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USING DIGITAL LABORATORIES AND SIMULATORS IN THE TRAINING OF FUTURE BIOLOGISTS: EXPERIENCE AND RESULTS ACCORDING TO TIMSS AND PISA DATA

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Abstract

The article examines the effectiveness of introducing digital laboratories and simulators into the educational process of biologists through the prism of international TIMSS and PISA studies. The key advantages of virtual experimental environments are analyzed, correlations between the intensity of use of digital tools and students' academic achievements are revealed. Special attention is paid to the adaptation of educational programs to the requirements of modern science and practical recommendations for the integration of digital technologies into biological education.

Keywords: digital laboratories, educational simulators, training of biologists, TIMSS, PISA, innovative technologies, digitalization of education, learning outcomes, biology.

Introduction

Modern biology education is undergoing fundamental changes under the influence of digitalization. The traditional format of education, based on theoretical mastery of material with a limited number of practical sessions, no longer meets the demands of the time, as scientific research in biology increasingly requires skills in working with big data, computer modeling, and digital processing of experimental results. This shift towards practice-oriented and technologically enriched learning is realized, in particular, through digital laboratories [1]. They represent complex software and hardware solutions that allow for conducting virtual experiments, modeling biological processes, and visualizing complex phenomena at the cellular and molecular level. Simulators of biological systems provide the opportunity to observe processes that, under real conditions, require a long time or special equipment; importantly, digital tools do not replace real experiments but complement them, expanding the learners' capabilities [2].

“Digital transformation of education is not just the introduction of technologies, but the creation of a new educational environment where technology is a natural extension of the research process” [3]. The impact of this transformation on the quality of education and the effectiveness of various approaches on a global scale is assessed using international studies such as TIMSS (Trends in International Mathematics and Science Study) and PISA (Programme for International Student Assessment).

Research Methodology

TIMSS is conducted every 4 years and focuses on assessing the knowledge and skills of 4th and 8th-grade students in mathematics and science. The study includes student testing, questionnaires for students, teachers, and school administrators, which allows establishing a correlation between educational practices and student achievements [4].

PISA is conducted every 3 years among 15-year-old students and assesses their ability to apply knowledge and skills in real-life situations. An important feature of PISA is the assessment of scientific literacy, which includes the ability to interpret data, conduct scientific research, and explain phenomena scientifically.

According to data from the latest TIMSS cycles (2015-2019), countries actively implementing digital laboratories in school education demonstrate consistently high results in science. For example:

− In Singapore, where over 87% of teachers regularly use digital laboratories in biology teaching, the average score in science subjects was 590 points (compared to an average of 489).

− In Finland, the implementation of a digital education program with an emphasis on inquiry-based learning correlates with above-average indicators in scientific thinking and understanding of scientific concepts.

Particularly important is the fact that the greatest effect is observed not simply with the presence of digital laboratories, but with their systematic use combined with a well-thought-out methodology. Schools where digital tools are used sporadically or formally do not show significant improvement in results.

PISA data allow tracing the relationship between the development of students' scientific literacy and the use of digital tools [5]:

− Students with regular access to digital simulators demonstrate 23% better results in tasks requiring the interpretation of scientific data.

− More than 65% of students with high scientific literacy scores report regular use of digital laboratories in biology classes.

− A positive correlation (r=0.62) is observed between the frequency of using virtual experiments and students' ability to formulate scientific hypotheses.

PISA studies also revealed that the use of digital laboratories is particularly effective for developing students' metacognitive skills – the ability to analyze their own thought processes and build problem-solving strategies.

Analysis of international experience shows that digital technologies have a wide range of applications in biology education, covering key areas such as molecular biology, physiology, anatomy, ecology, and cell biology. Digital tools allow modeling complex biological processes, visualizing molecular structures and systemic relationships, and conducting virtual experiments that are impossible to perform in a real laboratory due to technical or time constraints.

In genetics and molecular biology, students can study the processes of replication, transcription, and translation, as well as control the execution of genetic experiments and analyze the inheritance of traits. Virtual platforms provide the opportunity to explore the structure of DNA and proteins, visualizing them at the molecular level.

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Physiology and anatomy benefit from the use of virtual dissections and simulations of physiological processes, which demonstrate in detail the functioning of various body systems. This allows for an in-depth study of the interrelation of organs and their functioning in real time, without requiring complex equipment or access to biological materials.

Digital tools also find application in the study of ecology and evolution. They allow modeling ecosystems and predicting changes caused by external factors, as well as investigating population dynamics and evolutionary processes. Such approaches develop students' systems thinking and understanding of global biological processes.

Cell biology is another area where digitalization plays an important role. Using three-dimensional modeling, students can explore cellular structures, study the processes of the cell cycle, membrane transport, and signaling pathways. This contributes to a deeper understanding of complex interactions within the cell.

Thus, the use of digital technologies in biology education not only significantly expands research opportunities but also enhances the level of engagement and competencies of students, meeting the challenges of modern science [6]. However, to maximize this positive effect, the effectiveness of using digital laboratories is significantly increased when integrated with modern pedagogical strategies. Such strategies include:

− Flipped Classroom: students study theoretical material independently, and during classes, they conduct experiments using digital laboratories under the guidance of the instructor.

