

## VIRTUAL LABORATORIES IN SECONDARY EDUCATION IN UKRAINE: PREVALENCE, IMPLEMENTATION PRACTICES, TEACHER'S PERCEPTIONS, AND SYSTEMIC BARRIERS

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### ABSTRACT

The four-year full-scale war in Ukraine has profoundly disrupted the functioning of the national education system and exacerbated structural inequalities in access to quality learning. As of 2023, more than 1,880 educational institutions had been damaged or destroyed. By June 2025, 391,337 students were engaged in fully remote learning, while 759,147 were studying in blended formats. In this context, virtual laboratories (VLs) have evolved from an educational innovation into an essential component of instructional infrastructure. However, systematically collected nationwide empirical evidence on their adoption in school practice remains limited. This study investigates the prevalence of VL use, teachers' perceived benefits, and barriers to implementation in general secondary education (grades 1–12). Grounded in the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), a cross-sectional online survey of 1,873 teachers from all Ukrainian regions not under Russian occupation was conducted in June 2025, representing the first study of this scale. Data were analyzed using descriptive statistics, Spearman's rank correlation, Pearson's chi-square test, Cramer's V, and cross-tabulation procedures in SPSS 28.0. The findings indicate that only 22.4% of respondents use virtual laboratories regularly (6.4%) or frequently (16.0%), whereas 39.7% do not use them at all, and 25.2% report only prospective intention to adopt them. The most frequently reported advantages include 24/7 accessibility (33.0%), enhanced visualization of abstract concepts (28.3%), and improved safety in experimental learning (26.0%). The primary barriers identified are unstable internet connectivity (18.0%), high licensing costs (14.5%), and technical malfunctions (14.9%). A weak but statistically significant association was observed between teaching experience and frequency of VL use ( $r_s = 0.046$ ;  $p < 0.05$ ), while a strong relationship was identified between usage frequency and perceived accessibility ( $r_s = 0.601$ ;  $p < 0.0001$ ). This latter finding extends the TAM framework by demonstrating the dynamic formation of perceived usefulness through hands-on experience. Despite their substantial pedagogical potential, the adoption of virtual laboratories in Ukrainian schools remains constrained primarily by systemic and infrastructural barriers rather than individual teacher characteristics.

## KEYWORDS

Virtual Laboratories, Science Education, Ukraine, Education in Wartime, Teacher Perceptions, Cross-Sectional Survey

## 1. INTRODUCTION

The integration of virtual laboratories into the educational process has gained unprecedented relevance in Ukraine due to the severe and long-term consequences of the full-scale invasion for the educational infrastructure. According to Labster and UN/UNICEF, by 2023, more than 1,880 schools had been damaged or destroyed (Labster, 2023), while as of June 2025, 759,147 students were studying in a blended format and 391,337 were studying completely remotely. These circumstances make the issue of virtual laboratories relevant as a necessary tool for ensuring the continuity of the educational process in conditions of limited or impossible access to physical laboratories, transforming them from a pedagogical innovation into an infrastructural necessity. A significant step in this direction was the agreement concluded in late 2022 between the Ministry of Education and Science of Ukraine and Labster, which provided over 4.5 million students with access to over 300 virtual laboratory simulations. This solution not only meets the goals of the New Ukrainian School Concept (NUS) and the strategy for digitalization of education in terms of developing digital competence, but also demonstrates institutional recognition of the potential of such tools at the level of state education policy. Virtual laboratories are defined as computer simulations that reproduce physical laboratory research in a digital environment (Potkonjak et al., 2016) and offer improved visualization, safe conduct of experiments, unlimited possibilities of repetition and accessibility regardless of the state of the physical infrastructure (de Jong et al., 2013). In the modern scientific understanding, a virtual laboratory is not just a simulator, but a complex "in silico" equivalent of a physical research space that mediates the interaction between the student and the object of study through a digital interface. Klami et al. (2024) propose to consider these systems as a set of interconnected digital twins that include equipment models, processes for reproducing physico-chemical phenomena, and models of human interaction that allow the system to be adapted to the needs of a specific user. Such a holistic approach makes it possible to transform isolated software tools into a comprehensive research infrastructure that supports the full cycle of scientific research - from experiment planning to data analysis and interpretation. The effectiveness of virtual laboratories is traditionally assessed through the prism of Bloom's taxonomy, where researchers distinguish cognitive, affective, and psychomotor spheres of influence. Systematic reviews confirm that virtual learning environments contribute to the improvement of scientific literacy, in particular by increasing motivation, academic achievement and critical thinking skills in science education (Mafarja et al., 2025). The affective impact is manifested through the increase in intrinsic motivation, engagement and self-efficacy of students, who are given the opportunity to conduct experiments without fear of making mistakes or damaging expensive equipment (Alnaser & Forawi, 2024). However, in the psychomotor domain, which concerns direct manual skills, virtual laboratories show slightly lower results compared to traditional methods, which is explained by the lack of authentic tactile feedback and specific muscle sensations when working with laboratory tools (Safaeipour et al., 2025). That is why modern scientific thought is increasingly inclined to the implementation of hybrid models, where virtual training precedes work in a real laboratory, allowing students to first master the algorithms of actions in a safe

