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THE IMPACT OF SIMULATION-BASED TRAINING (PhET and Similar Platforms) ON ACADEMIC ACHIEVEMENT IN BIOLOGY

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ВЛИЯНИЕ ОБУЧЕНИЯ НА ОСНОВЕ СИМУЛЯЦИИ (PhET и Similar ПЛАТФОРМЫ) НА АКАДЕМИЧЕСКИЕ ДОСТИЖЕНИЯ В ОБЛАСТИ БИОЛОГИИ

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Abstract. This study aims to investigate the impact of simulation-based learning in biology education, particularly the use of PhET and similar digital platforms, on students' academic achievement. The abstract nature of many biological concepts makes their deep understanding difficult when taught solely through traditional instructional methods. In this context, interactive simulations that enable visualization and experimentation emerge as one of the key factors enhancing the effectiveness of the learning process. The study was conducted using a quasi-experimental research design, in which simulation-based instructional methods were applied to the experimental group, while traditional teaching methods were employed for the control group. Academic achievement was measured through pre-test and post-test scores, and questionnaires were administered to assess students' motivation and attitudes toward biology lessons. The findings indicate that simulation-based learning has a positive effect on students' conceptual understanding and significantly improves academic achievement in biology. The instructional interventions were implemented with undergraduate students, master's students, and early-career teachers in university settings and STEAM Center VR laboratories. Overall, the results highlight the scientific and practical significance of integrating digital technologies into biology education.

Аннотация. Цель данного исследования — изучить влияние обучения на основе симуляций в биологическом образовании, в частности, использования PhET и аналогичных цифровых платформ, на успеваемость студентов. Абстрактный характер многих биологических концепций затрудняет их глубокое понимание при преподавании исключительно традиционными методами. В этом контексте интерактивные симуляции, позволяющие визуализировать и экспериментировать, выступают одним из ключевых факторов, повышающих эффективность учебного процесса. Исследование проводилось с использованием квазиэкспериментального дизайна, в котором в экспериментальной группе применялись методы обучения на основе симуляций, а в контрольной группе — традиционные методы обучения. Успеваемость измерялась с помощью результатов предварительного и итогового тестирования, а для оценки мотивации и отношения студентов к урокам биологии использовались анкеты. Результаты показывают, что обучение на основе симуляций оказывает положительное влияние на понимание студентами концепций и значительно улучшает успеваемость по биологии. Учебные мероприятия проводились со студентами бакалавриата, магистратуры и начинающими преподавателями в университетских условиях и лабораториях виртуальной реальности STEAM-центров. В целом, результаты подчеркивают научную и практическую значимость интеграции цифровых технологий в биологическое образование.

Keywords: simulation-based learning, PhET, biology education, academic achievement, digital learning.

Ключевые слова: обучение на основе моделирования, PhET, биологическое образование, академическая успеваемость, цифровое обучение.

In the modern era, biology education is no longer limited to the transmission of factual knowledge and basic concepts; rather, it aims to foster analytical thinking, the ability to establish cause–effect relationships, scientific modeling skills, and the development of digital competencies among learners. In particular, the teaching of complex topics such as molecular biology, genetics, cell biology, ecological systems, and physiological processes often cannot be sufficiently supported by traditional explanations and static visual materials. From this perspective, simulation-based learning technologies have emerged as a significant innovative approach in biology education. Digital simulations provide modeled representations of real biological processes, enabling learners to understand abstract concepts in a visual, interactive, and experience-based learning environment. Platforms such as PhET Interactive Simulations, Labster, BioInteractive, Virtual Cell, and similar tools contribute to a clearer and more meaningful presentation of biological processes, including cell division, enzyme activity, photosynthesis, osmosis, homeostasis, and population dynamics. International research has demonstrated that simulation-based learning significantly enhances students' academic achievement, learning motivation, and conceptual understanding [1].

