2024;

Marougkas et al., 2023). Therefore, there is a clear need for more rigorous and theory-driven research that examines how VR can be effectively utilized to enhance conceptual understanding in science education.

In addition to the limited focus on conceptual outcomes, another important research gap lies in the insufficient exploration of factors that influence the effectiveness of VR in learning. While VR technology offers advanced features such as high immersion, interactivity, and realism, these technological attributes alone do not guarantee improved learning outcomes. The effectiveness of VR depends on a combination of technological and pedagogical factors, including the level of immersion, usability, absence of cybersickness, and alignment with instructional design. Studies suggest that higher levels of immersion are associated with greater learning gains, as they enable students to engage more deeply with the learning content. However, excessive immersion or poorly designed VR environments may lead to cognitive overload or discomfort, which can negatively affect learning (Matovu et al., 2022; Dhanil & Mufit, 2024).

Moreover, user perceptions of VR, such as perceived usefulness, ease of use, and enjoyment, play a significant role in determining its adoption and effectiveness. When students perceive VR as a valuable and enjoyable learning tool, they are more likely to engage actively and persist in the learning process. Conversely, negative experiences, such as technical difficulties or physical discomfort (e.g., cybersickness), can hinder learning and reduce the effectiveness of VR-based instruction (Ferdinand et al., 2023; Sumardani & Lin, 2024). These findings highlight the importance of considering user experience and technological quality in the design and implementation of VR learning environments.

Equally important are the pedagogical factors that shape how VR is integrated into the learning process. Research indicates that VR is most effective when it is aligned with appropriate instructional strategies, such as inquiry-based learning, guided inquiry, collaborative learning, and experiential learning. These approaches emphasize active participation, critical thinking, and knowledge construction, which are essential for developing conceptual understanding. For example, studies have shown that VR combined with guided inquiry significantly improves students' understanding of scientific concepts, such as heat and temperature, compared to traditional teaching methods (Torres et al., 2026). Similarly, VR-based instruction has been found to enhance students' understanding of 3D structures and improve test scores in STEM disciplines by 12–25% (Wong et al., 2024; Ka et al., 2025).

Furthermore, research in biology education demonstrates that VR can facilitate conceptual understanding by enabling students to visualize complex biological processes and structures, thereby bridging the gap between abstract concepts and concrete experiences (Tolentino & Varela, 2025). Meta-analytical evidence also supports the effectiveness of VR in improving science learning outcomes, indicating that VR-based instruction generally leads to better performance compared to conventional teaching methods (Dhanil & Mufit, 2024). However, these positive outcomes are not universal and often depend on how VR is implemented within the instructional context.

The variability in research findings suggests that the effectiveness of VR in enhancing conceptual understanding is not solely determined by the technology itself but is strongly influenced by the design of the learning experience. In particular, the integration of VR with learning theories such as constructivism and experiential learning is crucial for maximizing its educational potential. Constructivist approaches emphasize that learners actively construct knowledge through interaction and experience, which aligns well with the immersive and interactive nature of VR. Similarly, experiential learning theory highlights the importance of learning through direct experience, reflection, and application, all of which can be facilitated through VR environments (Mallek et al., 2024; Marougkas et al., 2023).

Another important aspect is the role of cognitive and motivational factors in VR-based learning. Studies indicate that interventions that emphasize the usefulness of VR for learning can enhance students' motivation and improve learning outcomes. For instance, priming students to perceive VR as a valuable learning tool has been shown to increase their engagement and achievement in science learning tasks (Ferdinand et al., 2023). This finding underscores the importance of not only designing effective VR environments but also preparing students to use them in a meaningful way.

Based on the aforementioned issues, this study identifies a significant research gap in the existing literature: the lack of comprehensive analysis of VR effectiveness in enhancing conceptual understanding in science, particularly when considering both technological and pedagogical factors. While previous studies have provided valuable insights into the potential of VR, there is still a need for integrative research that examines how these factors interact to influence learning outcomes. This study addresses this gap by adopting a holistic approach that considers both the effectiveness of VR in improving conceptual understanding and the factors that determine its success.

The novelty of this research lies in its focus on conceptual understanding as the primary learning outcome, rather than solely on engagement or motivation. In addition, this study integrates technological and pedagogical perspectives to provide a more comprehensive analysis of VR-based learning. By examining factors such as immersion, usability, instructional design, and learning strategies, this study aims to contribute to the development of more effective VR-based instructional models for science education.

