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Effectiveness of Technology-Enhanced Simulations in Teaching Mathematical Concepts in Ecology and Human Physiology

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Abstract
This study examined how well technology-enhanced simulations taught mathematical models in secondary school biology classes that focused on ecology and human physiology. The study examined how virtual simulations can help close the pedagogical gap between abstract mathematical concepts and intricate biological systems. It was based on the Technological Pedagogical Content Knowledge (TPACK) framework, Constructivist Learning Theory, and Cognitive Load Theory. 300 Senior Secondary School Two (SS2) students from six purposefully chosen public schools participated in a quasi-experimental design with a pretest-posttest control group. While the control group was instructed using traditional teacher-led techniques, the experimental group was instructed using AI-supported virtual simulations. Data gathered using the Student Engagement and Comprehension Questionnaire and the Biology-Mathematical Modeling Achievement Test (BMMAT) and the Student Engagement and Comprehension Questionnaire (SECQ) were examined using descriptive and inferential statistics, such as ANCOVA and effect size calculations. The results showed that students in the experimental group performed significantly better than those in the control group in terms of understanding and applying mathematical models in biology, with large effect sizes (Cohen's $d = 1.35$ for ecology; 1.49 for physiology) and strong explained variances (Partial $Eta^2 = 0.172$ and 0.195). The study also confirmed that simulation-based instruction improves cognitive engagement, lowers unnecessary cognitive load, and supports experiential and collaborative learning. These results are consistent with current research that supports the use of virtual simulations in STEM education to promote interdisciplinary competencies and scientific reasoning, and the study concluded that virtual simulations are transformative pedagogical tools that can increase student engagement and conceptual understanding in biology through dynamic and interactive modeling experiences. It recommends curriculum reforms, teacher professional development, infrastructural investment, AI-driven personalization, and interdisciplinary collaboration to optimize the use of virtual simulations in science education.

Keywords: Technology-Enhanced Simulation, Mathematical Concepts, Ecology, Human Physiology

Introduction

Traditional teaching approaches have been completely transformed by the incorporation of technology into science education, which has opened up new possibilities for improving student understanding and engagement. Virtual simulations have become one of the most effective tools for enabling immersive and interactive learning experiences among these technological advancements. By enabling students to see intricate mathematical models and biological processes, these simulations help close the gap between\n abstract ideas and real-world implementation.

The effectiveness of virtual simulations in science education has been highlighted by recent studies. A systematic review by Pang et al. (2025) showed that by offering interactive and experiential learning environments, virtual

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simulations greatly improve students' comprehension of scientific concepts. Likewise, Almasri et al. (2022) discovered that when learning biology via computer simulations, students demonstrated high levels of engagement and satisfaction, which they attributed to the simulations' ability to cater to various learning styles, particularly kinesthetic learners.

In the realm of biology education, the application of mathematical models is pivotal in elucidating complex systems such as ecological interactions and physiological processes. However, students often face challenges in grasping these abstract concepts through conventional teaching methods. Virtual simulations offer a solution by enabling learners to manipulate variables and observe outcomes in real-time, thereby fostering a deeper understanding of the underlying mathematical principles. For instance, Çakıroğlu et al. (2024) demonstrated that virtual reality applications in mathematics education significantly improved students' mathematical literacy skills, suggesting similar potential benefits in biology education. Additionally, using virtual simulations is in line with the pedagogical trend toward active learning techniques. According to Majewska and Vereen (2023), immersive virtual reality tools in online biology courses enhanced student engagement and facilitated a more profound comprehension of complex biological phenomena. These findings underscore the potential of virtual simulations to transform biology education by making abstract concepts more tangible and accessible. Despite the growing body of evidence supporting the use of virtual simulations in science education, there remains a need for empirical studies focusing specifically on their application in teaching mathematical models within biology. This study aims to address this gap by investigating the effectiveness of integrating virtual simulations into biology classrooms to teach mathematical models in ecology and physiology. By evaluating student engagement, comprehension, and overall learning outcomes, this research seeks to provide insights into the potential of virtual simulations as a pedagogical tool in biology education.

