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VIRTUAL EXPERIMENTS AND SIMULATION-BASED LEARNING IN NATURAL SCIENCE EDUCATION: ENHANCING THE TEACHING PROCESS AND ITS SCIENTIFIC-PSYCHOLOGICAL FOUNDATIONS

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ВИРТУАЛЬНЫЕ ЭКСПЕРИМЕНТЫ И ОБУЧЕНИЕ НА ОСНОВЕ МОДЕЛИРОВАНИЯ В ЕСТЕСТВОЗНАНИИ: ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ПРОЦЕССА ОБУЧЕНИЯ И ЕГО НАУЧНО-ПСИХОЛОГИЧЕСКИЕ ОСНОВЫ

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Abstract. The rapid development of digital educational technologies has transformed traditional approaches to teaching and learning in natural science education. Virtual experiments and simulation-based learning environments provide students with opportunities to observe complex scientific processes, conduct safe experimental activities, and develop conceptual understanding through interactive experiences. This study examines the contribution of virtual experimental environments to improving teaching effectiveness and analyzes the scientific and psychological mechanisms underlying learning processes in digital educational contexts. Particular attention is given to cognitive engagement, motivation, experiential learning, and the development of higher-order thinking skills supported by simulation-based instructional approaches. The findings suggest that integrating virtual experiments into natural science education can strengthen academic performance, promote meaningful learning, and contribute to more adaptive, student-centered educational practices. Virtual laboratories enable students to model physical, chemical, and biological processes in interactive environments, manipulate variables, and systematically analyze experimental outcomes. Contemporary digital platforms, such as PhET Interactive Simulations, Labster, and BioDigital Human, facilitate the visualization of complex scientific phenomena while fostering higher-order cognitive skills, including hypothesis formulation, experimental design, and data interpretation. The integration of these technologies enhances students' understanding of complex topics such as cell biology, molecular mechanisms, chemical reactions, energy transformations, and physical laws. Furthermore, the ability to repeatedly conduct experiments in virtual environments promotes reflective learning and supports error-based learning processes. Empirical evidence indicates that the systematic use of virtual laboratories and simulations significantly improves students' academic performance, learning motivation, and engagement. Additionally, these technologies support interdisciplinary integration in line with the principles of STEAM education and contribute to the development of a cohesive learning ecosystem that bridges theoretical knowledge with practical application. In conclusion, virtual laboratories and simulation technologies in natural science education should be regarded not only as technological innovations but also as strategic pedagogical tools that enhance instructional quality, foster scientific thinking, and develop research-oriented competencies in learners.

Аннотация. Быстрое развитие цифровых образовательных технологий трансформировало традиционные подходы к преподаванию и обучению в естественнонаучном образовании. Виртуальные эксперименты и учебные среды на основе моделирования предоставляют студентам возможность наблюдать за сложными научными процессами, проводить безопасные экспериментальные работы и развивать концептуальное понимание посредством интерактивного опыта. В данном исследовании рассматривается вклад виртуальных экспериментальных сред в повышение эффективности преподавания и анализируются научные и психологические механизмы, лежащие в основе процессов обучения в цифровом образовательном контексте. Особое внимание уделяется когнитивной вовлеченности, мотивации, обучению на основе опыта и развитию навыков мышления более высокого порядка, поддерживаемых подходами к обучению на основе моделирования. Результаты показывают, что интеграция виртуальных экспериментов в естественнонаучное образование может повысить успеваемость, способствовать осмысленному обучению и внести вклад в более адаптивные, ориентированные на студента образовательные практики. Виртуальные лаборатории позволяют студентам моделировать физические, химические и биологические процессы в интерактивных средах, манипулировать переменными и систематически анализировать результаты экспериментов. Современные цифровые платформы, такие как PhET Interactive Simulations, Labster и BioDigital Human, облегчают визуализацию сложных научных явлений, одновременно способствуя развитию когнитивных навыков более высокого порядка, включая формулирование гипотез, проектирование экспериментов и интерпретацию данных. Интеграция этих технологий улучшает понимание студентами сложных тем, таких как клеточная биология, молекулярные механизмы, химические реакции, преобразования энергии и физические законы. Кроме того, возможность многократно проводить эксперименты в виртуальной среде способствует рефлексивному обучению и поддерживает процессы обучения, основанные на ошибках. Эмпирические данные показывают, что систематическое использование виртуальных лабораторий и симуляций значительно улучшает успеваемость студентов, мотивацию к обучению и вовлеченность. Помимо этого, эти технологии поддерживают междисциплинарную интеграцию в соответствии с принципами STEAM-образования и способствуют развитию целостной учебной экосистемы, которая связывает теоретические знания с практическим применением. Виртуальные лаборатории и технологии симуляции в естественнонаучном образовании следует рассматривать не только как технологические инновации, но и как стратегические педагогические инструменты, повышающие качество обучения, способствующие развитию научного мышления и формирующие исследовательские компетенции у учащихся.

