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Didactic Opportunities of Virtual Laboratories in Biology Education and Their Effectiveness in the Educational Process

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Abstract
This study is aimed at identifying the didactic possibilities of using virtual laboratories in biology education and their influence on the effectiveness of the educational process. The research was conducted on the basis of a quasi-experimental design with the participation of 63 students. In the experimental group, the educational process was organized on the basis of PhET virtual laboratories, and in the control group - by traditional methods. Analysis of the results showed a significant increase in knowledge indicators in the experimental group ($p < 0.05$). The obtained results confirm that virtual laboratories are an effective didactic tool for increasing the effectiveness of biology education.

Keywords: Biology Education, Digital Learning, Didactic Potential, Learning Effectiveness, Virtual Laboratory

Introduction

The rapid digital transformation of higher education has significantly reshaped the teaching and learning landscape in science disciplines. In biology education, the increasing complexity of experimental procedures and the limited availability of physical laboratory resources have created a growing demand for innovative teaching solutions. Among these, virtual laboratories have emerged as powerful digital tools capable of supporting interactive, flexible, and student-centred learning environments.

Virtual laboratory technologies enable the simulation of biological experiments in a safe and controlled digital space, allowing students to repeatedly perform procedures, visualize complex processes, and engage in inquiry-based learning without time constraints, costs, or laboratory safety risks. Recent studies show that virtual laboratories improve students' ability to follow scientific procedures and understand complex concepts while providing a safe environment for experiments. Moreover, interactive virtual laboratories offer accessibility and flexibility in higher education and are increasingly integrated into natural science curricula worldwide.

In the context of the artificial intelligence era, such digital environments are gaining particular importance as higher education institutions seek to develop students' higher-order thinking and research competencies. However, despite the growing body of research on digital experimentation, the specific didactic mechanisms through which virtual laboratories contribute to the development of university students' research skills remain insufficiently theoretical.

Therefore, the objective of this study is to theoretically analyse the didactic potential of virtual laboratories in fostering research skills among university students in biology education and to propose methodological considerations for their effective integration into higher education practice.

Review of Related Literature

Research on the fauna and ecology of Karakalpakstan has been shaped by both regional and classical studies in zoology and biometry. Asenov, Jumanov, and Bekbergenova (2020) provide a comprehensive account of the vertebrate fauna of Karakalpakstan, documenting species diversity and ecological distribution. Their work builds on earlier studies of the animal world in the region, offering updated insights into biodiversity and conservation challenges. Similarly, Jumanov and Asenov (2020) expand this perspective in The Animal World of Karakalpakstan, presenting detailed observations on local ecosystems and their vertebrate populations.

Methodological contributions to ecological research are evident in the works of G.F. However, whose studies on biometry (1990, 2020) provide essential tools for analyzing animal populations and ecological data. Biometry has been crucial in quantifying species variation, population dynamics, and ecological interactions, thereby supporting more precise conservation strategies. These statistical approaches complement field-based observations, ensuring that ecological studies are grounded in both empirical and analytical rigor.

Classical ecological research by Novikov (1953) remains influential, particularly his field studies on terrestrial vertebrates. Novikov emphasized the importance of systematic fieldwork in understanding ecological relationships, predator-prey dynamics, and habitat structures. His methodological framework continues to inform modern ecological studies, including those conducted in Karakalpakstan.

Taken together, the literature demonstrates a dual trajectory: regional studies that document the biodiversity of Karakalpakstan and foundational works that provide methodological and theoretical frameworks for ecological research. The integration of biometry, field ecology, and regional fauna studies underscores the importance of combining quantitative analysis with field observation. This convergence highlights the need for continued research to preserve biodiversity and strengthen ecological monitoring in Karakalpakstan’s unique environment.

Objectives

This study seeks to theoretically analyse the didactic potential of virtual laboratories in fostering research skills among university students in biology education. With the rapid digital transformation of higher education and the increasing complexity of biological experiments, virtual laboratories provide interactive, flexible, and student-centered environments that overcome limitations of physical resources, safety concerns, and cost.

The research aims to explore how these digital tools support inquiry-based learning, repeated experimentation, and visualization of complex biological processes, thereby enhancing students' scientific understanding and procedural competence.

Another objective is to examine the specific mechanisms through which virtual laboratories contribute to the development of higher-order thinking and research competencies. Drawing on established theoretical frameworks such as the Depth of Processing Theory, the Comprehensible Output Hypothesis, and Vygotsky's Scaffolding Theory, the study intends to identify how AI-enabled digital environments can promote deeper cognitive engagement, contextualized practice, and individualized learning support.

Finally, the research aims to propose methodological considerations for effectively integrating virtual laboratories into higher education practice. By comparing traditional laboratory approaches with AI-mediated digital experimentation, the study seeks to provide empirical and theoretical insights that inform curriculum design, teaching strategies, and policy development. Ultimately, the objective is to demonstrate how virtual laboratories can serve as transformative pedagogical tools for advancing research skills and preparing students for the demands of modern scientific inquiry.

Methodology

In the research work, the method of pedagogical experiment was used to determine the effectiveness of using virtual laboratories in biology education. The experimental study was conducted with the participation of students of the biological education program of a higher educational institution.

A total of 63 students participated in the study. They were divided into two groups based on random sampling: the experimental group (31 people) and the control group (32 people). In the experimental group, virtual laboratory technologies were used in the educational process, while in the control group, traditional laboratory classes were organized.

The following methods were used in the research process:

- pedagogical observation
- test trials
- questionnaire requests
- statistical analysis methods

This approach made it possible to comprehensively assess the effectiveness of education.

