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THE ROLE OF VIRTUAL AND AUGMENTED REALITY IN ENHANCING SCIENTIFIC LITERACY IN SECONDARY EDUCATION TO SUPPORT SUSTAINABLE DEVELOPMENT GOALS (SDGS)

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Abstract

This study examines how virtual and augmented reality enhance scientific literacy in secondary science. We also determined whether immersive tools improve conceptual understanding, practical competence, engagement, and problem-solving compared with conventional instruction. A quasi-experimental design with pretest and posttest and a control group was used across biology and physics lessons, alongside surveys, observations, and interviews. Students who learned with immersive tools showed greater achievement, stronger application of concepts, and higher motivation than peers taught through traditional lessons. These outcomes arise because immersive environments make abstract processes concrete, allow safe experimentation, and sustain attention through interactive exploration. Teachers also reported richer questioning and collaboration. The study provides evidence that integrating immersive technologies supports inquiry-based, student-centered learning in secondary science. The results suggest practical implications for curriculum design, teacher preparation, and school investment so that immersive learning can broaden access to high-quality science experiences and strengthen lasting interest in science.

Keywords: Augmented reality, Pedagogy, Scientific literacy, Secondary education, STEM education, Virtual reality.

1. Introduction

In the 21st century, the rapid advancement of digital technology has significantly reshaped the educational landscape [1-6]. Among these emerging innovations, virtual reality (VR) and augmented reality (AR) have received growing attention as tools for creating immersive, interactive, and engaging learning environments [7-12]. Unlike conventional instruction that often relies on static visuals and textbooks, VR and AR allow learners to visualize abstract scientific phenomena, perform virtual experiments, and interact with dynamic content, thereby enriching the learning experience.

Scientific literacy, as emphasized by global frameworks is a core competency of modern science education. It involves not only understanding scientific concepts but also the ability to apply them, reason critically, and make informed decisions in real-world contexts. However, fostering high levels of scientific literacy among secondary students is often hindered by limited laboratory access, difficulty in illustrating abstract processes like molecular dynamics or ecological systems, and a lack of hands-on engagement. VR and AR present a unique opportunity to address these limitations by simulating real-world environments, encouraging inquiry-based exploration, and providing risk-free experimentation.

Table 1 presents a selection of previous studies on the use of immersive technologies in education. These works collectively show that VR/AR environments can enhance student motivation and deepen conceptual understanding. Nevertheless, much of the existing research has focused on higher education, leaving a gap in empirical studies that measure the impact of immersive tools on scientific literacy at the secondary level.

By addressing this gap, the current study investigates how VR and AR technologies affect scientific literacy among secondary school students. It specifically explores how immersive tools influence students' conceptual understanding, motivation, and engagement in comparison to traditional teaching methods. The novelty of this study lies in its focus on the secondary education level, where empirical research is scarce, and in its use of mixed methods to comprehensively measure learning outcomes. The expected impact is to provide practical and pedagogically grounded recommendations for integrating immersive technologies into secondary science classrooms, thereby fostering long-term interest and competence in science learning. This study supports current issues in sustainable development goals (SDGs).

Table 1. Previous research.

No.	Title	Ref.
1	The meaning of scientific literacy.	[13]
2	A case study of immersive virtual field trips in education. interactive learning environments	[14]
3	A structural equation modeling investigation of the emotional value of immersive virtual reality in education. educational technology research and development	[15]
4	Scientific literacy. science education	[16]
5	Cognitive and affective processes in learning with VR.	[17]
6	A systematic review of immersive virtual reality applications for higher education.	[18]

2. Literature Review

Emerging research highlights the capacity of VR and AR technologies to increase student engagement and motivation in science learning environments [17]. These immersive tools enable students to interact with content in dynamic ways that are often unachievable through traditional classroom setups. For example, AR applications in chemistry allow students to visualize molecular structures in three dimensions, promoting deeper conceptual understanding [14]. Similarly, VR simulations facilitate virtual laboratory experiences, offering safe, repeatable, and resource-efficient alternatives to physical labs [15]. This aligns with constructivist learning theory, which emphasizes the role of active exploration in knowledge acquisition.

Scientific literacy refers to the ability to understand, apply, and evaluate scientific information to make informed decisions in everyday life. It encompasses not only factual knowledge but also critical thinking, inquiry skills, and real-world problem-solving abilities. Pedagogical strategies that foster scientific literacy through contextualized and student-centered learning, moving beyond rote memorization. In this framework, students are encouraged to engage with science as a process rather than as static content [13].