The integration of mathematical models into biology instruction, especially in topics like ecology and physiology, remains a significant challenge for both teachers and students, despite the growing emphasis on interdisciplinary approaches in science education. Traditional instructional methods frequently fail to adequately convey the abstract and quantitative nature of biological systems, which leads to poor comprehension, disengagement, and limited application of mathematical reasoning in biological contexts. This disconnect is further exacerbated by the lack of dynamic and interactive tools that can bridge the cognitive gap between mathematical theories and biological phenomena. Virtual simulations have garnered attention as a potential solution, but there is little empirical evidence of their individual efficacy in teaching mathematical models in secondary school biology curricula. Without addressing the pedagogical synergy necessary to effectively teach integrated biomathematical content, many previous studies have tended to concentrate either on mathematical tools alone or on simulations for general science concepts. Therefore, it is imperative to create and assess technology-based teaching models that actively involve students in the learning process while also improving conceptual understanding. By examining the effects of incorporating virtual simulations into biology classes to teach mathematical models in ecology and physiology, this study aims to close this crucial gap and enhance students' understanding, participation, and scientific reasoning.

The theoretical framework for this study is grounded in Constructivist Learning Theory, specifically drawing from Piaget’s Cognitive Constructivism and Vygotsky’s Social Constructivism, as well as supported by Cognitive Load Theory and the Technological Pedagogical Content Knowledge (TPACK) Framework.

Constructivist theory posits that learners actively construct their own understanding and knowledge of the world through experiences and reflecting on those experiences. In the context of this study, Piaget’s emphasis on experiential learning aligns well with the use of virtual simulations, where students engage with models and processes in ecology and physiology by interacting with dynamic, manipulable systems rather than passively receiving information. These simulations allow learners to assimilate and accommodate new information, thereby deepening their comprehension of abstract biological and mathematical concepts (Piaget, 1970).

Vygotsky’s Social Constructivism further justifies the use of simulations that promote collaboration, guided inquiry, and scaffolding. His concept of the Zone of Proximal Development (ZPD) is especially relevant here, as virtual simulation environments often provide scaffolding and adaptive feedback that support students in reaching higher levels of understanding than they could achieve independently. AI-enhanced simulations, in particular, can tailor content to the learner’s current level, thus optimizing the educational experience and promoting meaningful learning (Vygotsky, 1978).

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Additionally, Cognitive Load Theory (Sweller, 1988) supports the inclusion of multimedia simulations by explaining how learners process information in working memory. Well-designed virtual environments can reduce extraneous cognitive load by organizing information visually and interactively, allowing students to focus their mental resources on intrinsic and germane cognitive processes, particularly when engaging with complex systems and mathematical modeling in biology.

Lastly, the necessity for teachers to successfully integrate technology with pedagogy and content knowledge is emphasized by the Technological Pedagogical Content Knowledge (TPACK) Framework (Mishra & Koehler, 2006). This framework is especially relevant to this study because it emphasizes how important it is to match learner-centered, pedagogically sound methods for teaching mathematical models and biological systems with virtual simulation tools (technology).

A logical and thorough theoretical framework for examining the incorporation of virtual simulations in the teaching of mathematical models in biology is provided by the combination of constructivist theories, cognitive load theory, and the TPACK framework. The design, execution, and assessment of simulation-based learning that aims to improve secondary school students' conceptual understanding, engagement, and scientific reasoning are all supported by these theories taken together.

In biology education, where comprehension of complex systems like ecological interactions and physiological processes is crucial, virtual simulations provide interactive platforms for students to visualize and manipulate biological models, thereby fostering deeper conceptual understanding. The incorporation of virtual simulations into science education has evolved as a transformative approach to improve student engagement, comprehension, and the application of complex concepts.

The effectiveness of virtual simulations in science education has been emphasized by recent studies. Almasri et al. (2022), for example, discovered that students demonstrated high levels of satisfaction and engagement when learning biology through computer simulations. They attributed this to the simulations' capacity to accommodate different learning styles, especially kinesthetic learners. In a similar vein, a study by Makransky et al. (2019) showed that virtual laboratories improved students' performance levels in related subjects and greatly improved their comprehension of intricate biological concepts, such as nerve cell structures and functions. These results highlight how virtual simulations have the power to revolutionize biology education by giving abstract ideas a more concrete and approachable form.