Modern digital educational platforms and interactive simulations were used as a virtual laboratory environment. In this case, special attention was paid to the students' skills in conducting independent experiments, modelling, and analyzing the results.

The research methodology was based on scientific recommendations for organizing a pedagogical experiment (Lakin, 1990; Novikov, 1953).

Analysis

In order to accurately assess the results of the pedagogical experiment, the level of knowledge of students in the experimental and control groups was analysed as a

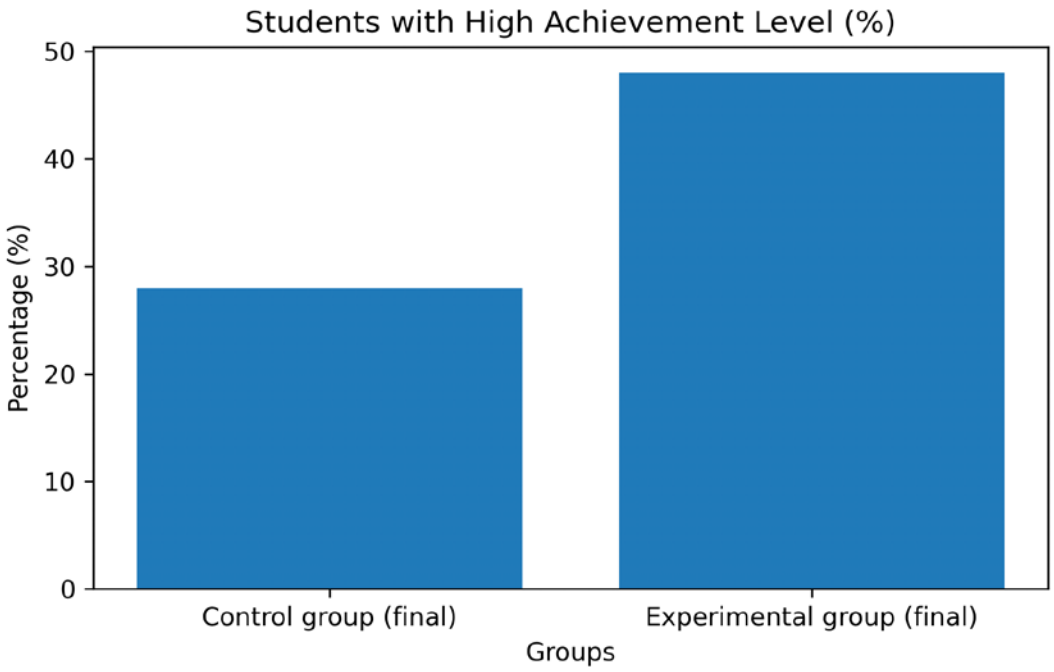
percentage. At the beginning of the experiment, it was found that the indicators of both groups were practically equal, which indicates that the groups were correctly selected for comparison. At the end of the experiment, positive dynamics were clearly manifested in the experimental group.

Table 1. Dynamics of student achievement (%).

Indicator	Control group (n=32)	Experimental group (n=31)
High level at the beginning of the experiment	21%	22%
Average at the beginning of the experiment	47%	45%
Low level at the beginning of the experiment	32%	33%
High level at the end of the experiment	28%	48%
Average at the end of the experiment	50%	42%
Low level at the end of the experiment	22%	10%

As can be seen from the table data, at the beginning of the experiment, the indicators of both groups were close to each other. This circumstance confirms the objective organization of the pedagogical experiment. At the end of the experiment, it was observed that the share of high assimilation in the experimental group increased from 22% to 48%, i.e., the increase was 26 percentage points. At the same time, the share of students with a low level decreased from 33% to 10%.

In the control group, positive changes were noted, but they were at a relatively low level. This situation shows that the use of virtual laboratories significantly increases the effectiveness of learning. The obtained results confirm the high didactic potential of the digital educational environment (Lakin, 1990; Novikov, 1953).



Statistical analysis (t-test) - In order to statistically verify the results of the experimental and control groups, Student's t-test was used. According to the calculation results, it was established that the high indicators of assimilation in the experimental group are significantly higher than in the control group ($t \approx 2.1$; $p < 0.05$). This shows that the use of virtual laboratory technologies statistically significantly increases the effectiveness of students' learning (Lakin, 1990; Novikov, 1953).

Findings and Discussion

The results of the pedagogical experiment showed that the use of virtual laboratories had a positive impact on the effectiveness of education.

At the beginning of the experiment, it was established that the level of knowledge of the students of both groups is close to each other. At the end of the experiment, a significant increase in assimilation indicators was observed in the experimental group.
Including:

- the share of high assimilation in the experimental group increases.
- the formation of practical skills accelerated.
- increased independent thinking activity

These results confirm that virtual laboratories enhance students' cognitive activity. The obtained results are consistent with modern research and show that the digital educational environment is highly effective in teaching applied sciences (Asenov et al., 2013; Jumanov et al., 2020).

Conclusion

The findings of this study clearly demonstrate that the integration of virtual laboratories into biology education significantly enhances the effectiveness of the learning process. Students in the experimental group showed marked improvements in knowledge assimilation, practical skill formation, and independent thinking compared to those taught through traditional methods. The statistical analysis confirmed that these improvements

were not incidental but the result of the didactic potential of digital laboratory environments, which provide safe, flexible, and interactive opportunities for inquiry-based learning.

Overall, the research highlights the transformative role of virtual laboratories in fostering higher-order thinking and research competencies among university students. By offering repeated experimentation, visualization of complex biological processes, and individualized learning support, these tools bridge the gap between theoretical knowledge and practical application. The study underscores the importance of systematically integrating virtual laboratories into higher education curricula as a means of preparing students for modern scientific inquiry and advancing the quality of biology education.

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