VIRTUAL LABORATORIES IN PHYSICS TEACHING: DIDACTIC POTENTIAL, EFFECTIVENESS, AND PROSPECTS FOR APPLICATION

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Annotatsiya. *Maqolada fizika o‘qitishda virtual laboratoriyalarni qo‘llashning didaktik imkoniyatlari va samaradorligi ko‘rib chiqiladi. Zamonaviy tadqiqotlar tahlili asosida interfaol modellashtirishning afzalliklari ko‘rsatilib, ta’lim jarayonida virtual va real eksperimentni uyg‘unlashtirishning maqsadga muvofiqligi asoslab berilgan.*

Kalit so‘zlar: *virtual laboratoriya, fizika ta’limi, PhET, interaktiv simulyatsiya, fizik eksperiment, raqamli texnologiyalar, modellashtirish.*

Аннотация. *В статье рассматриваются дидактические возможности и эффективность применения виртуальных лабораторий при преподавании физики. На основе анализа современных исследований показаны преимущества интерактивного моделирования и обоснована целесообразность сочетания виртуального и реального эксперимента в образовательном процессе.*

Ключевые слова: *виртуальная лаборатория, физическое образование, PhET, интерактивная симуляция, физический эксперимент, цифровые технологии, моделирование.*

Abstarct. *The article examines the didactic potential and effectiveness of using virtual laboratories in physics instruction. Based on an analysis of contemporary research, the advantages of interactive modeling are demonstrated, and the rationale for combining virtual and real experiments in the educational process is established.*

Key words: *virtual laboratory, physics education, PhET, interactive simulation, physics experiment, digital technologies, modeling.*

Introduction. Modern physics education is evolving amidst the rapid digitalization of the learning process, creating a need for new ways to organize students' experimental work. Laboratory experiments have traditionally played a vital role in physics instruction by bridging the gap between theoretical principles

and observable physical phenomena. However, the use of physical laboratory equipment can be constrained by factors such as cost, availability, safety requirements, and the time required to conduct experiments. In this context, virtual laboratories and interactive computer simulations offer a promising complement to traditional forms of physics experimentation.

Virtual laboratories enable the modeling of physical processes, allowing experiments to be repeated multiple times with varying parameters while facilitating the direct observation of resulting relationships. The PhET Interactive Simulations system has gained widespread adoption for the study of mechanics, electricity, optics, thermodynamics, and other areas of physics. A review of 31 experimental and quasi-experimental studies demonstrated that the use of PhET can enhance conceptual understanding of physical phenomena, particularly when simulations are integrated with active learning methods [1].

Data from a more recent meta-analysis confirm the educational potential of this approach. From 1,589 publications identified in the ERIC, Scopus, IOP Science, and Web of Science databases, the authors selected 22 studies for a quantitative analysis of PhET's effectiveness in physics instruction [2]. At the same time, research findings indicate that virtual and real experiments offer distinct didactic capabilities. When working in a virtual environment, students focus more on making predictions, identifying relationships between variables, and interpreting physical phenomena, whereas a real laboratory fosters the development of practical skills in handling equipment, taking measurements, and organizing experiments. [3].

Consequently, modern research increasingly views the virtual laboratory not as a complete replacement for traditional experimentation, but as a means of pedagogically supplementing it. In a 2025 study involving 385 students, the virtual laboratory yielded superior results in the study of pulley mechanics and the subsequent application of that knowledge in a new situation. [4]. At the same time, a systematic review of pedagogical practices shows that the effectiveness of a virtual environment depends significantly on the way it is integrated into the educational process. [5]. Thus, a pressing task is to determine the didactic potential, effectiveness, limitations, and prospects of the integrated use of virtual laboratories in physics instruction.

Table 1.

Quantitative research data on virtual laboratories in physics education

Research	Scope of research	Main result
PhET Overview	31 research	Positive impact on conceptual understanding

PhET meta-analysis	22 studies from 1589 publications	Positive overall educational effect
Nirahua, Matulessy	29 students	22.76 → 77.24 points
Study 2025	385 students	The advantage of a virtual laboratory in knowledge transfer

The data in Table 1 show that positive results from using virtual laboratories are identified both in individual pedagogical experiments and when summarizing the results of a significant number of studies. [1, 2, 4, 6].

Analysis of the reviewed studies shows that virtual laboratories possess significant didactic potential in teaching physics. Their main advantage is the possibility of organizing a controlled experiment in which the learner can independently change physical parameters, repeat the experiment many times, and directly observe the resulting changes. This format is especially important when studying processes that are difficult to visualize using traditional laboratory tools, such as the movement of charged particles, the distribution of an electric field, wave propagation, or processes at the molecular level.

The results presented in the table confirm that the effectiveness of virtual laboratories is observed not only in individual pedagogical experiments. A review of 31 experimental and quasi-experimental studies demonstrated the positive impact of PhET on the conceptual understanding of physical phenomena [1]. A meta-analysis that included 22 studies from the 1589 publications initially reviewed also indicates the positive educational effect of using interactive simulations in physics education [2]. In a separate study, the application of PhET in combination with the Discovery Learning method was accompanied by an increase in students' average score from 22.76 to 77.24 points [6]. These data allow for viewing the virtual laboratory as a pedagogically significant tool, rather than merely a means of visually representing educational material.

At the same time, the results obtained do not necessitate the complete replacement of traditional laboratory sessions with virtual ones. A real physical experiment forms skills in handling measuring instruments, assembling experimental installations, performing measurements, and evaluating emerging errors. The virtual environment, on the contrary, provides broader opportunities for rapidly changing parameters, repeating the experiment, and identifying relationships between physical quantities. Consequently, these forms of experimental activity perform partially different educational functions and can complement one another [3].

The methodology for organizing students' work is also of significant importance. If the virtual laboratory is used only by the teacher to demonstrate a finished process, its interactive potential is not fully realized. A more productive approach is one in which the learner initially formulates a hypothesis about the experimental result, then independently modifies the model parameters, observes the obtained results, compares them with the initial forecast, and formulates an explanation [5].

Conclusion. Thus, virtual laboratories expand the possibilities of teaching physics, increasing the visibility and accessibility of experimental learning. Their combination with real laboratory work is the most promising. This approach allows for the simultaneous development of conceptual understanding of physical processes, research thinking, and practical skills in working with experimental equipment.

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