digital space, and then practice them in practice with real equipment. The theoretical foundations of virtual laboratories are formed at the intersection of the constructivist approaches of Piaget and Vygotsky and modern cognitive theories, among which a special place is occupied by Mayer's theory of multimedia learning, which explains the mechanisms of information processing through various sensory channels. The central theoretical construct in the study of virtual learning is the theory of cognitive load (Cognitive Load Theory, CLT), which claims that the learning process is inhibited if the amount of information being processed exceeds the capabilities of working memory (Surbakti et al., 2024). Researchers are integrating CLT principles to design virtual laboratory environments that minimize unproductive extraneous workload, while inquiry learning theory finds natural application in virtual laboratories as learners can safely manipulate variables and explore cause-and-effect relationships (de Jong, 2006; Pedaste et al., 2015). Of particular importance is the so-called "presence paradox", where highly immersive environments induce higher levels of subjective engagement and enjoyment, but at the same time worse learning outcomes compared to simpler desktop simulations – and this is due to excessive extraneous load caused by interface complexity or redundancy of visual stimuli. Makransky et al. (2019b) empirically confirmed that immersive VR induces higher levels of presence, but lower learning outcomes, and studies using biometric sensors – oculography and electrodermal activity measurements – indicate higher levels of mental stress and physiological fatigue when interacting with highly immersive systems (Surbakti et al., 2024). The technological diversification of the modern market covers a wide range of solutions – from traditional desktop simulations to immersive VR environments with head-mounted displays (Potkonjak et al., 2016; Radianti et al., 2020), and augmented reality technologies open up unique opportunities for visualizing invisible processes and creating hybrid learning experiences (Akçayır & Akçayır, 2017). A qualitatively new stage in the development of virtual laboratories is associated with the integration of artificial intelligence technologies, which marked the transition from static simulations to adaptive learning systems that can adjust to the pace and level of preparation of each student (Klami et al., 2024). AI agents play the role of virtual mentors who provide tips at critical moments of the experiment, preventing the emergence of cognitive dissonance and supporting learning motivation. In addition, AI enables the generation of dynamic scenarios where the results of the experiment are not predetermined, which encourages students to analyze errors more deeply and find alternative solutions, forming a true investigative mindset. Despite the growing research interest in the problem, the degree of implementation of virtual laboratories by Ukrainian teachers remains insufficiently studied: existing research focuses mainly on higher education and is mainly theoretical and methodological in nature, while large-scale empirical data on the practice of their application in general secondary education institutions is still lacking. Filling this research gap is the goal of this study. The study answers four questions: 1) DP1: What is the current prevalence of WL among teachers in terms of subjects and experience? 2) DP2: What benefits do teachers consider to be the most important and how does perception depend on the frequency of use? 3) DP3: What barriers hinder WL and how do they differ between users and non-users? 4) DP4: What are the relationships between teacher characteristics and WL implementation models?

