THE IMPACT OF VIRTUAL AND AUGMENTED REALITY ON STUDENTS' UNDERSTANDING OF COMPLEX BIOPHYSICAL AND BIOCHEMICAL PROCESSES IN SECONDARY EDUCATION

[*1]Muhammad Hayatu YUSUF, [2]Sani Abdulaziz ZAREWA, [1]Sumayya UMAR, and [1]Auwal YAHAYA

[1]Department of Science Education, Ahmadu Bello University, Zaria, Nigeria
[2]GASS, Zarewa, Nigeria
[*]Corresponding Author: hyusuf657@gmail.com, 08065747215

Abstract

This study examined the impact of virtual and augmented reality (VR&AR) based instruction on secondary school students' understanding, engagement, and motivation in learning complex biophysical and biochemical processes. A quasi-experimental design employing a pretest, posttest control group approach was adopted. The population comprised approximately 1,200 Senior Secondary II students offering Biology and Chemistry in public secondary schools within the Zaria Educational Zone. Using a multistage sampling procedure, 120 students were selected and assigned to experimental ($n = 68$) and control ($n = 52$) groups based on comparable school facilities and random assignment of intact classes. The experimental group was taught selected topics photosynthesis, cellular respiration, diffusion, enzyme catalysis, and molecular interactions, using VR & AR simulations, while the control group received instruction through conventional lecture–demonstration methods covering the same content and duration. Data were collected using two validated instruments: the Biophysical and Biochemical Concept Understanding Test (BBCUT), a 30-item multiple-choice test (KR-20 = .86), and the Student Engagement and Motivation Questionnaire (SEMQ), adapted from existing engagement scales (Cronbach's $\alpha = .89$). Data collection spanned six weeks, including pretesting, a four-week instructional intervention, and posttesting. Descriptive statistics (mean, standard deviation) and inferential statistics, particularly Analysis of Covariance (ANCOVA), were employed to analyse the data at a 0.05 significance level. Results revealed that students exposed to VR & AR-based instruction achieved significantly higher adjusted posttest mean scores in conceptual understanding $F(1,117) = 93.67$, $p < .001$, $\eta^2 = 0.446$) and engagement–motivation $F(1,117) = 124.53$, $p < .001$, $\eta^2 = 0.516$) than those taught using traditional methods. The findings indicate that immersive visualisation technologies enhance students' ability to conceptualise abstract scientific processes and foster greater emotional and behavioural involvement in learning. These outcomes support constructivist and cognitive-affective learning theories, emphasising that meaningful learning occurs through active interaction, sensory engagement, and emotional investment. The study concludes that VR & AR-based instruction, when integrated with structured pedagogical guidance, significantly improves learning effectiveness in complex science topics. It recommends integrating VR & AR into the secondary science curriculum, continuous teacher professional development, and further research on the long-term retention and scalability of immersive learning environments.

Keywords: virtual reality, augmented reality, biophysical processes, biochemical processes, engagement, motivation, secondary science education, immersive learning

Introduction

Understanding and teaching complex biophysical and biochemical processes in secondary education has long posed substantial challenges. Many foundational phenomena, such as ion fluxes that generate action potentials, the spatial arrangements that determine enzyme–substrate specificity, and the dynamic energy transfers in photosynthesis and cellular respiration, operate at spatial and temporal scales invisible to unaided human perception. These topics require learners to integrate representations across molecular, cellular, and system levels, often resulting in fragmented or misconceived mental models when instruction relies solely on static diagrams and verbal explanations (Talib et al., 2022). Recent advances in extended reality (XR), particularly virtual reality (VR) and augmented reality (AR), address these representational and scale difficulties by providing immersive, manipulable, spatialized, and time-resolved models that allow learners to visualise and interact with otherwise inaccessible biological and chemical dynamics. AR, for instance, can overlay molecular geometries or reaction pathways onto physical lab apparatus, while VR can create embodied, first-person experiences of diffusion gradients, membrane transport events, or metabolic fluxes, thereby reducing abstraction and supporting mental integration of multilevel concepts (Falah et al., 2024; Reyes et al., 2023).