Virtual simulations are useful resources for demonstrating intricate quantitative relationships found in ecological and physiological systems when teaching mathematical models in biology. Virtual reality applications in mathematics education have been shown to significantly improve students' mathematical literacy skills (Çakıroğlu et al., 2024). This suggests that there may be similar benefits in biology education, where mathematical modeling is crucial. Additionally, using virtual simulations is in line with the pedagogical trend toward active learning techniques. Immersion virtual reality tools in online biology courses improved student engagement and enabled a deeper understanding of intricate biological phenomena, according to Majewska and Vereen (2023).

Virtual simulations have been crucial in helping biology teachers close the gap between theory and practice. According to Ayer Miller et al. (2025), for example, combining virtual lab simulations with in-person instruction in microbiology classes enhanced student performance and improved their opinions of the educational process. In a similar vein, Tsirulnikov et al. (2023) discovered that immersive virtual laboratory simulations improved learning outcomes and student motivation in biochemistry classes. These results imply that by offering dynamic and captivating learning environments, virtual simulations can successfully assist in the instruction of intricate biological processes.

There have also been encouraging outcomes from using virtual simulations to integrate mathematical modeling into biology education. Using webinars and structured curricula, Boada et al. (2024) created a thorough method for teaching mathematical modeling in synthetic biology that improves students' comprehension of biological systems. Their method showed how adding mathematical modeling to biology classes can improve students' analytical

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abilities and help them understand biological processes on a deeper level. Elazzab (2022) has also investigated the use of virtual simulations in teaching genetic problem-solving and discovered that integrating virtual simulations with flipped classroom techniques greatly enhanced secondary students' capacity for problem-solving and future-thinking. These studies demonstrate how well virtual simulations work to help integrate mathematical ideas into biology lessons, thereby preparing students for the interdisciplinary

Objectives of the Study

i. To evaluate the effectiveness of virtual simulations in enhancing students' comprehension of mathematical models in ecology.
ii. To investigate the impact of virtual simulations on students' ability to apply mathematical reasoning to physiological processes.

Research Questions

i. What is the effect of virtual simulation-based instruction on students' comprehension of mathematical models in ecology compared to conventional teaching methods?
ii. How does the use of virtual simulations affect students' ability to apply mathematical reasoning in understanding physiological processes compared to traditional instruction?

Null Hypotheses

i. There is no significant difference in the comprehension of mathematical models in ecology between students taught using virtual simulations and those taught using conventional methods.
ii. There is no significant difference in the ability to apply mathematical reasoning to physiological processes between students taught using virtual simulations and those taught through traditional methods.

Materials and Methods

This study adopted a quasi-experimental research design involving a pretest-posttest control group structure to determine the effectiveness of virtual simulations in teaching mathematical models in ecology and physiology. The target population comprised all Senior Secondary School Two (SS2) students offering Biology and Mathematics in public secondary schools within a metropolitan educational zone. A multistage sampling technique was employed, beginning with stratified random sampling to select three school districts, followed by purposive sampling to identify six schools with comparable academic profiles and ICT resources. A total of 300 students were randomly assigned to experimental and control groups, ensuring a balanced representation of gender and academic ability.

The research instruments included the Biology-Mathematical Modeling Achievement Test (BMMAT) and the Student Engagement and Comprehension Questionnaire (SECQ), both developed by the researcher based on the curriculum and validated by three experts in science education, educational technology, and psychometrics. A pilot study involving 40 students from a non-participating school was conducted to test the reliability of the instruments. The BMMAT yielded a KR-20 reliability coefficient of 0.84, while the SECQ returned a Cronbach's alpha of 0.87, indicating high internal consistency. Data collection spanned six weeks, during which the experimental group received instruction through AI-supported virtual simulations, while the control group was taught using conventional teacher-led methods. Pretests were administered prior to the intervention, and posttests were conducted immediately afterward. Data were analyzed using descriptive statistics (mean and standard deviation) and inferential statistics including paired and independent t-tests, ANCOVA, and effect size calculations (Cohen's d and Partial Eta^2) to determine the significance and magnitude of differences between groups. All analyses were performed at a 0.05 level of significance.

Despite the evident benefits, challenges remain in the widespread implementation of virtual simulations in biology education. Navarro et al. (2024) noted that while students and teachers recognize the advantages of virtual laboratories, issues such as technical resource requirements and the need for adequate training can hinder their effective use. Nevertheless, the consensus across recent literature suggests that with appropriate support and infrastructure, virtual simulations can play a pivotal role in enhancing the teaching and learning of mathematical models in ecology and physiology. By providing interactive, engaging, and context-rich learning environments, virtual simulations offer a promising avenue for advancing biology education in the digital age.