Although many studies affirm the benefits of VR and AR in higher education, few have systematically examined their impact on secondary school students, particularly in terms of measurable gains in scientific literacy. The existing literature often lacks quantitative validation and comparative analysis across instructional approaches. This gap underscores the need for targeted research that evaluates how immersive technologies can influence science education outcomes at the secondary level, where foundational skills and interest in STEM fields are actively being shaped.

3. Method

This study employed a mixed-methods design to comprehensively explore the role of VR and AR in enhancing scientific literacy among secondary school students. Detailed information for this method is explained elsewhere [19]. The primary research framework was quasi-experimental, utilizing pre-test and post-test evaluations and incorporating a control group for comparison.

The experimental structure involved two distinct groups of students. The experimental group received instruction using VR/AR-based tools, while the control group was taught through conventional methods. Both groups completed the same scientific literacy assessment before and after the instructional intervention to measure learning gains.

A total of 120 students, aged approximately between 14 and 16 years, from two secondary schools participated in the study. They were randomly assigned to two equal groups (n = 60 each). Additionally, four biology teachers participated by facilitating the lessons and providing reflective input on classroom dynamics and tool implementation. To capture a holistic view of the impact, multiple data collection techniques were applied:

(i) Testing Method: A scientific literacy test adapted from the PISA scientific literacy framework was administered. This instrument measured students' ability to explain scientific phenomena, interpret data, and apply scientific reasoning to real-life problem-solving.

(ii) Survey Method: A Likert-scale questionnaire was used to assess students' attitudes toward science, their motivation levels, and their perception of learning using VR/AR. The aim was to examine the affective outcomes of immersive technology integration.

(iii) Observation Method: Structured classroom observations were conducted using predefined rubrics to evaluate student participation, collaboration, and interaction with digital learning content. Both direct observation and video recording were employed to ensure reliability and accuracy.

(iv) Interview Method: Semi-structured interviews were held with teachers and a subgroup of students to gather qualitative insights on their experiences, challenges faced, and perceived benefits of using immersive technology in science learning.

Quantitative data collected from the tests and surveys were analyzed using SPSS software. Detailed information regarding the method is explained elsewhere [20]. The following statistical techniques were employed:

(v) Paired sample t-tests to compare pre- and post-test results within each group.

(vi) Analysis of Covariance (ANCOVA) to compare post-test scores between the experimental and control groups, adjusting for pre-test scores.

(vii) Chi-square tests to analyze categorical responses from the attitude surveys.

Qualitative data from interviews and classroom observations were analysed using thematic coding. Themes such as motivation, engagement, perceived learning benefits, and implementation challenges were identified. Data triangulation was used to ensure the trustworthiness of the findings by cross-verifying qualitative and quantitative results.

The study followed ethical protocols by securing informed consent from all student participants, their parents, and participating teachers. Anonymity and confidentiality were maintained throughout the research process, in accordance with ethical standards in educational research.

4. Results and Discussion

Table 2 presents the comparison of pre-test and post-test scores between the experimental group (taught with VR/AR tools) and the control group (taught with traditional methods). The analysis revealed that both groups showed improvement after instruction, but the experimental group demonstrated substantially greater gains in scientific literacy.

Students in the experimental group improved from an average score of 56.2 to 78.5, reflecting a gain of 22.3%, while those in the control group improved from 55.8 to 68.1, with a gain of 12.3%. Statistical analysis using paired sample t-tests showed that the difference in the experimental group was significant ($t = 8.71$, $p < 0.001$). Furthermore, ANCOVA confirmed a significant difference between the post-test scores of both groups, even after adjusting for pre-test results ($F = 12.36$, $p < 0.01$). These findings provide strong evidence that the integration of VR/AR in instruction leads to more effective science learning outcomes.

Table 2. Comparison of pre-test and post-test scores.

Group	N	Mean Pre-Test Score	Mean Post-Test Score	Gain (%)
Experimental (VR/AR)	60	56.2	78.5	+22.3
Control (Traditional)	60	55.8	68.1	+12.3

To complement these findings, Table 3 shows students' responses to the Likert-scale questionnaire regarding their experience with VR/AR in biology lessons. The results indicate consistently high levels of satisfaction and perceived benefit. The highest-rated item was students' support for the frequent use of VR/AR in science classes (mean = 4.70), followed by increased interest and understanding (means ranging from 4.48 to 4.62).

These results support the idea that immersive technologies can positively affect students' motivation, comprehension, and engagement. By making abstract scientific processes visual and interactive, VR/AR appears to foster not only cognitive but also affective learning outcomes, aligning with the previous findings [17, 18].

Table 3. Students' perceptions of VR/AR in learning (Likert scale, 1-5).