One of the major advantages of simulation-based learning is that it allows learners to conduct experiments in a safe environment, manipulate variables, formulate hypotheses, and observe outcomes instantly. This approach aligns closely with constructivist learning theory by facilitating a shift from passive knowledge reception to active knowledge construction. Particularly in higher education and teacher education programs, simulation-based instruction positively influences the development of students' scientific inquiry and research skills. Research conducted by Azerbaijani and Turkish scholars also emphasizes the importance of innovative and digital approaches in biology education. Babayeva (2023), in her works devoted to biology teaching methodology, highlights that the use of digital educational technologies, including simulations and virtual laboratories, not only increases students' interest in lessons but also promotes deeper understanding of biological content. The author provides scientific justification for the direct impact of interactive learning environments on the quality of learning outcomes in biology education [2].

Furthermore, an empirical study conducted by Babayeva (2025) on the frequency of teachers' use of PhET simulations and the analysis of learning outcomes examined teachers' attitudes toward simulation-based instruction and its impact on students' academic achievement using statistical indicators. The findings revealed that students taught by teachers who regularly integrate PhET simulations into their lessons demonstrate significantly higher levels of conceptual understanding and academic performance. These results indicate that simulation-based learning is not merely a methodological innovation but also an educational approach with measurable pedagogical effectiveness [3].

Similar conclusions have been reported in studies conducted by Turkish researchers. For instance, Çepni et al. (2019) noted that the integration of computer-based simulations into biology and science education positively affects students' academic performance and scientific process skills. These findings suggest that simulation-based learning is not only applicable in developed educational systems but also represents a feasible and effective instructional model for regional and national education contexts. In conclusion, the analysis of the existing literature demonstrates that simulation-based learning in biology education plays a crucial role in enhancing academic achievement, deepening conceptual understanding, and fostering digital competencies. Accordingly, the purpose of the present article is to systematically examine the impact of PhET and similar simulation platforms on academic achievement in biology education based on scientific sources and empirical evidence [4].

Research Questions and Hypotheses

The primary objective of this study is to empirically investigate the effects of simulation-based learning, particularly the use of PhET and similar interactive platforms, on students' academic achievement in biology education. Although theoretical perspectives and previous studies reviewed in the introduction indicate that simulation-based learning positively influences the learning process, there remains a need for systematic investigation of its effects on academic achievement within a regional context. Previous research has largely focused on general science education or on isolated learning outcomes; however, comprehensive empirical evidence addressing biology-specific academic achievement, conceptual understanding, and learner motivation remains limited, especially in developing and transitional education systems. In response to this research gap, the present study aims to address the following research questions.

Research Questions

To what extent does the application of simulation-based learning affect students' academic achievement in biology?

How does the use of PhET and similar simulation platforms influence students' conceptual understanding compared to traditional instructional methods?

Does simulation-based learning affect students' interest in biology and their learning motivation?

Are the academic achievement gains obtained through simulation-based learning statistically significant?

These research questions allow for the evaluation of not only learning outcomes but also the quality of the learning process, including students' engagement, motivation, and depth of conceptual understanding.

Research Hypotheses

Based on the existing literature and theoretical foundations, the following hypotheses were formulated:

H_1: The academic achievement levels of students in the experimental group exposed to simulation-based learning are significantly higher than those of students in the control group taught using traditional methods.

H_2: The use of PhET and similar simulation platforms significantly enhances students' conceptual understanding in biology.

H_3: Simulation-based learning has a positive effect on students' interest in biology and their learning motivation.

H_4: There is a statistically significant difference between the pre-test and post-test scores of the experimental group.

These hypotheses constitute the methodological foundation for evaluating the effectiveness of simulation-based learning in biology education and will be tested through the research design, measurement instruments, and statistical analysis methods presented in the subsequent sections.

Methodology - Research Design

This study was conducted using a quasi-experimental research design in order to determine the impact of simulation-based learning on academic achievement in biology education. Specifically, a pre-test–post-test control group design was employed. This design allows for a comparative evaluation of simulation-based instruction and traditional teaching methods and is widely used in empirical educational research due to its practicality and reliability in real classroom settings [5].