Therefore, the main objective of this study is to analyze the effectiveness of Virtual Reality (VR) in enhancing students' conceptual understanding of science and to identify the key technological and pedagogical factors that influence its success. Through this analysis, the study seeks to provide empirical evidence and practical insights that can guide educators, researchers, and policymakers in optimizing the use of VR in science education. Ultimately, this research aims to support the development of innovative and effective learning environments that can address the challenges of teaching complex scientific concepts in the digital age.

2. METHOD

This study employs a quantitative research approach with an explanatory design to examine the effectiveness of Virtual Reality (VR) in enhancing students' conceptual understanding of science and to identify the technological and pedagogical factors influencing its success. The population of this study consists of students in secondary or higher education who have experienced VR-based learning in science subjects. A purposive sampling technique is applied to select participants who meet specific criteria, including (1) active involvement in VR-assisted science learning, (2) exposure to VR learning modules for at least one instructional unit, and (3) willingness to participate in the study. Data are collected using a structured questionnaire developed based on established constructs, including conceptual understanding (e.g., comprehension, application, and interpretation of scientific concepts), technological factors (e.g., level of immersion, ease of use, perceived usefulness, and absence of cybersickness), and pedagogical factors (e.g., instructional design, inquiry-based learning, and learning interaction). The instrument uses a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). In addition, a pre-test and post-test design is incorporated to measure changes in students' conceptual understanding before and after the implementation of VR-based learning.

The data analysis is conducted through several systematic stages to ensure the robustness and validity of the findings. First, descriptive statistical analysis is used to present an overview of students' perceptions and learning outcomes related to VR utilization. Second, validity and reliability tests are performed using Pearson correlation and Cronbach's alpha to confirm the consistency and accuracy of the research instruments. Third, paired sample t-tests are applied to examine the differences between pre-test and post-test scores, thereby determining the effectiveness of VR in improving conceptual understanding. Furthermore, multiple linear regression analysis is conducted to analyze the influence of technological and pedagogical factors on learning outcomes. Prior to regression analysis, classical assumption tests—including normality, multicollinearity, and heteroscedasticity are carried out to ensure model suitability. The coefficient of determination (R^2) is used to evaluate the explanatory power of the independent variables, while hypothesis testing through t-tests and F-tests is employed to determine the significance of the relationships. The results are then interpreted comprehensively to provide insights into how VR can be optimally implemented to enhance conceptual understanding in science learning.