## **2. USING VIRTUAL LABORATORIES IN THE EDUCATIONAL PROCESS AS A SCIENTIFIC PROBLEM**

### **2.1 The Problem of Virtual Laboratories: An International Context**

Systematic reviews of the scientific literature convincingly demonstrate that virtual laboratories provide unique opportunities for visualizing abstract concepts (de Jong et al., 2013), allow overcoming infrastructural barriers to distance learning (Potkonjak et al., 2016), and are effective for developing practical skills in a safe learning environment (Safaeipour et al., 2025). Virtual learning environments have been found to have a positive impact on scientific literacy in a broad sense – knowledge acquisition, critical thinking, scientific reasoning, problem solving, and attitudes toward science in general (Mafarjaa et al., 2025), while properly integrated communication tools further facilitate collaborative learning.

Research in the field of biology education confirms that the use of virtual laboratories leads to improved conceptual understanding, development of practical skills and positive dynamics of test results (Byukusenge et al., 2022), and the wide adaptability of these tools covers various scientific disciplines – chemistry, physics, biology, engineering and medicine (Zhang et al., 2024). Of fundamental importance for the Ukrainian context of distance learning is the equivalence of results when using desktop VR simulation at home and in the classroom (n = 112 biology students) proven by Makransky et al. (2019a), although the same researchers (Makransky et al., 2019b) found that immersive VR, despite a higher level of presence, may lead to less effective learning due to increased cognitive load, which emphasizes the decisive role of instructional design.

At the level of general secondary education, a significant transformation of STEM education in K-12 is noted due to increased student engagement, deepening conceptual understanding, and development of critical thinking, and Alnaser & Forawi (2024) confirm the positive impact of virtual laboratories on intrinsic motivation and attitude towards science based on a survey of 237 students in grades 7–11. An analysis of 21 articles on learning analytics in virtual laboratories from 2015 to 2021 found that 48% of the research was conducted in higher education (Elmoazen et al., 2023), while a survey of 4,570 students at the National Open University of Nigeria revealed mixed consumer preferences: 49% of respondents preferred physical laboratories, 21% preferred a virtual system, and only 8% chose a hybrid format, indicating a persistent demand for integrated approaches (Ndunagu et al., 2023). The pedagogical potential of virtual laboratories is revealed primarily in the ability to increase conceptual understanding through the visualization of abstract processes, develop research competence without the risks associated with working with hazardous substances, enhance learning motivation through interactivity, and compensate for the lack of material and technical resources. At the same time, a critical analysis of the available research points to significant limitations: virtual laboratories do not always provide effective formation of manipulative skills, cannot completely replace traditional laboratory classes, require systematic pedagogical support, and their widespread implementation remains dependent on stable access to the Internet.

An analysis of international experience in studying the problem of virtual laboratories shows that this industry is at the stage of active formation and conceptualization, but remains internally contradictory in both theoretical and empirical dimensions. The accumulated body of research convincingly proves the didactic effectiveness of virtual laboratories in the formation of

cognitive competencies, motivational sphere and scientific thinking of pupils and students, however, the issues of full development of practical skills and long-term preservation of knowledge remain open and require further study. The research focus is gradually shifting from studying basic effects to analyzing the conditions for effective pedagogical design, differentiated application in different disciplines and educational levels, and finding the optimal balance between the virtual and physical components of laboratory training. A separate and rapidly growing area of international research is the integration of artificial intelligence technologies into virtual laboratory environments. Current developments in this area are aimed at implementing adaptive learning, where AI algorithms dynamically adjust the complexity of tasks and the nature of feedback according to the individual profile of the student, at automated analysis of learning analytics to identify gaps in understanding and predict learning difficulties, as well as at generating personalized learning scenarios and prompts in real time. Despite the technological promise of these developments, their pedagogical effectiveness remains insufficiently verified, and most of the existing research in this area is characterized by small samples, short-term interventions, and limited reproducibility of results. Thus, the state of research on the problem of virtual laboratories in the international context is characterized by a combination of significant heuristic potential and methodological immaturity, which opens up a wide scope for systematic, longitudinal and cross-cultural research.