Statement	Mean Score	Standard Deviation (SD)
VR/AR makes biology lessons more interesting	4.62	0.51
VR/AR helps me understand complex concepts easily	4.48	0.57
VR/AR increases my motivation to learn science	4.55	0.54
VR/AR should be used more frequently in classrooms	4.70	0.46

In addition to the quantitative data, insights from teacher interviews revealed that students in the VR/AR group were more active in discussions, asked more inquiry-driven questions, and demonstrated stronger collaborative problem-solving behaviors. For instance, during lessons on cell division, students reportedly exhibited curiosity beyond textbook explanations by exploring virtual 3D cell animations. Teachers observed that VR/AR provided an authentic context for learning, allowing students to visualize phenomena that are otherwise abstract or invisible in a traditional setting.

These qualitative observations were reinforced by classroom video recordings, which showed the experimental group demonstrating sustained attention, enthusiasm, and confidence during lessons. In contrast, the control group showed more passive engagement, with fewer instances of student-initiated inquiry.

The results align with the literature asserting the benefits of immersive learning for science education [14, 15]. The constructivist principles underpinning VR/AR (such as exploration, interaction, and learner agency) seem to enhance the internalization of scientific concepts. Moreover, the positive emotional responses observed may contribute to long-term interest in science, a critical factor for STEM pipeline development. Previous studies on SDGs as shown in Table 4.

Table 4. Previous studies on SDGs.

No.	Title	Ref.
1	Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches	[21]
2	Sustainable packaging: Bioplastics as a low-carbon future step for the SDGs	[22]
3	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting SDGs	[23]
4	HIRADC for workplace safety in manufacturing: A risk-control framework and bibliometric review to support SDGs	[24]
5	Techno-economic analysis of production ecobrick from plastic waste to support SDGs	[25]
6	Techno-economic analysis of sawdust-based trash cans and their contribution to Indonesia’s green tourism policy and the SDGs	[26]
7	Definition and role of sustainable materials in reaching global SDGs completed with bibliometric analysis	[27]
8	Bibliometric insight into materials research trends and innovation to support SDGs	[28]
9	Physical adaptation of college students in high-altitude training to support SDGs	[29]
10	Enhancing job satisfaction through HRIS and communication: A commitment-based approach to SDGs	[30]
11	Enhancing innovative thinking through theory-based instructional model to support SDGs	[31]
12	Influence of self-efficacy on affective learning outcomes in social studies education toward achieving SDGs	[32]
13	Enhancing occupational identity and self-efficacy through self-education in art/design aligned with SDGs	[33]
14	Integrating generative AI-based multimodal learning in education to enhance literacy aligned with SDGs	[34]
15	Dataset on Sulawesi schools and cultural implications to support SDGs	[35]
16	Enhancing professional readiness in vocational education aligned with SDGs	[36]
17	School feeding program and SDGs in education: Linking food security to learning outcomes	[37]
18	Influence of eco-friendly packaging on consumer interest to meet SDGs	[38]
19	SDG 12 implementation through lemon commodities and waste reduction	[39]
20	Mediterranean diet patterns and sustainability to support SDGs	[40]
21	Education on food diversification through infographic to improve SDGs	[41]
22	Safe food treatment technology to achieve SDG zero hunger and optimal health	[42]
23	Student awareness of sustainable diet and carbon footprint reduction to support SDGs 2030	[43]

However, some challenges were noted. Teachers reported initial technical difficulties, such as device compatibility and internet bandwidth issues. They also expressed the need for professional development to effectively facilitate VR/AR sessions. These challenges highlight the importance of systemic support for teachers, particularly during the transition from conventional to technology-integrated classrooms.

The integration of VR/AR into science instruction resulted in measurable improvements in students' performance and engagement. When implemented with proper infrastructure and teacher training, immersive technologies can become a transformative force in developing scientific literacy in secondary education. Several recommendations are as follows:

(i) Teacher Training: Professional development programs are essential for effective VR/AR integration.

(ii) Curriculum Integration: VR/AR should be embedded into science curricula as complementary tools rather than add-ons.

(iii) Accessibility: Schools must adopt affordable and scalable solutions to ensure equal access.

This study support current issues in SDGs as reported elsewhere [21-43].

5. Conclusions

This study confirms that integrating Virtual and Augmented Reality into science instruction significantly enhances students' scientific literacy, motivation, and engagement. Through immersive experiences, students develop a deeper understanding of abstract concepts and participate more actively in learning. These findings demonstrate that VR/AR can serve as powerful pedagogical tools, especially when aligned with inquiry-based and student-centered approaches. The study contributes to the literature by providing empirical evidence from secondary education and highlights the potential of immersive technology to strengthen long-term interest in science and support more equitable access to quality STEM education.

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