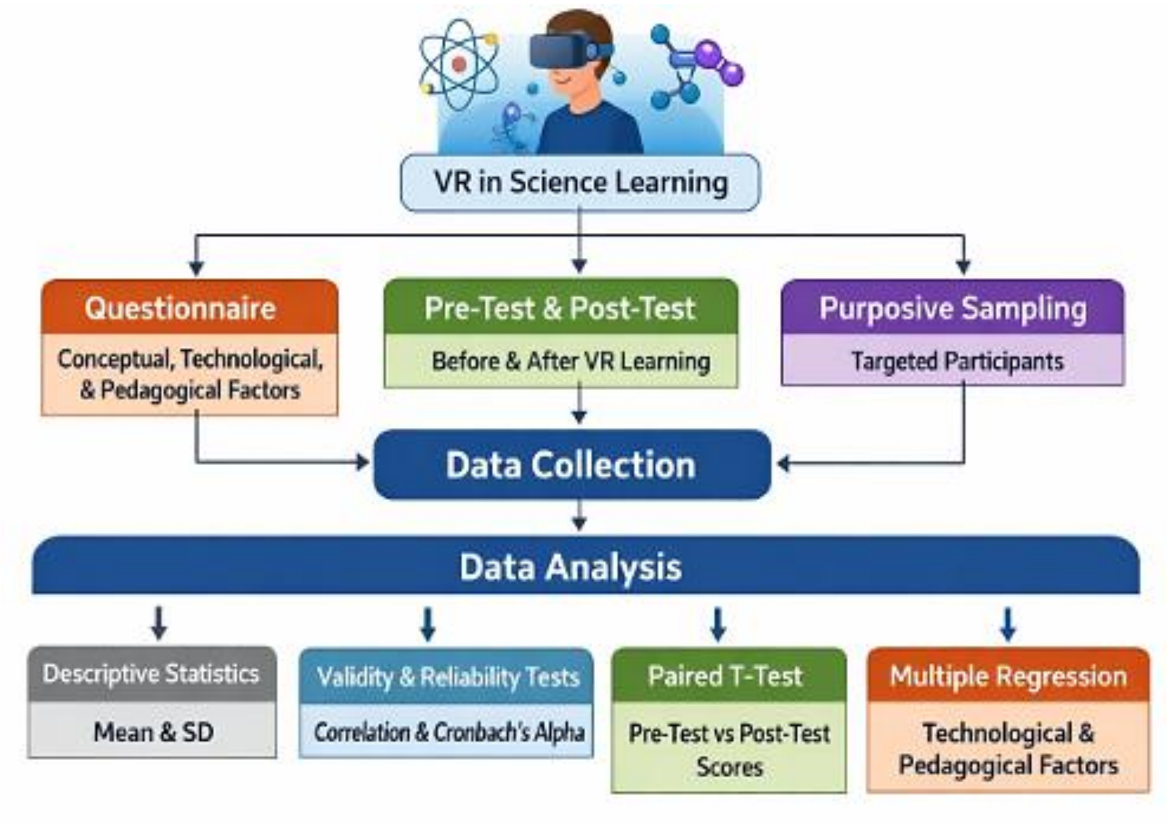

Figure 1. Journal of Learning Spectrum

3. RESULTS AND DISCUSSION

3.1. Results

To provide an overview of students' perceptions and learning outcomes after the implementation of Virtual Reality (VR) in science learning, a descriptive statistical analysis was conducted on the main research variables.

Table 1. Descriptive Statistics of Research Variables

Variable	Mean	Std. Deviation	Category
Conceptual Understanding	4.18	0.54	High
Pre-Test Score	68.25	8.40	Moderate
Post-Test Score	82.70	7.15	High
Learning Engagement	4.22	0.50	Very High
Technological Factors	4.15	0.52	High
Immersion Level	4.20	0.49	Very High
Ease of Use	4.12	0.55	High
Pedagogical Factors	4.08	0.60	High
Instructional Design	4.05	0.58	High
Guided Inquiry Learning	4.10	0.56	High

The results presented in Table 1 indicate that the use of VR in science learning significantly enhances students' conceptual understanding, as reflected by the high mean score (4.18). The comparison between pre-test (68.25) and post-test scores (82.70) demonstrates a substantial improvement in students' learning outcomes after VR implementation. This suggests that VR effectively facilitates deeper comprehension of scientific concepts. Additionally, learning engagement shows a very high category (4.22), indicating that VR creates an immersive and interactive learning experience. Technological factors, particularly immersion level, also score highly, reinforcing the importance of immersive environments in supporting conceptual learning. Meanwhile, pedagogical factors such as instructional design and guided inquiry also contribute positively, although their scores are slightly lower than technological factors. This finding highlights the need for stronger pedagogical integration to maximize the effectiveness of VR in science education.

To examine the effectiveness of VR and the influence of technological and pedagogical factors on conceptual understanding, inferential statistical analysis was conducted using paired sample t-tests and multiple regression.

Table 2. Results of Inferential Analysis

Variable	Value	Sig. (p-value)	Result
Paired t-test (Pre–Post)	t = 9.845	0.000	Significant
Technological Factors (β)	0.495	0.000	Significant
Pedagogical Factors (β)	0.352	0.000	Significant
R Square	0.72		
F-value	128.67	0.000	Significant

The results in Table 2 show that there is a statistically significant difference between pre-test and post-test scores ($p < 0.05$), confirming that VR has a strong positive effect on students' conceptual understanding of science. The regression analysis further indicates that both technological and pedagogical factors significantly influence learning outcomes. Technological factors have a stronger effect ($\beta = 0.495$), suggesting that immersion, usability, and system quality are key drivers of VR effectiveness. However, pedagogical factors also play a crucial role ($\beta = 0.352$), emphasizing the importance of instructional design and guided learning strategies. The R Square value of 0.72 indicates that 72% of the variance in conceptual understanding can be explained by these two variables, demonstrating a strong model. Overall, these findings confirm that the effectiveness of VR in enhancing conceptual understanding depends on the integration of advanced technology with well-designed pedagogical approaches.