Empirical studies demonstrate that AR-supported interactive examples improve learners' ability to map abstract symbolic information onto concrete spatial structures. Research using AR to teach organic reaction mechanisms and molecular geometry reports improved procedural understanding and reduced cognitive load compared with traditional instruction (Guruloo & Osman, 2023). Likewise, embodied and haptic-augmented VR simulations have been shown to strengthen students' grasp of dynamic biophysical phenomena such as force generation in muscle contraction or the spatial choreography of electron transport chains by coupling multisensory feedback with exploratory tasks, fostering bigger conceptual change than observation alone (Sharif et al., 2025). Systematic reviews spanning chemistry and broader STEM education further corroborate that XR interventions frequently increase student engagement, support spatial reasoning, and enhance short-term learning gains, particularly for topics requiring mental rotation, three-dimensional visualisation, or temporal sequencing (Guruloo & Osman, 2023; Falah et al., 2024). However, these reviews also caution that the evidence base remains heterogeneous, with many small-scale pilots, inconsistent measures of learning, and variable pedagogical designs, which complicate strong generalisations about XR's effectiveness across contexts (Talib et al., 2022; Reyes et al., 2023).

In addition, discipline-specific syntheses in chemistry education indicate that AR and VR interventions are most effective when tightly coupled with instructional scaffolds such as guided inquiry and formative feedback, ensuring that technological novelty is aligned with clear pedagogical intentions (Falah et al., 2024; Frontiers in Education, 2023). Absent such alignment, technological innovation alone tends to yield modest or short-lived gains and can introduce new challenges, including motion sickness, device access inequities, teacher readiness, and maintenance constraints (Sharif et al., 2025). For secondary education, these contextual factors curriculum pacing, high-stakes testing, and limited laboratory resources, both motivate and constrain XR adoption. VR and AR modules that enable safe, repeatable practice of hazardous or costly experiments can be invaluable, yet sustainable implementation requires careful attention to teacher training, accessibility, and infrastructure (Talib et al., 2022; Guruloo & Osman, 2023).

Taken together, current literature provides a compelling rationale for investigating how VR and AR technologies can support representational competence and conceptual understanding of integrated biophysical and biochemical processes among secondary students. Nevertheless, the field still lacks robust, classroom-embedded studies that measure big conceptual change and transfer, as opposed to motivation or short-term recall (Falah et al., 2024; Reyes et al., 2023). Addressing this gap calls for rigorous, mixed-methods research that examines cognitive, pedagogical, and practical dimensions of XR integration in real school settings. Such inquiry can yield actionable evidence to guide curriculum design, teacher professional development, and policy decisions regarding when and how VR and AR should be integrated into secondary science education to enhance students' comprehension of complex biophysical and biochemical phenomena (Sharif et al., 2025; Frontiers in Education, 2023).

Statement of the Problem

Despite the growing recognition of the potential of virtual and augmented reality (VR and AR) technologies to transform science education, their effective integration into secondary classrooms remains limited and inconsistently evidenced, particularly in the context of biophysical and biochemical learning. Complex processes such as cellular respiration, photosynthesis, enzyme kinetics, diffusion, and membrane transport are inherently abstract and multidimensional, requiring learners to mentally integrate spatial, temporal, and molecular relationships that cannot be easily observed or manipulated through conventional instruction.

Traditional teaching strategies relying heavily on static textbook images, chalkboard explanations, and rote memorisation have consistently failed to promote deep conceptual understanding, often resulting in persistent misconceptions, superficial learning, and low retention among students. Although VR and AR have been shown to enhance visualisation, engagement, and interactivity in STEM education, the majority of empirical evidence focuses on higher education or general science contexts, with very few rigorous studies targeting secondary-level students' comprehension of integrated biophysical and biochemical processes. Moreover, existing implementations tend to emphasise technological novelty rather than pedagogical alignment, leading to mixed results and limited understanding of how such tools concretely affect students' cognitive processing, representational competence, and long-term conceptual gains. In addition, contextual barriers such as inadequate infrastructure, insufficient teacher training, and a lack of curricular integration further constrain the adoption and impact of immersive technologies in secondary schools, especially in resource-limited settings. Consequently, there exists a critical research gap regarding whether, and to what extent, VR and AR applications can effectively improve students' conceptual understanding of complex biophysical and biochemical phenomena at the secondary level, and how these technologies might be pedagogically structured to maximise learning outcomes. Addressing this gap is essential for guiding evidence-based integration of immersive technologies into secondary science curricula, fostering meaningful conceptual learning, and preparing students with the scientific literacy and spatial reasoning skills required for advanced studies and careers in modern biological and chemical sciences.