## **2.2 The Problem of Virtual Laboratories: The Ukrainian context**

Analysis of the current state of research on virtual laboratories in general secondary education institutions in Ukraine as of December 2025 reveals significant gaps: Ukrainian scientific publications in international peer-reviewed journals remain extremely limited, and most of the available research focuses on the needs of higher education, leaving out the specifics of teaching students in grades 1–12.

The most relevant empirical study of the effectiveness of virtual laboratories in the domestic scientific space is the work of Sippii et al. (2024), devoted to studying the impact of virtual laboratories on the formation of research competencies of future biology teachers ( $n=230$  students of 2–3 years, September 2023 – May 2024). The results obtained showed statistically significant differences between the experimental and control groups in three of the four skills studied: application of scientific methods ( $p=0.002$ ), ability to conduct experiments ( $p=0.002$ ) and processing of results ( $p=0.003$ ), while the teamwork indicator did not demonstrate significant intergroup differences ( $p=1.00$ ).

An important contribution to the development of the methodological dimension of the problem was the materials of the ITE-2025 conference, organized by the Institute for Digitalization of Education of the National Academy of Sciences of Ukraine, where Skvortsova and Britzkan (2025) presented a study dedicated to the organization of mathematics teaching in primary school with the involvement of virtual laboratories. The authors conducted a systematic comparative analysis of available platforms – GeoGebra Elementary, PhET Colorado, GoLabz, Math Learning Center Apps, Toy Theater, National Library of Virtual Manipulatives (NLVM) and IXL Math – according to the criteria of compliance with the New Ukrainian School program, language interface, accessibility and freeness, interactivity and didactic potential, as well as opportunities for assessing academic achievements. A significant practical achievement of the research is the development of methodological recommendations covering the structure of a lesson using a virtual laboratory (preparatory, main and final stages), algorithms for

choosing a platform depending on the didactic goal, recommendations for organizing individual, pair and group work, as well as differentiated approaches to assessing the results of educational activities, in particular automated assessment, analysis of digital products, self- and peer assessment. Despite the above achievements, domestic research clearly outlines a set of systemic problems that hinder the spread of virtual laboratories in primary school practice: the low level of awareness of teachers about the capabilities of these resources is combined with the limited material and technical base of educational institutions, the lack of methodological support and ready-made lesson plans, as well as the dominance of English-language interfaces of most platforms, which significantly complicates their implementation in the Ukrainian-speaking educational environment – the only exception is GeoGebra Elementary. The most large-scale empirical contribution to the study of this issue remains the study by Lozova (2025), which, based on a survey of 962 teachers of general secondary education institutions in Ukraine, recorded an average level of readiness of teachers to master innovative forms of STEM education, including virtual laboratories, which indicates the need for systematic and targeted support for this process. The state of research on the problem of virtual laboratories in the Ukrainian scientific context is characterized by a contradictory combination of active scientific and methodological understanding and obvious empirical insufficiency. On the one hand, there are solid comparative and methodological developments that form the conceptual basis for practical implementation, on the other hand, there is a critical lack of large-scale verified pedagogical experiments in the system of general secondary education, and the industry itself develops mainly through the adaptation of foreign platforms with a practically complete absence of national virtual laboratories developed taking into account the requirements of the Ukrainian educational standard and the specifics of the curricula. The almost complete absence in the domestic research space of works devoted to the integration of artificial intelligence into virtual laboratory environments deserves special attention. While the international community is actively exploring the possibilities of AI for implementing adaptive learning, automated analysis of educational analytics, and generation of personalized educational scenarios within virtual laboratories, Ukrainian researchers are practically not addressing this area, which creates a critical gap in both the scientific and practical-methodological dimensions. Given that martial law has significantly increased the demand for effective distance learning tools, and the level of digital literacy of teaching staff remains insufficient, promising areas of further research appear to be studying the conditions for effective implementation of virtual laboratories in teaching natural sciences in general education schools, developing Ukrainian-language platforms with integrated AI components, and systematically training future teachers to use these tools in their professional activities.