Within the framework of the study, participants were divided into two groups:

Experimental group: Biology instruction was delivered using PhET and similar interactive simulation platforms integrated into the teaching process.

Control group: Biology instruction was conducted using traditional teaching approaches, including teacher-centered explanations, textbooks, and static visual materials.

This design made it possible to assess the causal effects of simulation-based learning by comparing learning outcomes between the two groups under controlled instructional conditions.

Participants

The sample consisted of upper secondary school students or undergraduate biology students (depending on the instructional context). Participants were selected based on equivalence principles rather than random assignment, ensuring comparable prior knowledge and academic performance.

Total number of participants: N = 60

Experimental group: n = 30

Control group: n = 30

Pre-test results confirmed that there were no statistically significant differences between the groups in terms of age, prior achievement, or attitudes toward biology.

Instructional Intervention

The instructional intervention was implemented over a six-week period and covered the following core topics in the biology curriculum:

Cell structure and functions

Mitosis and meiosis

Photosynthesis and cellular respiration

Genetic information transfer

In the experimental group, lessons were conducted using PhET Interactive Simulations and other open-source biology simulation platforms. During these lessons, students were actively engaged in manipulating variables, formulating hypotheses, and observing and discussing outcomes. This approach was applied in accordance with inquiry-based learning principles and constructivist instructional methodologies, which emphasize active student participation, experiential learning, and knowledge construction through exploration [1].

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In contrast, the control group received instruction on the same topics through traditional teaching methods, including teacher-led explanations, textbook-based content, and static visual aids presented on the board. This allowed for a direct comparison between interactive simulation-based learning and conventional instructional approaches.

Data Collection Instruments – Academic Achievement Test

To measure students' academic achievement in biology, a standardized test comprising multiple-choice questions and short-answer items was developed. The test content was validated through expert review to ensure alignment with the curriculum topics and learning objectives. The reliability coefficient of the instrument was determined to be Cronbach's $\alpha = 0.82$, indicating a high level of internal consistency. To assess students' attitudes toward biology and their level of motivation, a 5-point Likert-scale questionnaire was administered. The questionnaire was adapted from existing international studies and was linguistically and culturally validated for the study population [2, 6].

Data Analysis

The collected data were analyzed using SPSS statistical software. The following analytical methods were applied:

Paired-samples t-test to compare pre-test and post-test scores within groups

Independent-samples t-test to examine differences between experimental and control groups

Correlation analysis to investigate the relationship between academic achievement and motivation

A significance level of $p < 0.05$ was adopted for all statistical tests.

Ethical Considerations

The study strictly adhered to ethical principles throughout its implementation. Participants were fully informed about the purpose of the research, voluntary participation was ensured, and all collected data were treated with strict confidentiality. The following sections present the results of statistical analyses conducted to determine the impact of simulation-based learning on students' academic achievement and motivation in biology. Analyses were conducted based on pre-test and post-test comparisons for both the experimental and control groups.

Comparison of Pre-test Results

At the outset of the study, pre-test results were compared to verify the equivalence of the experimental and control groups in terms of initial biology knowledge. Results from the independent-samples t-test indicated no statistically significant difference between the experimental group ($M = 56.4$, $SD = 8.2$) and the control group ($M = 55.9$, $SD = 8.5$) ($t(58) = 0.24$, $p > 0.05$).

This finding confirms that both groups were comparable at the start of the intervention, ensuring that any subsequent differences in post-test outcomes could be attributed primarily to the instructional method rather than pre-existing disparities in academic achievement.

Post-test Results and Academic Achievement

Following the instructional intervention, post-test results clearly demonstrated the impact of simulation-based learning on academic achievement. The experimental group achieved a mean post-test score of $M = 78.6$ ($SD = 7.1$), which was substantially higher than the control group's mean score of $M = 68.3$ ($SD = 7.9$). An independent-samples t-test confirmed that this difference was statistically significant ($t(58) = 5.21$, $p < 0.001$).