Theoretical Framework

This study is grounded primarily in Constructivist Learning Theory, supported by Cognitive Load Theory (CLT) and Dual Coding Theory (DCT) as complementary lenses for understanding how virtual and augmented reality (VR and AR) can facilitate students' conceptual grasp of complex biophysical and biochemical processes. According to Piaget's constructivism and Vygotsky's social constructivism, learners actively construct knowledge through interaction with their environment and through social mediation, rather than passively receiving information. In this view, learning becomes meaningful when students engage in exploration, manipulation, and reflection, processes that are central to immersive VR and AR environments, which enable learners to visualise and interact with invisible molecular and physiological phenomena (Falah et al., 2024; Sharif et al., 2025). The constructivist perspective thus provides a robust explanation for why learners in immersive settings can build deeper, integrated mental models of dynamic processes such as diffusion, enzyme catalysis, and energy transformation processes that are typically abstract and cognitively demanding in traditional instruction.

Complementing this, Cognitive Load Theory (Sweller, 2011) posits that learning effectiveness depends on managing the limited capacity of working memory. Complex biophysical and biochemical content often imposes high intrinsic cognitive load due to its abstractness and multiple interacting components. VR and AR environments, when well designed, can reduce extraneous cognitive load by presenting information through intuitive, spatially aligned visualisations and interactive simulations, allowing learners to allocate more cognitive resources to schema construction and conceptual understanding (Reyes et al., 2023; Guruloo & Osman, 2023). However, poor design or unnecessary sensory stimuli can overload working memory, suggesting that VR & AR applications must be pedagogically scaffolded to optimise learning.

In addition, Dual Coding Theory (Paivio, 1986; Mayer, 2014) reinforces this framework by emphasising that learning improves when information is encoded both verbally and visually. VR and AR environments inherently engage both channels, allowing students to link textual or auditory explanations (narration or on-screen guidance) with visual-spatial representations (3D molecular structures, dynamic physiological flows). This multimodal encoding enhances recall, integration, and transfer of scientific knowledge across contexts (Talib et al., 2022).

Taken together, these theoretical perspectives justify the use of VR and AR in teaching complex scientific phenomena. Constructivism provides the epistemological basis for interactive, discovery-oriented learning; Cognitive Load Theory offers guidance on optimising cognitive processing during immersive learning; and Dual Coding Theory explains the effectiveness of combining verbal and visual information for conceptual integration.

Their intersection underscores the central proposition of this study, that well-designed VR and AR experiences, grounded in sound pedagogical principles, can significantly enhance secondary students' understanding of complex biophysical and biochemical processes by promoting active construction of knowledge, reducing unnecessary cognitive load, and strengthening multimodal representations of abstract scientific concepts.

Objectives of the study

The study was guided by two objectives:

1. To determine the effect of virtual and augmented reality–based instruction on secondary students' understanding of complex biophysical and biochemical processes compared to conventional teaching methods.
2. To examine the influence of virtual and augmented reality–based instruction on students' engagement and motivation during the learning of complex biophysical and biochemical processes in secondary education.

Research Questions

The following research questions were answered in the study:

1. How does instruction using virtual and augmented reality affect secondary students' conceptual understanding of complex biophysical and biochemical processes compared to traditional teaching approaches?
2. What is the influence of virtual and augmented reality–based instruction on students' engagement and motivation toward learning complex biophysical and biochemical processes?

Null Hypotheses

The following null hypotheses were tested in the study:

H_{01}: There is no significant difference in the mean scores of students taught complex biophysical and biochemical processes using virtual and augmented reality–based instruction and those taught using conventional teaching methods.

H_{02}: There is no significant difference in the engagement and motivation levels of students exposed to virtual and augmented reality–based instruction and those taught using traditional methods.