Keywords: digital skills, STEAM, innovative methods, simulation-based learning; virtual experiments; scientific-psychological foundations.

Ключевые слова: цифровые навыки, STEAM, инновационные методы, обучение на основе моделирования; виртуальные эксперименты; научно-психологические основы.

The educational landscape of the 21st century is characterized by the intensive integration of information and communication technologies (ICT). This integration extends beyond the mere use of technical tools and necessitates fundamental transformations in teachers' pedagogical practices. The modern teacher is no longer solely a transmitter of knowledge but assumes the role of a facilitator who creates a learning environment in which students are actively engaged and where analytical and critical thinking skills are systematically developed [34].

This transformation is particularly evident in the teaching of natural sciences — such as biology, chemistry, and physics — where learning is not limited to theoretical instruction but must be complemented by practical skills and laboratory experiences. In biology education, laboratory activities play a multifaceted role. First, they enable students to connect theoretical knowledge with real biological processes. For instance, topics such as cell division, genetic inheritance patterns, photosynthesis, and respiration can be fully understood only through experimental engagement. Second, laboratory work fosters students' analytical thinking, observation, and evaluative skills. Third, it allows learners to apply scientific methodologies and research skills in practice. Therefore, laboratory instruction serves not only as a means of knowledge acquisition but also as a critical platform for the development of scientific reasoning and problem-solving competencies. However, real laboratory environments are not always accessible and are often associated with several challenges. First, the limitation of laboratory equipment presents a significant barrier. Modern biology laboratories require advanced technological instruments, including high-resolution microscopes, PCR devices, molecular biology tools, and specialized reagents. In many higher education institutions, the lack of such equipment or the outdated nature of existing resources restricts students' ability to conduct experiments. As a result, some experimental procedures are reduced to visual demonstrations or theoretical explanations. Second, safety regulations impose constraints on laboratory activities. Working with biological and chemical substances carries inherent risks, and improper handling of reagents may pose serious health and safety hazards. Consequently, laboratory sessions are typically conducted under strict supervision and with a limited number of students, which reduces the intensity and accessibility of practical training [1-10].

Third, the high cost of experiments further limits the implementation of laboratory-based learning. The provision of reagents, materials, equipment, and technical support requires substantial financial investment. This is particularly problematic when repeated experimentation is necessary, thereby restricting students' opportunities for individualized learning experiences. In response to these challenges, virtual laboratories and simulation technologies have emerged as effective alternatives in recent years. Virtual laboratories provide students with safe, interactive, and repeatable experimental environments, thereby overcoming the constraints of traditional laboratory settings and enabling broader student participation. Within virtual environments, students can explore complex biological processes — such as cell division, photosynthesis, genetic mechanisms, and ecological interactions — by manipulating variables and comparing outcomes. Moreover, virtual laboratories enhance students' scientific interest and motivation while supporting both individual and collaborative experimentation. Contemporary simulation tools foster higher-order cognitive skills, including hypothesis formulation, experimental design, data analysis, and scientific reasoning. Thus, virtual laboratories should be regarded not merely as technological innovations but as essential pedagogical instruments that increase interactivity and improve the overall effectiveness of the teaching and learning process. The aim of this study is to systematically investigate the application of virtual laboratories and simulation technologies in biology education and to evaluate their impact on instructional effectiveness, as well as on students' knowledge, skills, and motivation. Furthermore, the study highlights tools that facilitate the practical integration of academic knowledge and analyzes the role of digital technologies in enhancing the quality of education [11, 39].