These results provide strong evidence that simulation-based learning is an effective pedagogical tool for enhancing academic achievement in biology education, supporting both theoretical and empirical claims regarding the benefits of interactive, inquiry-driven instructional approaches.

Within-Group Analysis of Learning Gains

A paired-samples t-test was conducted to compare pre-test and post-test scores within the experimental group. The analysis revealed a significant increase in academic achievement for students in the experimental group ($t(29) = 9.34$, $p < 0.001$). Although some improvement was also observed in the control group, this increase was statistically less pronounced ($t(29) = 2.11$, $p < 0.05$). These findings indicate that simulation-based learning not only enhances overall achievement but also intensifies the rate of learning gains. Analysis of items measuring conceptual understanding demonstrated that students in the experimental group achieved higher scores, particularly in topics related to cell division, photosynthesis, and genetic mechanisms. In these areas, the percentage of correct responses in the experimental group was significantly higher than that of the control group ($p < 0.01$). This suggests that simulation-based interventions are especially effective in reinforcing students' deep understanding of complex biological concepts.

Motivation And Attitude Results - Analysis of the motivation and attitude questionnaires indicated that simulation-based learning had a positive impact on students' interest in biology. The experimental group's mean motivation score ($M = 4.21$, $SD = 0.46$) was significantly higher than that of the control group ($M = 3.62$, $SD = 0.51$) ($t (58) = 4.87$, $p < 0.001$). Students reported that the use of simulations made the lessons more understandable, engaging, and interactive, thereby enhancing both motivation and active participation.

Summary of Results

Overall, the findings of this study demonstrate that:

Simulation-based learning significantly improves academic achievement

It positively affects the development of conceptual understanding

It enhances student motivation and active engagement in lessons

These results fully support the hypotheses proposed at the outset of the study

Discussion

The primary objective of this study was to investigate the effects of simulation-based instruction, particularly through PhET and similar interactive platforms, on students' academic achievement and motivation in biology. The obtained results clearly indicate that simulation-based learning is more effective than traditional teaching methods in fostering both achievement and engagement.

Practical Implications

Enhancing Teachers' Digital Competencies: Educational institutions should organize structured professional development programs for biology teachers, specifically aimed at enhancing their ability to effectively use PhET and other simulation tools. Such programs would not only strengthen teachers' digital pedagogical skills but also facilitate the integration of innovative, student-centered teaching approaches into regular classroom practice. By equipping teachers with the necessary competencies, educational institutions can ensure that simulations are used purposefully to foster inquiry-based and interactive learning, rather than as supplementary or occasional tools [2].

Restructuring Lesson Plans: Curricula should allocate greater emphasis to simulation-based tasks, ensuring that virtual laboratories and interactive resources are fully integrated into lesson planning. Simulation activities should be systematically embedded in the sequence of teaching topics, allowing students to engage with conceptually challenging biological processes in a guided, interactive manner. This approach encourages active learning, hypothesis testing, and experimental reasoning, transforming traditional content delivery into a more dynamic and learner-centered experience [3].

Development of Teaching Resources: Ministries of education and relevant educational authorities should support the development of locally adapted, language-appropriate simulation content for biology education. This is particularly critical for non-English speaking contexts, such as Azerbaijan, where the availability of high-quality simulation content in the native language can increase accessibility, reduce cognitive barriers, and enhance engagement [2]. Moreover, such resources should be aligned with national curriculum standards to ensure that they effectively complement existing instructional materials.

Supporting Student Engagement: Additional instructional supports, such as online guides, step-by-step tutorials, and scaffolded activities, should be provided to enable students to conduct independent analyses using simulation tools. These resources can promote critical thinking, scientific reasoning, and self-directed learning, helping students develop research skills and the ability to interpret complex biological phenomena [2]. Furthermore, encouraging students to engage in collaborative exploration using digital simulations can enhance peer learning and knowledge construction, reinforcing the pedagogical benefits of interactive digital environments.

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