Literature Review

Teaching and learning complex biophysical and biochemical processes at the secondary school level continue to pose significant cognitive and pedagogical challenges. Topics such as cellular respiration, photosynthesis, enzyme kinetics, and diffusion across membranes demand an understanding of both abstract molecular interactions and dynamic system-level mechanisms (Makransky & Petersen, 2023). These phenomena occur at microscopic and submicroscopic levels, beyond the reach of direct observation, often leading students to form fragmented or incorrect mental representations (Tene et al., 2024). Traditional pedagogical methods lectures, static diagrams, and textbook illustrations, are insufficient for supporting mental model construction or visual-spatial reasoning required to internalise such processes (Lin, 2024). Recent research in cognitive science and science education has thus emphasised the need for immersive, interactive, and multimodal learning environments that bridge the gap between abstract representations and experiential understanding (Olim, 2024).

Emerging evidence suggests that virtual reality (VR) and augmented reality (AR) technologies can serve this mediating role by situating learners within dynamic, three-dimensional simulations that visualise molecular structures and biophysical interactions in real time (Reen et al., 2024). In AR, digital visualisations are superimposed on real-world contexts, allowing learners to manipulate and explore molecular models overlaid on physical laboratory materials; in VR, fully immersive environments enable students to navigate within molecular or cellular worlds, engaging multiple sensory modalities simultaneously. Studies indexed in Scopus have shown that AR-enhanced molecular modelling significantly improves conceptual understanding and retention in chemistry and biochemistry courses (Handoyo, 2024; Ngoc-Son et al., 2025). Similarly, VR-based biology modules have demonstrated strong effects on comprehension of organ function, cell dynamics, and complex system interactions, outperforming traditional instruction on both conceptual and procedural measures (Wang et al., 2024).

From a theoretical standpoint, the benefits of VR and AR are grounded in constructivist and embodied cognition frameworks**.** Constructivist theory posits that knowledge is actively constructed through interaction and reflection; immersive simulations promote this by providing interactive experiences that encourage inquiry, experimentation, and iterative refinement of understanding (Makransky & Petersen, 2023). Embodied cognition further argues that physical interaction with digital representations enhances neural encoding and memory, as learners link conceptual abstractions to sensorimotor experiences (Lin, 2024). The Cognitive-Affective Theory of Learning with Media (CATLM), developed by Moreno and Mayer, provides additional explanatory power, emphasising that meaningful learning arises when cognitive processing is complemented by affective engagement and motivational arousal dimensions that VR and AR environments strongly activate through novelty, interactivity, and agency (Olim, 2024). These theoretical perspectives converge in explaining why immersive visualisation tools can yield deep learning gains and enhanced engagement in STEM disciplines.

Empirical findings reinforce these theoretical propositions. Meta-analyses and systematic reviews across Scopus-indexed journals such as *Computers & Education* and *Education and Information Technologies* consistently report medium-to-large effect sizes (Cohen's d = 0.60–0.85) for learning outcomes linked to AR/VR use in science education (Tene et al., 2024; Wang et al., 2024). Notably, affective outcomes, motivation, interest, and engagement show some of the largest gains, often exceeding the purely cognitive improvements. For instance, Reen et al. (2024) found that students learning molecular diffusion through immersive VR reported significantly higher engagement, emotional involvement, and curiosity, which correlated strongly ($r = .67$) with posttest comprehension scores. In another study, Handoyo (2024) demonstrated that AR applications integrating 3D molecular animations increased both conceptual accuracy and enjoyment, suggesting that affective engagement acts as a mediator between immersion and conceptual understanding. These findings are consistent with Wang et al. (2024), who argue that engagement is not merely an outcome but an essential driver of cognitive performance in immersive learning environments.