### 3. METHODOLOGY

The study is based on TAM (Davis, 1989) and UTAUT (Venkatesh et al., 2003). According to TAM, technology adoption is determined by subjectively perceived usefulness (PU) and ease of use (PEOU). In educational research, TAM has been extended to include pedagogical beliefs and technical infrastructure (Tondeur et al., 2017). A theoretically significant contribution of the study is the concept of dynamic PU formation: the strong correlation ( $r_s = 0.601$ ) between the frequency of VL use and perceived accessibility suggests that PU is actively formed through practical experience, rather than being a static prior belief. This extends TAM by considering

the feedback mechanism of “use → recognition → in-depth use”. The study suggests that VL implementation is driven by: (1) perceived pedagogical benefits; (2) technical and infrastructural barriers; (3) pedagogical experience; (4) systemic constraints of martial law.

### **3.1 Research Tools**

In order to determine the current state of use of virtual laboratories by teachers of general secondary education institutions in Ukraine, an online survey using a cross-sectional survey design was conducted in June 2025. The choice of the time period was strategically justified: teachers had just completed the academic year and had the opportunity to reflexively evaluate their own pedagogical practice, while the conditions of martial law remained relatively stable for correct data collection. The questionnaire was developed by the authors of the study based on a literature review on the implementation of virtual laboratories and the adaptation of elements from validated instruments, in particular the Technology Acceptance Model (TAM); in addition, a reference list of virtual laboratory platforms was generated using the Claude.ai chatbot. The draft questionnaire was reviewed by three researchers in the field of educational technology, after which a preliminary check was carried out for the clarity of the wording and an analysis of the internal consistency of the responses. The final version of the questionnaire was implemented in Google Forms, which ensured anonymity of participation and wide technical accessibility for respondents. The questionnaire contained two main sections. Section A (“General information”, 3 questions) covered information about the respondent’s academic subject (multiple-choice question with the possibility of adding your own option), teaching experience (closed-ended question with five categories), and frequency of use of artificial intelligence tools in professional activities (closed-ended question with answer options). Section B (“Implementation and perception of virtual laboratories”, 3 questions) aimed to study the frequency of use of virtual laboratories (five-point ordinal scale: regularly, sometimes, rarely, plan to try, do not use), perceived benefits (multiple-choice of nine options and open-ended question), and barriers to implementation (multiple-choice of nine options and open-ended question). As a contextual reference, section B provided a list of current virtual laboratory platforms: PhET Interactive Simulations (physics, chemistry, mathematics), Labster (biology, chemistry, physics), ChemSketch (chemistry), GeoGebra (mathematics), NASA Virtual Lab (astronomy, physics), Google Earth VR (geography) Nearpod VR (various items), Minecraft Education Edition, Go-Lab, and ROQED Science. The reliability of the Perceived Benefits Scale, considered as a multi-item measure, was estimated using the Kuder–Richardson formula ( $KR-20 = 0.78$ ), indicating an acceptable level of internal consistency.

### **3.2 Research Sample and Data Collection Procedure**

The target population of the study was teachers of secondary education institutions (grades 1–12) of all regions of Ukraine, except for temporarily occupied territories, who have access to the Internet and work in educational institutions of various types. The questionnaire was distributed from June 1 to 25, 2025 through professional pedagogical communities on social networks Facebook, Telegram and Viber, regional institutes of postgraduate pedagogical education, as well as networks of graduates of leading pedagogical universities, which ensured representative access to the target audience. Participation in the study was voluntary and anonymous; respondents were informed about the purpose of the study and the procedure for

using the data obtained, personal information of the participants was not collected or stored. The total sample size was 1,873 respondents from approximately 450,000 teachers of Ukraine (State Statistical Service, 2024), which corresponds to 0.42% of the general population. With a confidence level of 95% and a permissible error of  $\pm 2.5\%$ , the minimum required sample size is 1537 people, so the achieved volume provides sufficient statistical power to generalize the results. The subject distribution of the sample included teachers of natural sciences – physics, chemistry and biology (24.8%), primary education (22.1%), humanities and social sciences (19.1%), mathematics (18.3%) and Ukrainian language (15.7%). Experienced specialists prevailed in terms of teaching experience: over 20 years – 60.7%, from 11 to 20 years – 21.9%, from 6 to 10 years – 9.5%, up to 5 years – 8.0%. Geographically, all regions of Ukraine were represented in the study. Participation is voluntary and anonymous. Respondents were informed about the goals. No personal data was collected. The principles of the Declaration of Helsinki were adhered to.