The integration of digital technologies into education has become one of the central themes in contemporary pedagogical research. These technologies are no longer perceived merely as tools for knowledge transmission but as instruments for creating interactive learning environments that foster active learning, analytical thinking, and problem-solving skills. Within this context, computer-based

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simulations have been widely recognized as effective tools for enhancing students' understanding of complex scientific phenomena. As highlighted by De Jong and Van Joolingen, simulations facilitate conceptual learning by enabling students to actively engage in experimentation, manipulate variables, and observe the outcomes of their actions in a controlled environment. This approach shifts the learning paradigm from passive reception of information to active knowledge construction. For example, in topics such as cell division and genetic inheritance, students can utilize virtual simulations to explore how changes in variables influence biological processes, thereby deepening their conceptual understanding [33, 34].

From a theoretical perspective, Mayer's Cognitive Theory of Multimedia Learning emphasizes the importance of integrating visual and interactive elements into instructional design. According to this theory, multimedia resources enhance learners' ability to connect abstract theoretical concepts with concrete representations, leading to improved comprehension and retention. In biology education, complex biochemical processes — such as photosynthesis and cellular respiration — can be effectively visualized through simulations, significantly improving students' understanding of otherwise abstract mechanisms [38].

Empirical studies further support the effectiveness of virtual laboratories in science education. Rutten, van Joolingen, and van der Veen demonstrated that the use of virtual laboratories significantly enhances both conceptual understanding and practical skills [39].

Their findings indicate that virtual environments promote the development of key scientific competencies, including hypothesis generation, experimental design, data comparison, and analytical evaluation. Moreover, simulations allow students to perform experiments that may be difficult, expensive, or hazardous in real laboratory settings, thereby ensuring both safety and accessibility. In addition, Makransky and Petersen emphasize the role of immersive virtual environments in increasing students' motivation and engagement. Their research shows that when students are provided with opportunities to repeat experiments, modify parameters, and explore alternative scenarios, their level of interest and cognitive involvement increases significantly [36].

This is particularly relevant in disciplines such as cell biology, genetics, molecular biology, and ecology, where many processes are either microscopic or too complex to observe directly. International research consistently identifies virtual laboratories and simulations as essential didactic tools in modern science education. These technologies contribute to: The development of scientific reasoning and analytical skills; Improved understanding of complex biological processes; Enhanced problem-solving and research competencies; The safe and interactive execution of experiments; The promotion of both individual and collaborative learning [12-15].

Furthermore, cross-national studies indicate that the use of virtual laboratories not only improves students' academic performance but also significantly enhances their motivation and interest in science. For instance, a study by Makransky et al. (2020) reported that students participating in virtual laboratory-based instruction demonstrated 30–40% higher levels of engagement and conceptual understanding compared to those in traditional laboratory settings. In conclusion, virtual laboratories and simulation technologies should be regarded not merely as technological innovations but as indispensable pedagogical tools in modern biology education. They play a crucial role in developing students' knowledge, skills, and motivation while supporting interdisciplinary integration in line with STEAM principles. Moreover, these approaches enhance learners' ability to investigate complex biological problems, thereby aligning science education with the demands of the digital age [35, 36].

This study employed a mixed-methods research design, integrating experimental and survey-based approaches to systematically evaluate the application of virtual laboratories and simulation technologies in biology education. The primary objective was to assess their impact on instructional effectiveness, as well as on students' knowledge acquisition, skill development, and learning motivation.

Object of the study: Biology education in higher education institutions.

Subject of the study: The implementation of virtual laboratories and simulation technologies and their impact on the teaching and learning process.

Classroom implementation of virtual laboratories was systematically observed. Students' interactive engagement within simulation environments, their ability to follow experimental procedures, and their capacity to manipulate variables were carefully documented. Additionally, students' motivation levels and the challenges they encountered while using virtual laboratories were evaluated through structured observation protocols.