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3.2. Discussion

The findings of this study provide strong empirical evidence that the utilization of Virtual Reality (VR) significantly enhances students' conceptual understanding in science learning, particularly for abstract and complex topics. This is clearly reflected in the substantial increase between pre-test and post-test scores, as well as the high mean value of conceptual understanding (4.18), indicating that students achieved a deeper level of comprehension after experiencing VR-based instruction. These results are consistent with a growing body of literature emphasizing the effectiveness of VR in improving learning outcomes in science education. Systematic reviews in higher education contexts have consistently reported that VR and augmented reality (AR) technologies produce significant positive effects on students' understanding of complex scientific concepts, especially when compared to traditional instructional methods (Tene et al., 2024; Matovu et al., 2022; Mallek et al., 2024). Thus, this study reinforces the argument that VR is not merely an engaging tool but also a cognitively effective medium for facilitating conceptual learning.

One of the most important contributions of VR to science learning lies in its ability to support visualization, particularly for concepts that are difficult to represent using conventional two-dimensional media. The findings of this study demonstrate that students exposed to VR achieved higher conceptual understanding scores, which can be attributed to the immersive and interactive nature of the technology. In line with this, previous research in chemistry education shows that VR-based learning significantly improves students' understanding of abstract concepts such as orbital hybridization, primarily due to enhanced spatial visualization capabilities (Qorbani et al., 2024). Similarly, studies in physics have found that students using VR outperform those using traditional methods in tasks requiring spatial reasoning, such as understanding three-dimensional vectors and electromagnetic fields (Campos et al., 2022). These findings highlight that VR is particularly effective in domains where spatial representation and visualization are critical to conceptual understanding.

The effectiveness of VR in enhancing conceptual understanding is further supported by its impact on learning outcomes in various STEM disciplines. For example, research in engineering education indicates that VR-based instruction can improve quiz scores by up to 12% and increase understanding of 3D structures by approximately 13% compared to traditional 2D video-based learning (Ka et al., 2025). These improvements are comparable to the findings of this study, where a significant increase in post-test scores was observed. Such evidence suggests that VR provides a more meaningful and immersive learning experience, enabling students to construct knowledge more effectively. The interactive nature of VR allows learners to manipulate objects, explore environments, and observe cause-and-effect relationships in real time, which are essential processes for developing deep conceptual understanding.

In addition to improving immediate learning outcomes, VR also plays a significant role in enhancing knowledge retention, particularly for abstract scientific concepts. Although this study primarily focuses on conceptual understanding, the observed improvement in post-test scores implies that VR may also contribute to better retention of knowledge. Supporting this assumption, previous studies have shown that VR-based laboratory environments can lead to superior long-term retention compared to traditional laboratory methods. For instance, VR simulations of electron movement and electromagnetic fields have been found to improve students' ability to retain knowledge over time, even when immediate comprehension levels are similar (Akdag et al., 2025). This suggests that the immersive and experiential nature of VR not only facilitates initial understanding but also strengthens memory retention through repeated interaction and visualization.

The ability of VR to represent phenomena that cannot be directly observed in the real world is another key factor contributing to its effectiveness. Many scientific concepts, such as atomic structures, electromagnetic fields, and astronomical systems, are inherently abstract and inaccessible to direct observation. VR addresses this limitation by providing interactive 3D simulations that allow students to explore these phenomena in a controlled virtual environment. Previous studies have highlighted that VR is particularly effective for teaching concepts at both micro and macro levels, as it bridges the gap between theoretical knowledge and experiential learning (Rojas-Sánchez et al., 2022; Matovu et al., 2022; Qorbani et al., 2024; Mallek et al., 2024; Georgiou et al., 2021). This capability makes VR a powerful tool for science education, where understanding often depends on the ability to visualize complex systems and processes.

The findings of this study also reveal that the effectiveness of VR is influenced by both technological and pedagogical factors, as indicated by the regression analysis results. Technological factors, with a higher beta coefficient ($\beta = 0.495$), play a dominant role in determining the success of VR-based learning. This highlights the importance of features such as immersion, interactivity, and system usability in enhancing conceptual understanding. High levels of immersion enable students to feel present within the virtual environment, which increases engagement and facilitates deeper cognitive processing. This is consistent with previous research showing that immersive VR environments can significantly enhance learning outcomes by promoting active exploration and interaction (Matovu et al., 2022; Dhanil & Mufit, 2024).

Moreover, the role of interactivity in VR cannot be overstated. The ability to manipulate virtual objects and engage in real-time interactions allows students to actively construct their understanding of scientific concepts. Studies have shown that interactive VR environments support spatial reasoning and conceptual development more effectively than passive learning methods (Rojas-Sánchez et al., 2022; Campos et al., 2022). For example, in physics education, students can explore vector directions and magnitudes by physically interacting with virtual representations, which enhances their understanding of abstract mathematical concepts. Similarly, in chemistry, students can manipulate molecular structures to better understand bonding and spatial relationships. These interactive features are essential for promoting active learning and deeper conceptual engagement.