### **3.3 Data Analysis Methods**

The analysis of the collected data was carried out using SPSS 28.0 software and Microsoft Excel using a set of statistical procedures. Descriptive statistics included frequency analysis, percentage distributions and measures of central tendency for all variables. To test the hypotheses about the independence of categorical variables, the Pearson  $\chi^2$  criterion was used with the calculation of the effect size according to Cramer's V (small effect – 0.10, medium – 0.30, large – 0.50); to analyze monotonic relationships between ordinal variables - Spearman's rank correlation ( $|r_s| < 0.30$  – weak relationship, 0.30–0.70 – moderate,  $> 0.70$  – strong). Cross-tabulation analysis was used to compare the distributions of perceived benefits and barriers in groups with different frequencies of using virtual laboratories; The statistical significance level was set at  $\alpha = 0.05$ . Missing data, the volume of which did not exceed 2% for any of the questionnaire items, were processed by the listwise exclusion method for specific analyses, which did not affect the overall quality of the results.

## **4. RESULTS**

### **4.1 Research Tools**

Only 6.4% of teachers use VL regularly, 16.0% – sometimes, 12.8% – rarely. The largest group is non-users (39.7%); 25.2% have intentions. In total, 64.9% are not active users. Analysis of the results of the respondents' responses (Table 1) indicates that the majority of teachers 39.7% do not use virtual laboratories and AI-based simulations in their teaching. Only 6.4% of respondents use them constantly and 16% – sometimes.

VIRTUAL LABORATORIES IN SECONDARY EDUCATION IN UKRAINE: PREVALENCE, IMPLEMENTATION PRACTICES, TEACHER'S PERCEPTIONS, AND SYSTEMIC BARRIERS

Table 1. Frequency of use of virtual labs and AI-based simulations in education

Response option	Frequency	Percentages	Valid percentage
Yes, regularly	119	6.4	6.4
Yes, sometimes	299	16.0	16.0
Rarely	240	12.8	12.8
No, but I plan to try	472	25.2	25.2
No, I don't use it	743	39.7	39.7
Total	1873	100.0	100.0

Teachers with different professional experience participated in the survey. Therefore, the question arose of establishing a connection between the teacher's work experience and the frequency of their use of virtual laboratories in the educational process. The results of the study showed that among the respondents who regularly use virtual laboratories and simulations with AI, teachers with more than 20 years of work experience dominate (Fig. 1). However, in other groups, the indicated category of teachers (more than 20 years) also prevails in terms of the frequency of use of virtual laboratories. The results of the correlation analysis confirm that the advantage of one group in terms of work experience is only a general trend against the background of a relatively uniform distribution of other participants.

Figure 1 shows the distribution of the frequency of use of VL by categories teaching experience.

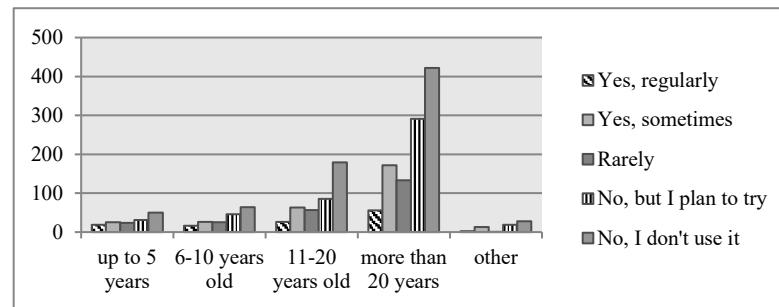


Figure 1. Distribution of respondents by teaching experience and frequency of use of virtual laboratories