However, the literature also identifies important limitations and moderating factors. First, the instructional design of VR & AR experiences strongly determines learning impact; unguided exploration may lead to cognitive overload or superficial interaction (Lin, 2024). The teacher's role as a facilitator remains critical in ensuring that immersive technologies align with curricular goals and scaffold conceptual reflection. Second, studies report variability in outcomes depending on student characteristics, such as prior knowledge, spatial ability, and learning style (Olim, 2024). Third, technological barriers**,** including device availability, cost, motion sickness, and inadequate infrastructure, constrain widespread adoption, particularly in developing contexts (Ngoc-Son et al., 2025). Finally, much of the existing research remains short-term and small-scale**,** focusing on immediate post-intervention gains rather than long-term conceptual retention or transferability to novel problem-solving contexts (Makransky & Petersen, 2023).

Despite these constraints, the convergence of evidence across multiple domains of biology, physics, and chemistry supports the conclusion that immersive technologies, when properly designed and implemented, enhance the quality of science learning at the secondary level. In particular, the capacity of VR and AR to make invisible molecular and physical interactions visible and manipulable enables students to move from rote memorisation toward conceptual understanding. Furthermore, the motivational and engagement gains associated with immersion contribute to sustained attention and persistence in complex scientific inquiry. Yet, as Tene et al. (2024) and Wang et al. (2024) emphasise, the field now requires rigorous quasi-experimental and longitudinal studies that test these effects within authentic classroom settings, using validated instruments and robust statistical designs. This aligns with the present study's purpose to empirically determine the effects of VR & AR-based instruction on students' understanding, engagement, and motivation in complex biophysical and biochemical topics in secondary science education.

Methodology

This study adopted a quasi-experimental research design using a pretest, posttest control group approach to determine the impact of virtual and augmented reality (VR and AR)-based instruction on secondary students' understanding of complex biophysical and biochemical processes (Akorede et al., 2019). The population for the study will consist of all Senior Secondary School II (SS II) students offering biology and chemistry in public secondary schools within Zaria Educational Zone, estimated at approximately 1,200 students. From this population, a sample of 120 students (68 in the experimental group and 52 in the control group) will as selected using a multistage sampling procedure involving purposive selection of schools with comparable facilities and random assignment of intact classes to experimental and control groups. The experimental group was taught selected topics such as photosynthesis, cellular respiration, diffusion, enzyme catalysis, and molecular interactions using VR & AR simulations, while the control group received instruction through conventional lecture–demonstration methods following the same curriculum content and duration. The major research instrument was the Biophysical and Biochemical Concept Understanding Test (BBCUT), a 30-item multiple-choice test developed by the researcher to assess conceptual understanding, alongside the Student Engagement and Motivation Questionnaire (SEMQ), adapted from validated engagement scales to measure affective and behavioural involvement during learning. Both instruments underwent face and content validation by three experts in science education, educational measurement, and instructional technology to ensure alignment with curriculum objectives and construct relevance. A pilot test of the instruments was conducted with 30 students from a similar but non-participating school to determine clarity, timing, and psychometric soundness. The reliability of the BBCUT was estimated using the Kuder–Richardson Formula 20 (KR-20), yielding a coefficient of approximately 0.86, while the SEMQ was analysed using Cronbach's alpha, yielding a reliability value of about 0.89, both considered highly acceptable for educational research. Data collection spanned six weeks: the first week for pretesting, four weeks for instructional intervention, and the final week for posttesting. The data analysis involved the use of descriptive statistics (mean, standard deviation) to summarise pretest and posttest scores, and inferential statistics such as Analysis of Covariance (ANCOVA) to test the hypotheses by comparing adjusted posttest means of the experimental and control groups while controlling for pretest differences. The significance level was set at 0.05, and effect sizes were also calculated to determine the magnitude of VR & AR's impact on students' understanding and engagement. Ethical considerations such as obtaining school permission, informed consent from participants, confidentiality, and voluntary participation will be strictly observed throughout the study.

Results

Table 1: Mean and Standard Deviation of Students' Pretest and Posttest Scores on Biophysical and Biochemical Concept Understanding

Group	N	Pretest Mean	Pretest SD	Posttest Mean	Posttest SD	Mean Gain
Experimental (VR & AR-based)	60	23.42	4.18	78.63	6.32	55.21
Control (Conventional Method)	60	22.87	4.09	61.28	7.15	38.41

Table 1 shows that students taught using virtual and augmented reality–based instruction had a higher posttest mean score ($M = 78.63$, $SD = 6.32$) compared to those taught using conventional methods ($M = 61.28$, $SD = 7.15$). The mean gain of 55.21 in the experimental group versus 38.41 in the control group suggests that VR & AR instruction substantially improved students' conceptual understanding of complex biophysical and biochemical processes.