Questionnaires administered to both students and instructors were used to assess perceptions of the effectiveness of virtual laboratories. The survey measured students' attitudes toward simulation-based learning, their motivation, the perceived clarity of experimental procedures, and the development of analytical skills. A comparative analysis was conducted between traditional laboratory instruction and virtual laboratory-based learning. This analysis enabled the identification of differences in students' ability to apply theoretical knowledge, develop experimental skills, and interpret results. The findings indicated that virtual laboratories provide enhanced support for both conceptual understanding and practical skill development [16, 17].

An experimental intervention was conducted focusing on key biology topics, including cell division (mitosis and meiosis) and photosynthesis. Students engaged in simulation-based experiments under varying conditions by manipulating variables such as temperature, light intensity, and CO_2 concentration. This approach facilitated deeper conceptual understanding and promoted the development of scientific reasoning and evidence-based conclusions. PhET Interactive Simulations (University of Colorado, USA): Used for interactive simulations of biological processes such as cell division, photosynthesis, and respiration. BioDigital Human: Applied for the visualization of human anatomy and physiological processes through 3D interactive models. Labster: Provided a fully immersive virtual laboratory environment for molecular biology, genetics, and ecology experiments. Overall, this methodological framework enabled a comprehensive evaluation of the integration of virtual laboratories into the teaching process and allowed for a comparative analysis of students' theoretical understanding and practical competencies. Virtual Laboratories in Biology — Virtual laboratories represent a significant pedagogical innovation in modern biology education, offering students safe, interactive, and repeatable experimental environments. These platforms enable learners to explore complex biological processes — such as cell division, photosynthesis, genetic mechanisms, molecular interactions, and ecological dynamics — in a manner that closely simulates real-world conditions. Virtual laboratories eliminate the risks associated with handling biological and chemical substances. For example, procedures involving PCR techniques or hazardous reagents, which may pose risks in physical laboratories, can be conducted safely in virtual environments. Reduced Dependence on Equipment — The need for expensive laboratory equipment and consumable materials is significantly minimized. This is particularly beneficial for institutions with limited resources, ensuring equitable access to experimental learning opportunities. Repeatability and Flexibility — Experiments can be repeated multiple times without additional cost or resource constraints. Students can test different variables, compare outcomes, and learn from errors through iterative experimentation, thereby reinforcing learning. Visualization of Complex Processes: Microscopic and complex biological phenomena — such as mitosis, meiosis, photosynthesis, cellular respiration, and genetic processes — can be visualized in detail. This enhances students' conceptual understanding and facilitates the comprehension of abstract scientific concepts.

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Instructional Example: Cell Division (Mitosis and Meiosis). Instructional Approach: Students use PhET Interactive Simulations and Labster to observe all stages of cell division, including prophase, metaphase, anaphase, and telophase. Student Activities: Analyze each phase of cell division in detail; Manipulate environmental variables such as temperature and pH; Record simulation results and prepare scientific reports. Learning Outcomes: Students develop a comprehensive understanding of cell division not only at a theoretical level but also through interactive engagement. This process enhances knowledge retention, analytical thinking, and problem-solving skills. Additional Examples: Photosynthesis and Respiration — Students use PhET Interactive Simulations to manipulate variables such as light intensity and CO_2 concentration, observing their effects on oxygen production and energy transformation. This approach allows learners to understand how environmental factors influence biological processes through interactive visualization. Genetics Experiments — Using Labster, students simulate Mendelian inheritance patterns by experimenting with different parental genotype combinations. This enables them to observe genotype-phenotype relationships and understand hereditary mechanisms through practical application. Thus, virtual laboratories should be regarded not only as technological tools but also as essential pedagogical instruments that form the didactic and interactive foundation of modern biology education. They enable students to integrate theoretical knowledge with practical skills while simultaneously fostering scientific inquiry and experimental competencies [18].

Instructional Method: Students engage with virtual laboratory environments to observe all stages of cell division, while manipulating variables such as temperature, pH, and nutrient availability.