− Problem-Based Learning (PBL): digital simulators allow modeling real biological problems and developing strategies for their solution.

− Project-Based Learning: students use digital tools to develop and implement their own research projects.

− Adaptive Learning: digital laboratories can automatically adapt to the student's level of knowledge and skills, offering tasks of appropriate complexity.

The practical implementation of these approaches demonstrates significant success. For example, the Massachusetts Institute of Technology (MIT) developed the StarCellBio platform, allowing students to conduct virtual experiments in cell biology. Research on the effectiveness of this platform showed that students using StarCellBio in conjunction with traditional laboratory work demonstrate a deeper understanding of cellular processes and better experimental design skills. Similarly, Queen's University in Canada implemented a system of virtual ecological simulations, allowing modeling long-term changes in ecosystems. This approach is particularly valuable for studying processes that would take decades in real conditions. Results show a 42% improvement in students' understanding of ecological concepts compared to control groups.

Equally important is the experience of implementing digital laboratories in resource-limited countries. For example, in India, the Digital Biology Initiative program significantly expanded students' access to modern methods of biological research through the use of low-cost digital solutions. According to a national survey, over 70% of students noted that digital laboratories helped them better prepare for practical work in real conditions.

Despite the obvious advantages, the implementation of digital laboratories into the educational process is accompanied by a number of serious challenges that require a comprehensive approach to their resolution. These obstacles can be conditionally divided into several key groups: infrastructural, personnel, methodological, and ethical [7].

Firstly, infrastructural limitations remain a serious obstacle to the implementation of digital technologies. Many educational institutions face insufficient technical equipment, limited access to high-speed internet, and the high cost of specialized software. These factors particularly affect institutions located in resource-limited regions. Secondly, personnel issues play a key role. Insufficient digital competence among teachers and their resistance to change complicate the process of introducing new technologies. Furthermore, there is a shortage of specialists at the intersection of biology and information technology, which is especially important for the effective use of digital laboratories. The third important group consists of methodological challenges. Integrating digital laboratories into existing curricula requires rethinking traditional approaches and developing new criteria for assessing student skills. Complexity also arises from the risk of oversimplifying biological processes in digital models, which can lead to a distorted understanding among learners. Finally, ethical issues cannot be ignored. One of the main challenges is finding a balance between virtual and real experiments to maintain students' connection with the practical side of science. Issues of ownership and access to digital educational resources are also relevant, potentially exacerbating inequality among different student groups.

Thus, successfully overcoming existing barriers requires not only the implementation of technical solutions but also a comprehensive strategic approach. This implies improving infrastructure, enhancing teacher qualifications, revising methodological guidelines, and strictly adhering to ethical standards. Only a harmonious combination of these components will allow integrating digital laboratories into the education system with maximum efficiency.

Based on the analysis of TIMSS and PISA data, as well as the study of best global practices, the following recommendations can be highlighted for the successful digitalization of biology education:

Systematic approach to implementation: It is necessary to form a comprehensive digitalization strategy that provides for the integration of digital laboratories into curricula at all levels of training. Special attention should be paid to ensuring the continuity of using digital tools so that innovations fit harmoniously into traditional forms of learning and contribute to the formation of sustainable educational skills.

Teacher training and professional development: A competent teaching staff is a key element of digital transformation. It is recommended to develop specialized training programs for teachers aimed at mastering work with digital laboratories. Creating communities of practice for sharing experiences and mutual learning will serve as an additional stimulus for pedagogical innovations and the adoption of modern digital technologies in the educational process.

Development of methodological support: It is necessary to create detailed guides for conducting virtual experiments and develop integrated courses that combine traditional and digital teaching methods. Revising existing assessment methods to adapt them to the specifics of working with digital laboratories will allow for a more accurate reflection of students' knowledge and practical skills.

Collaboration with developers and research centers: To develop specialized solutions that meet high educational standards, it is important to establish close cooperation with development companies and research centers. Such integration will ensure the relevance and scientific accuracy of digital models, as well as contribute to the creation of open educational resources accessible to a wide range of users. These recommendations form a holistic digitalization model capable of not only significantly expanding research capabilities but also improving the quality of student training, meeting the challenges of modern science.

Conclusion

Digital laboratories and simulators are becoming an integral part of modern biology education. Data from international studies TIMSS and PISA confirm the positive impact of these tools on the quality of training for future biologists, the development of their research skills, and scientific literacy.

However, it is important to remember that technology alone does not guarantee success – a comprehensive approach is needed, including teacher training, the development of methodological support, and the creation of appropriate infrastructure. Only in this case can digital laboratories realize their potential and become an effective tool for improving the quality of biology education.

The future of biologist training lies at the intersection of traditional and innovative approaches, where digital technologies do not replace, but enhance the capabilities of the educational process, making it more flexible, personalized, and aligned with the requirements of modern science.

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