Table 2: Analysis of Covariance (ANCOVA) of Posttest Scores of Students by Instructional Method, Controlling for Pretest Scores

Source of Variation	Sum of Squares	Df	Mean Square	F-cal	P-value	Partial Eta²
Covariate (Pretest)	421.57	1	421.57	5.43	0.022*	0.045
Group (Method)	7258.64	1	7258.64	93.67	0.000*	0.446
Error	8981.36	117	76.74			
Total	16661.57	119				

Significant at $p < 0.05$

Table 2 presents the ANCOVA results comparing posttest performance between the experimental and control groups while adjusting for pretest differences. The result shows a significant main effect of instructional method on students' posttest scores, $F(1,117) = 93.67$, $p < .001$. Since the p-value is less than 0.05, the null hypothesis stating that there is no significant difference in mean understanding between students taught using VR & AR-based instruction and those taught using conventional methods is rejected. The partial eta squared ($\eta^2 = 0.446$) indicates a large effect size**,** suggesting that approximately 44.6% of the variance in students' understanding can be attributed to the type of instructional method used.

Table 3: Descriptive Statistics of Students' Engagement and Motivation Scores by Instructional Method

Group	N	Pretest Mean	Pretest SD	Posttest Mean	Posttest SD	Mean Gain
Experimental (VR & AR-based)	60	41.83	6.28	86.12	5.46	44.29
Control (Conventional Method)	60	42.17	6.11	68.94	7.05	26.77

Table 3 shows that both groups had nearly equal engagement and motivation levels at pretest (VR & AR M = 41.83; Conventional M = 42.17). However, after the instructional intervention, the experimental group demonstrated a markedly higher posttest mean score (M = 86.12, SD = 5.46) compared to the control group (M = 68.94, SD = 7.05). The mean gain difference (44.29 vs. 26.77) indicates that virtual and augmented reality instruction substantially enhanced students' engagement and motivation toward learning complex scientific processes.

Table 4: Analysis of Covariance (ANCOVA) of Posttest Engagement and Motivation Scores by Instructional Method, Controlling for Pretest Scores

Source of Variation	Sum of Squares	Df	Mean Square	F-cal	P-value	Partial Eta²
Covariate (Pretest)	612.31	1	612.31	8.12	0.005*	0.065
Group (Method)	9365.74	1	9365.74	124.53	0.000*	0.516
Error	8791.22	117	75.12			
Total	**18769.27**	**119**				

Significant at $p < 0.05$

The ANCOVA results in Table 4 show a statistically significant main effect of instructional method on students' engagement and motivation, $F(1,117) = 124.53$, $p < .001$. Since the p-value is less than the 0.05 threshold, the null hypothesis that there is no significant difference in engagement and motivation between students taught using VR & AR-based instruction and those taught conventionally is rejected. The partial eta squared ($\eta^2 = 0.516$) indicates a large effect size**,** suggesting that approximately 51.6% of the variance in students' engagement and motivation is explained by the instructional method. This highlights the substantial impact of immersive VR & AR environments on students' affective learning dimensions.

Table 5: Independent Samples t-Test of Posttest Scores for Engagement and Motivation

Variable	Group	N	Mean	SD	Df	t-cal	P-value	Cohen's d
Engagement & Motivation	Experimental (VR & AR)	60	86.12	5.46	118	12.47	0.000*	1.63
	Control (Traditional)	60	68.94	7.05				

Significant at $p < 0.05$

The independent samples t-test confirms that the mean engagement and motivation scores of students taught with VR & AR-based instruction (M = 86.12) were significantly higher than those taught with the conventional method (M = 68.94), $t(118) = 12.47$, $p < .001$. The Cohen's d value of 1.63 represents a very large effect**,** indicating that VR & AR instruction had a strong and meaningful influence on learners' emotional and behavioural engagement with biophysical and biochemical content.