Student Activities: Analyze each stage of the cell division process; Modify variables and observe resulting changes; Interpret experimental outcomes. Learning Outcomes: Students achieve a deeper understanding of the stages and закономерности (patterns) of cell division and develop scientific reasoning skills through interactive experimentation. Simulation technologies in biology education utilize computer-based models and interactive software to visualize and explore complex biological processes. These technologies move beyond passive knowledge acquisition, enabling students to model scientific phenomena, analyze outcomes, and test variables within controlled environments. Simulations provide opportunities for students to analyze data and interpret experimental results. For example, in photosynthesis simulations, students can manipulate variables such as light intensity, CO_2 concentration, and temperature to observe their effects on oxygen production. This process enhances their ability to draw evidence-based scientific conclusions. Simulation environments allow students to repeatedly perform complex or potentially hazardous experiments. This is particularly valuable in fields such as molecular biology, genetics, and cell biology. For instance, genetic simulations enable learners to explore Mendelian inheritance patterns by testing various parental genotype combinations. Simulations encourage students to approach problems from multiple perspectives. For example, when observing reduced oxygen production in plant respiration models, students can adjust variables such as light exposure or CO_2 levels to identify causal relationships and propose solutions. Simulation tools often present results in graphical and tabular formats, facilitating visual analysis and interpretation. This supports the development of scientific literacy and data-driven reasoning skills.

Instructional Examples in Biology. Photosynthesis and Respiration. Method: Students use PhET Interactive Simulations and Labster to manipulate environmental variables such as light intensity, water availability, and CO_2 concentration. Student Activities: Define and modify experimental variables; Record and compare results; Develop hypotheses and predictions based on observations. Learning Outcomes: Students gain an interactive understanding of how environmental factors influence biological processes, enhancing both analytical thinking and experimental skills. Cell Division and Genetics. Method: Using Labster, students observe the stages of cell division and conduct genetic simulations to determine phenotypic outcomes based on parental genotypes. Student Activities: Analyze chromosome movement and cytokinesis; Test different genetic combinations and document results; Compare outcomes across multiple experimental scenarios. Learning Outcomes: Students develop a practical understanding of both cell division and genetic principles, strengthening their experimental competence and scientific reasoning.

Pedagogical Significance of Simulation Technologies. Simulation technologies: facilitate the integration of theoretical knowledge with practical application; provide safe environments for conducting experiments; promote the development of scientific thinking and inquiry-based learning; support interdisciplinary connections in line with STEAM education, linking biology with chemistry, physics, and information technologies; enhance both individual and collaborative learning through interactive experimentation. Simulation technologies create a safe, interactive, and immersive learning environment in biology education. This approach not only reinforces theoretical knowledge but also significantly contributes to the development of experimental skills, analytical thinking, problem-solving abilities, and scientific literacy. The findings of this study indicate that the integration of virtual laboratories and simulation technologies into biology education plays a significant role in improving students' knowledge acquisition, enhancing practical skills, and increasing learning motivation [19-26].

The research was conducted using an experimental design involving two groups: An experimental group, which engaged with virtual laboratories and simulation tools; A control group, which participated in traditional laboratory instruction. The differences between these groups were evaluated through statistical analysis, allowing for a systematic comparison of learning outcomes, skill development, and student engagement levels.

Table 1

ASSESSMENT OF STUDENTS' THEORETICAL KNOWLEDGE

Group	*Number of Students*	*Mean Score*	*Standard Deviation*	*p-value*
Control (Traditional Laboratory)	45	74.6	8.3	–
Experimental (Virtual Laboratory)	48	88.9	6.7	< 0.05

Analysis: The results indicate a statistically significant difference between the control and experimental groups ($p<0.05$), with the experimental group demonstrating substantially higher performance. This finding suggests that virtual laboratories play a critical role in strengthening students' theoretical knowledge. Instructional Example: In the topic of cell division, students used PhET Interactive Simulations to interactively explore the stages of mitosis and meiosis, analyzing chromosome movement and cellular processes. Following the simulation-based intervention, students' theoretical performance increased by approximately 20%, indicating enhanced conceptual understanding. Students' practical competencies were evaluated based on experimental accuracy, ability to design experiments, and skills in analyzing results.