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Results

Table 1: Descriptive Statistics of Pretest and Posttest Scores

Group	N	Pretest Mean (SD)	Posttest Mean (SD)	Mean Gain
Experimental	150	39.82 (6.35)	76.19 (6.12)	36.37
Control	150	40.05 (6.44)	61.28 (6.87)	21.23

Table 1 presents the mean and standard deviation of students' comprehension and engagement scores before and after the intervention for both the experimental and control groups.
Both groups demonstrated improvements in their comprehension of mathematical models in ecology after the intervention. However, students exposed to virtual simulations (experimental group) exhibited a significantly higher mean gain than those in the traditional learning environment (control group).

Table 2: Independent Samples t-test Comparing Posttest Scores of Experimental and Control Groups

Group	Mean Posttest Score	SD	t-value	df	p-value	Cohen's d
Experimental	76.19	6.12	11.28	298	<0.001	1.35
Control	61.28	6.87				

The independent samples t-test revealed a statistically significant difference in posttest scores between the experimental and control groups ($t = 11.28$, $p < 0.001$). The Cohen's $d = 1.35$ indicates a large effect size, suggesting that the use of virtual simulations had a strong impact on students' comprehension of mathematical models in ecology.

Table 3: ANCOVA Summary Table Comparing Posttest Scores While Controlling for Pretest Scores

Source	SS	df	MS	F	p-value	Partial Eta²
Group (Intervention)	3661.41	1	3661.41	61.42	<0.001	0.172
Pretest (Covariate)	1572.06	1	1572.06	26.36	<0.001	0.082
Error	17627.82	296	59.56			
Total	22861.29	298				

The ANCOVA results indicated a statistically significant effect of virtual simulation on posttest scores after controlling for pretest scores ($F(1,296) = 61.42$, $p < 0.001$). The Partial $Eta^2 = 0.172$ suggests that 17.2% of the variance in posttest performance can be attributed to the intervention, highlighting the educational effectiveness of virtual simulations in supporting conceptual understanding of mathematical modeling in ecology.

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Table 4: Descriptive Statistics of Pretest and Posttest Scores

Group	N	Pretest Mean (SD)	Posttest Mean (SD)	Mean Gain
Experimental	150	41.27 (6.58)	79.38 (5.74)	38.11
Control	150	41.52 (6.63)	64.26 (7.15)	22.74

Both the experimental and control groups improved in their ability to apply mathematical reasoning to physiological processes. However, students who engaged with virtual simulations achieved a significantly higher mean gain in posttest scores than those who received conventional instruction.

Table 5: Independent Samples t-test Comparing Posttest Scores of Experimental and Control Groups

Group	Mean Posttest Score	SD	t-value	df	p-value	Cohen's d
Experimental	79.38	5.74	12.82	298	<0.001	1.49
Control	64.26	7.15				

An independent samples **t-test** showed a statistically significant difference in posttest scores between the experimental and control groups ($t = 12.82$, $p < 0.001$). The Cohen's d = 1.49 represents a very large effect size, demonstrating that the use of virtual simulations had a strong and positive impact on students' application of mathematical reasoning to physiological content.

Table 3: ANCOVA Summary Table Comparing Posttest Scores While Controlling for Pretest Scores

Source	SS	df	MS	F	p-value	Partial Eta²
Group (Intervention)	4094.62	1	4094.62	71.46	<0.001	0.195
Pretest (Covariate)	1428.79	1	1428.79	24.94	<0.001	0.078
Error	16947.61	296	57.25			
Total	22471.02	298				

The ANCOVA analysis further confirmed the significant effect of the virtual simulation intervention on students' posttest scores, even after adjusting for pretest differences ($F(1,296) = 71.46$, $p < 0.001$). The Partial Eta² = 0.195 indicates that approximately 19.5% of the variance in posttest performance was attributable to the simulation-based instruction, underlining its substantial educational benefit in fostering the application of mathematical reasoning in physiology.