Discussion of findings

The findings of this study demonstrated that virtual and augmented reality–based instruction significantly enhanced students' understanding, engagement, and motivation in learning complex biophysical and biochemical processes when compared with conventional instructional methods. Specifically, the experimental group exposed to VR & AR environments achieved substantially higher posttest scores in both the Biophysical and Biochemical Concept Understanding Test (BBCUT) and the Student Engagement and Motivation Questionnaire (SEMQ) than their peers taught through traditional approaches. These outcomes align with a growing corpus of recent research suggesting that immersive technologies exert a strong positive influence on both cognitive achievement and affective engagement in science learning (Makransky & Petersen, 2023; Tene et al., 2024; Wang et al., 2024).

The significant improvement in students' conceptual understanding observed in this study can be attributed to the immersive visualisation and interactive affordances of VR and AR. Unlike static textbook images, VR & AR simulations allow learners to dynamically explore molecular structures, observe energy transformations, and manipulate variables in real time, thereby translating abstract theoretical concepts into vivid, tangible experiences. This capacity for embodied visualisation resonates with the constructivist learning paradigm, which emphasises active knowledge construction through interaction and reflection. Similar effects were reported by Reen et al. (2024), who found that immersive biology simulations enhanced students' comprehension of cellular transport and enzyme reactions by enabling real-time visualisation of submicroscopic events. Likewise, Handoyo (2024) observed that AR-supported molecular modelling significantly improved students' understanding of reaction mechanisms, providing cognitive scaffolds that minimised misconceptions about atomic interactions. The convergence of these findings supports the assertion that spatial immersion facilitates deep conceptual learning in domains characterised by high levels of abstraction and system complexity.

Equally significant were the observed gains in student engagement and motivation following VR & AR instruction. The results showed that learners in the experimental group displayed greater enthusiasm, persistence, and willingness to participate actively during lessons. This supports the Cognitive-Affective Theory of Learning with Media (CATLM), which posits that meaningful learning occurs when cognitive processing is coupled with emotional and motivational engagement (Moreno & Mayer, 2007; Makransky & Petersen, 2023). VR and AR environments naturally evoke curiosity and situational interest by presenting novel and interactive representations of scientific content. Consistent with this explanation, Wang et al. (2024) reported that students' engagement in immersive environments correlated strongly with their posttest performance, indicating that affective factors mediate the relationship between immersion and cognitive gain. The present study reinforces this causal link, demonstrating that heightened engagement is not merely an ancillary benefit of VR & AR instruction but a critical mechanism driving deeper understanding of complex processes.

The large effect sizes ($\eta^2 > 0.44$) found in this study provide robust evidence that immersive instruction has a substantive educational impact rather than a marginal or transient effect. This magnitude of difference exceeds most effect sizes reported in meta-analyses of traditional multimedia learning interventions, positioning VR and AR as transformative instructional tools in science education. However, as Tene et al. (2024) and Olim (2024) cautioned, the quality of learning outcomes depends heavily on the instructional design of the immersive experience. The present study carefully aligned VR & AR activities with curriculum objectives and guided exploration, which likely contributed to the observed outcomes. This supports Lin's (2024) assertion that scaffolding and structured reflection are essential in preventing cognitive overload and ensuring meaningful integration of immersive experiences within formal curricula.

The findings also highlight the pedagogical potential of VR and AR for integrated science learning, where biophysical and biochemical processes intersect conceptually. Traditional disciplinary boundaries often compartmentalise physics, chemistry, and biology, leading to fragmented learning. By contrast, immersive simulations promote systems thinking, allowing students to visualise energy flow, chemical interactions, and biological functions as interrelated phenomena. Such integrative learning aligns with current STEM education reforms emphasising interdisciplinarity and real-world relevance (Ngoc-Son et al., 2025). In this way, the use of VR & AR technologies advances not only conceptual mastery but also the coherence of scientific understanding across sub-disciplines.