Table 2

ASSESSMENT OF STUDENTS' PRACTICAL KNOWLEDGE

Group	*Mean Practical Score*	*Standard Deviation*	*Improvement (%)*
Control	70.2	7.5	–
Experimental	85.6	5.9	+21.9%

Students who engaged with virtual laboratories demonstrated significantly higher practical skill levels. This improvement can be attributed to the ability to safely repeat experiments and manipulate variables within simulation environments, leading to deeper experiential learning. Instructional

Example: In the topic of photosynthesis, students used PhET Interactive Simulations to manipulate variables such as light intensity and CO_2 concentration. They measured oxygen production, visualized results graphically, and prepared analytical reports, thereby strengthening their experimental and data interpretation skills. Survey results revealed a substantial increase in students' motivation and interest following the use of virtual laboratories.

Table 3

ASSESSMENT OF STUDENTS' MOTIVATION AND INTEREST

Parameter	*Control Group*	*Experimental Group*	*Increase (%)*
Motivation Level (1–5)	3.1	4.5	+45%
Interest Level (1–5)	3.3	4.7	+42%

The findings demonstrate that virtual laboratories significantly enhance student engagement. The interactive and risk-free nature of simulations encourages active participation and sustained interest in the learning process. Instructional Example: In genetics lessons, students used Labster to simulate Mendelian inheritance patterns by testing different parental genotype combinations. Through group discussions and comparative analysis, students derived scientific conclusions, which contributed to increased engagement and deeper understanding [27, 28].

Figures 1–3 illustrate the comparative performance of the control and experimental groups in terms of theoretical knowledge, practical skills, and motivation/interest levels. The data clearly demonstrate that students in the experimental group outperformed those in the control group across all measured parameters. These findings provide strong empirical evidence for the positive impact of virtual laboratories and simulation-based learning environments on students' academic performance, practical competencies, and motivational outcomes. Overall, the visual analysis demonstrates that the experimental approach significantly enhances both cognitive and affective learning outcomes. The experimental group not only acquired greater theoretical knowledge and practical skills but also exhibited higher motivation and interest, suggesting improved engagement and learning effectiveness compared to the control group. The findings of this study demonstrate that the integration of virtual laboratories and simulation technologies into biology education yields significant pedagogical benefits. Specifically, the results indicate that these technologies: Enhance students' theoretical understanding of complex biological concepts; Improve practical skills and enable more accurate experimental execution; Increase students' motivation and engagement in the learning process; Foster higher-order cognitive skills, including analytical thinking, problem-solving, and scientific reporting [29-32].

These findings are consistent with prior international research, which highlights the effectiveness of virtual laboratories in promoting immersive and interactive learning environments. Through repeated experimentation and manipulation of variables, students are able to explore biological processes more deeply, leading to improved conceptual understanding and knowledge retention. Furthermore, the immersive nature of simulation-based learning environments supports inquiry-based learning and aligns with contemporary constructivist pedagogical approaches. Students actively construct knowledge by engaging in experimentation, rather than passively receiving information, thereby enhancing both cognitive engagement and learning outcomes [35, 38].

The integration of virtual laboratories and simulation technologies significantly enhances the quality of biology education by improving students' theoretical knowledge, practical competencies, and learning motivation. These technologies serve as effective tools for implementing STEAM-based approaches, fostering interdisciplinary learning, and supporting both individual and collaborative educational experiences. The study confirms that virtual laboratories and simulation technologies

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provide multifaceted benefits in biology education. The key findings can be summarized as follows [37-39]:

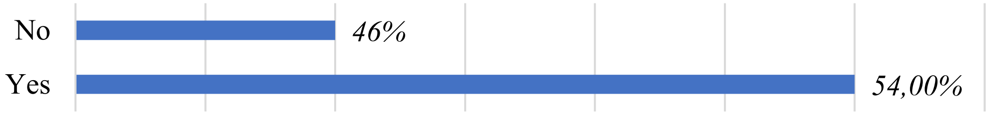

Figure 1. Average Teoretical Rnowlendge Scores

Figure 2. Average Practical Skills Scores

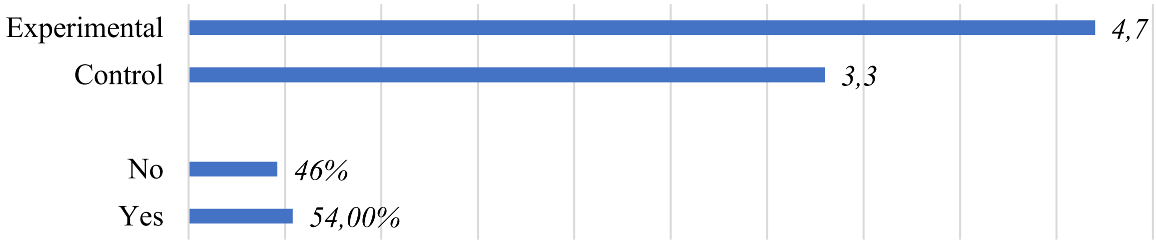

Figure 3. Motivation (1) and Interest Levels (2)

1. Strengthening of Theoretical Knowledge — Students demonstrated a deeper understanding of topics such as cell division, photosynthesis, respiration, and genetics when supported by virtual laboratory environments. This is particularly important for visualizing microscopic and abstract processes that are difficult to observe directly.

2. Development of Practical Skills — Virtual laboratories enable students to conduct experiments in safe, repeatable, and interactive settings. Through platforms such as PhET Interactive Simulations and Labster, students manipulate variables, analyze outcomes, and refine experimental procedures, thereby strengthening their practical competencies.

3. Increased Motivation and Engagement — Interactive simulations promote active participation and enhance students' interest in learning. This aligns closely with STEAM-based educational approaches, where students engage in scientific inquiry as active participants rather than passive learners.

4. Enhancement of Analytical and Problem-Solving Skills — Virtual laboratories support the development of scientific reasoning by enabling students to model phenomena, compare results, and draw evidence-based conclusions.

Instructional Example: In a cell division lesson, students used Labster to analyze mitosis and meiosis under varying temperature and pH conditions. By comparing results and participating in group discussions, they developed both individual understanding and collaborative problem-solving skills. To maximize the effectiveness of virtual laboratories and simulation technologies in biology education, the following recommendations are proposed.

1. Strengthening Digital Infrastructure — Higher education institutions should ensure access to stable internet connectivity and modern computing equipment to support seamless use of simulation platforms.

2. Professional Development for Educators — Teachers should receive targeted training and professional development opportunities to effectively integrate virtual laboratories and simulation tools into their instructional practices.

3. Curriculum Integration — Biology curricula should be updated to incorporate virtual laboratories alongside traditional experimental methods. This blended approach allows students to benefit from both real and simulated learning experiences.

4. Adaptation of Assessment Systems — Assessment frameworks should include students' performance in virtual laboratory activities. Analytical reports, graphical data interpretation, and simulation-based outcomes should be integrated into evaluation criteria.

5. Implementation of STEAM Approaches — Virtual laboratories should be actively used in interdisciplinary STEAM projects that integrate biology with mathematics, technology, and engineering. For example, analyzing the effects of light intensity and CO_2 concentration in photosynthesis simulations can also support the development of students' quantitative and analytical skills.

Virtual laboratories and simulation technologies are expected to play a central role in the future development of biology education. These technologies not only enhance the acquisition of theoretical knowledge but also significantly contribute to the development of students' creativity, research competencies, and scientific methodology skills. Future research in this field may focus on the following directions: The impact of virtual laboratories on individual learning styles and personalized education pathways; The integration of simulation-based learning into collaborative and group-based educational environments; The expansion of Virtual Reality (VR) and Augmented Reality (AR) applications in biology education to create more immersive and realistic learning experiences. In addition, future studies may explore adaptive learning systems powered by artificial intelligence to further personalize simulation-based instruction and improve student engagement and performance outcomes. In conclusion, virtual laboratories and simulation technologies create an innovative, safe, and interactive learning environment in biology education. These tools enable students to integrate theoretical knowledge with practical skills, engage in repeated experimentation, and develop analytical thinking and scientific reasoning abilities. Furthermore, they significantly enhance students' learning motivation and active participation in the educational process. This approach aligns with the fundamental principles of modern pedagogy and fully supports the integration of the STEAM framework into science education. By bridging theoretical understanding with experiential learning, virtual laboratories and simulation technologies represent a transformative shift in contemporary biology teaching and learning practices.

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