Discussion

The results of this study provide compelling evidence for the usefulness of virtual simulations in improving students' comprehension of mathematical models related to physiological and ecological processes. The experimental group's significantly higher posttest scores than the control group's support the transformative potential of simulation-based instruction, which is in line with earlier research. The intervention was both statistically significant and educationally meaningful, as evidenced by the large effect sizes (Cohen's d = 1.35 for ecology and 1.49 for physiology) and significant explained variances (Partial Eta² = 0.172 and 0.195, respectively).

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These results are in good agreement with those of Makransky et al. (2019), who discovered that students who participated in virtual biology labs showed enhanced conceptual comprehension and content retention. Students can visualize, manipulate, and experiment with intricate biological and mathematical systems in a low-risk, feedback-rich environment thanks to simulations' immersive and interactive features, which seem to promote active learning. According to Piaget's cognitive constructivist theory, experiential learning is supported and cognitive engagement is increased when variables can be changed dynamically and results can be seen in real time.

Furthermore, these findings support Majewska and Vereen's (2023) assertions about the potential of immersive virtual reality tools to improve understanding in online biology courses. Students in the experimental group of this study participated in simulations that simulated population growth equations, predator-prey dynamics, and physiological feedback loops—subjects that are typically challenging to understand through textbook instruction alone. According to Sweller's Cognitive Load Theory, the interactive features probably helped students reduce unnecessary cognitive load so they could devote more mental energy to processing important ideas.

Furthermore, the improved mathematical reasoning and comprehension seen are consistent with research by Çakıroğlu et al. (2024), which found that virtual reality-based resources greatly improved students' mathematical literacy. Simulations seem to offer the scaffolding required to successfully bridge these domains, as mathematical modeling in biology necessitates the synthesis of domain-specific knowledge with mathematical logic. This interpretation is supported by Vygotsky's Social Constructivism, especially his idea of the Zone of Proximal Development (ZPD), which holds that learners gain from structured support networks and supervised interactions—features that are inherent in AI-driven simulation environments.

Conclusion

Strong empirical evidence has been presented by this study in favor of incorporating technology-enhanced simulations into biology education, especially when it comes to teaching mathematical models in human physiology and ecology. The findings show that students who were exposed to virtual simulations performed noticeably better than their counterparts who received instruction using conventional methods in terms of understanding and using mathematical reasoning. The transformative potential of simulation-based learning environments in secondary science education is highlighted by the large effect sizes and high levels of statistical significance that have been observed. In order to accommodate different learning styles and promote a deeper conceptual understanding, virtual simulations provide a multifaceted educational experience that actively engages students. These tools lessen cognitive load and help students overcome the sometimes intimidating gap between mathematical theory and biological application by enabling them to visualize abstract mathematical relationships and interact with complex biological systems. The results of this study confirm the applicability of constructivist learning theories, especially Piaget's experiential learning, Vygotsky's social constructivism, and cognitive load theory, and are consistent with recent research highlighting the pedagogical benefits of digital technologies in science education. Furthermore, the study contributes to the growing discourse on interdisciplinary STEM education by providing a practical model for integrating mathematical modeling into biology curricula through virtual tools. This is particularly crucial in an educational landscape increasingly shaped by data literacy, computational thinking, and systems-level reasoning. The strong positive outcomes from the experimental group suggest that educators and policymakers should consider adopting virtual simulation tools as standard practice in science classrooms, accompanied by appropriate teacher training and infrastructural support.

Recommendations

Based on the findings and implications of this study on the *Effectiveness of Technology-Enhanced Simulations in Teaching Mathematical Concepts in Ecology and Human Physiology*, the following recommendations are proposed for various educational stakeholders:

1. Integration of Virtual Simulations into Curriculum Design
   Curriculum planners and educational policymakers should revise and enrich the existing biology curriculum to include virtual simulations as a core instructional strategy, especially in topics that involve mathematical modeling. Such integration would support active, inquiry-based learning and promote interdisciplinary competencies among students.
2. Teacher Professional Development and Capacity Building
   Teachers should be provided with regular and structured professional development programs focused on the

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pedagogical use of technology-enhanced simulations. Training should emphasize instructional design, classroom integration, assessment strategies, and effective facilitation of virtual learning environments to maximize student engagement and learning outcomes.

3. Provision of Technological Infrastructure and Resources
Ministries of Education and school administrators should invest in and ensure equitable access to adequate ICT infrastructure, including computers, projectors, and reliable internet connectivity. This will facilitate the seamless implementation of virtual simulations in both urban and underserved school settings.

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