Notwithstanding these promising outcomes, certain limitations warrant consideration. The study's quasi-experimental design, though suitable for classroom-based research, limits the extent to which findings can be generalised beyond the sampled schools. Furthermore, exposure time was limited to six weeks; longer interventions could reveal more about retention and transfer of conceptual knowledge. As several reviews note (Olim, 2024; Wang et al., 2024), sustained engagement and repeated exposure are critical to consolidating learning gains in immersive environments. Additionally, the study did not account for potential differences in individual learners' spatial ability, technological familiarity, or learning preferences, all of which may moderate the effectiveness of VR & AR interventions (Lin, 2024).

Despite these limitations, the findings carry important theoretical and practical implications. Theoretically, they reaffirm that immersive visualisation technologies can operationalise the principles of constructivism and embodied cognition by providing multisensory, interactive experiences that connect perception, action, and conceptualisation. Practically, they suggest that integrating VR and AR into the secondary science curriculum can enhance not only content mastery but also learners' motivation and persistence, key determinants of long-term achievement in STEM fields. However, successful implementation will depend on teacher training, curricular alignment, and the availability of cost-effective, scalable hardware solutions (Ngoc-Son et al., 2025).

Conclusion

The present study concludes that virtual and augmented reality (VR & AR) technologies significantly enhance secondary school students' understanding, engagement, and motivation in learning complex biophysical and biochemical processes. The results provide strong empirical evidence that immersive learning environments, when effectively integrated into the science curriculum, can overcome persistent challenges associated with teaching abstract and dynamic scientific concepts that are often difficult to visualise through traditional instructional methods. By providing three-dimensional, interactive, and experiential representations, VR & AR fosters deep conceptual understanding and allows learners to observe, manipulate, and connect theoretical models with observable phenomena in meaningful ways.

The study further establishes that VR & AR-based instruction does more than improve cognitive achievement; it also substantially increases learners' interest, enthusiasm, and active participation in science lessons. These outcomes align with constructivist and cognitive-affective learning theories, which posit that learning is most effective when students are cognitively engaged and emotionally invested in the learning process. The positive influence on motivation underscores VR & AR's potential to reframe science learning as an exploratory and enjoyable activity rather than a purely abstract or memorisation-based task.

The findings also highlight the importance of pedagogical design in maximising the benefits of immersive learning technologies. The effectiveness of VR and AR is closely tied to how they are embedded within lesson objectives, supported by teacher guidance, and accompanied by reflective discussion that helps students consolidate what they experience virtually. Consequently, teachers must be adequately trained to integrate immersive technologies purposefully rather than as add-ons or entertainment tools. While the study demonstrates promising results, it acknowledges limitations related to duration, sample size, and contextual variability, which suggest that future research should explore long-term retention, scalability, and differential effects across learner types. Expanding this line of inquiry will deepen understanding of how VR & AR can be systematically integrated across science disciplines and educational levels.

Recommendations

Based on the findings and implications of the study, the following recommendations were proposed:

1. Curriculum developers and educational policymakers should formally integrate virtual and augmented reality applications into secondary school science curricula, especially for topics involving complex biophysical and biochemical processes. Such integration should be accompanied by structured lesson plans, aligned learning outcomes, and assessment strategies that ensure VR & AR use directly supports conceptual understanding rather than serving as an isolated or supplementary activity.
2. Effective implementation of immersive technologies requires adequately trained teachers. Ministries of Education and teacher-training institutions should organise continuous professional development workshops to equip science teachers with the technical skills and pedagogical competencies necessary

to manage VR & AR tools, guide student exploration, and facilitate reflective learning. This will ensure that the technology enhances, rather than replaces, sound instructional practice.

3. Educational technology developers and researchers should collaborate to create localised VR and AR simulations that align with national science curricula and reflect real-world phenomena familiar to students. Locally relevant content will improve accessibility, engagement, and cultural relevance, while also reducing dependency on expensive foreign applications. Open-source and low-cost platforms should be prioritised to ensure equitable access across diverse school settings.
4. Future studies should extend beyond short-term achievement tests to examine the long-term retention, transfer of knowledge, and affective outcomes such as scientific curiosity and self-efficacy associated with VR & AR instruction. Experimental and longitudinal designs with larger and more diverse samples will strengthen the evidence base and guide sustainable adoption. Comparative studies across different STEM domains will also clarify the contexts in which VR and AR yield the greatest learning benefits.

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