However, while technological factors play a significant role, pedagogical factors are equally important in determining the effectiveness of VR. The regression results indicate that pedagogical factors ($\beta = 0.352$) also have a significant impact on conceptual understanding, emphasizing the importance of instructional design and teaching strategies. VR is most effective when it is integrated with appropriate pedagogical approaches, such as constructivism, experiential learning, and inquiry-based learning. These approaches encourage students to actively engage with the learning content, reflect on their experiences, and construct their own understanding. Previous studies have demonstrated that VR-based learning aligned with constructivist principles leads to deeper conceptual understanding and improved learning outcomes (Marougkas et al., 2023; Mallek et al., 2024; Ding et al., 2024).

In particular, the use of guided inquiry in VR-based learning has been shown to significantly enhance conceptual understanding. Guided inquiry provides students with structured opportunities to explore, question, and analyze scientific phenomena, while still offering sufficient support to prevent cognitive overload. This approach is particularly effective in VR environments, where the abundance of sensory information can be overwhelming if not properly managed. Studies have shown that VR combined with guided inquiry leads to better learning outcomes compared to unguided exploration, as it helps students focus on relevant information and develop meaningful connections between concepts (Torres et al., 2026; Ding et al., 2024). This finding is consistent with the results of this study, where guided inquiry was identified as an important pedagogical factor contributing to conceptual understanding.

Another important pedagogical element is the use of scaffolding and advance organizers, such as concept maps, to support learning in VR environments. Scaffolding provides learners with the necessary guidance to navigate complex learning tasks, while advance organizers help them structure and integrate new information with existing knowledge. Research indicates that the use of scaffolding in VR-based learning significantly improves conceptual understanding by reducing cognitive load and facilitating knowledge construction (Ding et al., 2024; Lee et al., 2022). In the context of this study, the relatively high scores for instructional design suggest that the integration of such pedagogical strategies contributed to the effectiveness of VR in enhancing conceptual understanding.

Furthermore, the findings of this study highlight the importance of aligning VR technology with learning objectives and instructional design. VR should not be used merely as a technological novelty but as a purposeful tool that supports specific learning outcomes. The effectiveness of VR depends on how well it is integrated into the overall learning process, including the design of learning activities, assessment methods, and feedback mechanisms. Studies have shown that VR-based learning is most effective when it is aligned with clear learning objectives and supported by appropriate instructional strategies (Mallek et al., 2024; Marougkas et al., 2023). This alignment ensures that students are not only engaged but also able to achieve meaningful learning outcomes.

Despite the positive findings, it is important to acknowledge that the effectiveness of VR is not universal and may vary depending on contextual factors. Issues such as technical limitations, user discomfort (e.g., cybersickness), and lack of familiarity with VR technology can negatively impact learning outcomes. Therefore, it is essential to ensure that VR systems are designed to be user-friendly, accessible, and free from technical issues. Additionally, adequate training and support should be provided to both students and instructors to facilitate the effective use of VR in education.

In conclusion, this study confirms that VR is a highly effective tool for enhancing conceptual understanding in science learning, particularly for abstract and complex topics. The findings demonstrate that VR improves learning outcomes, supports visualization, and enhances engagement, while also highlighting the importance of technological and pedagogical factors in determining its effectiveness. By integrating immersive technology with sound instructional design, educators can create meaningful and effective learning experiences that promote deep conceptual understanding. These findings provide valuable insights for the development of VR-based learning environments and contribute to the growing body of research on technology-enhanced science education.

4. CONCLUSION

This study concludes that the utilization of Virtual Reality (VR) is highly effective in enhancing students' conceptual understanding in science learning, particularly for abstract and complex concepts that require spatial visualization. The findings demonstrate a significant improvement in learning outcomes, confirming that VR provides meaningful and immersive learning experiences that support deeper cognitive processing. Furthermore, the effectiveness of VR is influenced by both technological and pedagogical factors, with technological aspects such as immersion, interactivity, and usability playing a more dominant role, while pedagogical elements such as guided inquiry, instructional design, and scaffolding remain essential in facilitating meaningful learning. Therefore, the study successfully answers its objective by showing that VR can significantly improve conceptual understanding when it is implemented through an integrated approach that aligns advanced technology with appropriate pedagogical strategies, ensuring optimal learning outcomes in science education.

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