Among regular users, teachers with more than 20 years of experience prevail – which reflects the demographic structure of the sample (60.7%). Spearman correlation:  $r_s = 0.046$  ( $p < 0.05$ ) – a statistically significant, but extremely weak relationship. The value of the Pearson  $\chi^2$  test criterion allowed us to reject the null hypothesis ( $H_0$ ) of no differences between the distributions of teaching experience and the frequency of their use of virtual laboratories  $\chi^2 = 34.811$  ( $p < 0.004$ ). However, given the large sample of respondents, this result indicates the presence of micro-trends rather than a real dependence. Therefore, we can conclude: work experience is not a determining factor that would significantly affect the intensity of use of virtual laboratories and AI simulations in the educational process. Thus, seniority is not a determinant of the intensity of VL use. The distribution by subject reflects broader trends: even among science teachers (24.8% of the sample) – natural potential VL users – the systemic indicator of 22.4% emphasizes the leading role of structural rather than subject-specific factors. These results highlight a significant gap between the potential of digital modeling tools and their actual

integration into pedagogical practice, which indicates the need for targeted professional development and institutional support.

## 4.2 Perceived Benefits

According to the survey data, the three most important benefits of virtual laboratories are: availability at any time (33.0%), visualization (28.3%), and security (26.0%). Note that the question contained multiple options for respondents (Table 2).

Table 2. The most important benefits of virtual laboratories for respondents

Advantage	N	Percentages	Percentage of observations
Safety of conducting experiments	486	11.1	26.0
Economy of material resources	443	10.2	23.7
Availability at any time	616	14.1	33.0
Visualization of complex processes	529	12.1	28.3
Possibility of multiple repetition	468	10.7	25.1
Individual pace of learning	313	7.2	16.8
High interactivity	269	6.2	14.4
Simulation of dangerous or expensive processes	285	6.5	15.3
I don't use AI	955	21.9	51.2
Total	4364	100.0	233.9

Among the difficulties that teachers face when using virtual laboratories are listed (Table 3): poor Internet connection (12.5%), technical problems and failures (10.3%), high cost of licenses (10.1%).

Table 3. List of difficulties that respondents face when using virtual laboratories

Difficulties	N	Percentages	Percentage of observations
Technical problems and failures	277	10.3	14.9
Insufficient technical equipment in the school	243	9.0	13.0
Bad internet connection	336	12.5	18.0
Difficulty in use	83	3.1	4.5
Lack of content in Ukrainian	239	8.9	12.8
High cost of licenses	271	10.1	14.5
Insufficient training of teachers	159	5.9	8.5
Pupils' resistance to new technologies	39	1.5	2.1
I don't use AI	1031	38.4	55.3
Other	10	0.4	0.5
Total	2688	100.0	144.2

To identify the nature of the relationship between the benefits of using virtual laboratories by respondents and the frequency of their use in education, a connectivity table was used (Table 4). Given the multiple nature of the respondents' responses, statistical testing of the relationship was not carried out; the analysis was conducted at the descriptive level using absolute and relative indicators.

VIRTUAL LABORATORIES IN SECONDARY EDUCATION IN UKRAINE: PREVALENCE, IMPLEMENTATION PRACTICES, TEACHER'S PERCEPTIONS, AND SYSTEMIC BARRIERS

The frequency of using virtual laboratories significantly affects the perceived benefits. Regular users (n = 119) most value accessibility (86.6%), security (73.1%) and economy (58.0%). These percentages gradually decreased among occasional users: “sometimes” – 70.6%; 54.8%; 51.5%; “rarely” – 58.8%; 41.7%; 43.3%.

It is worth noting that 51.2% of respondents indicated that they do not use AI tools, with 39.7% not using and another 12.15% who may have skipped the question.

Note: The frequency in the column exceeds 100%, as the question contained multiple answer options from respondents. The three most frequently confirmed benefits were: availability at any time (33.0% of respondents), visualization of complex processes (28.3%) and security (26.0%). It is worth noting that 51.2% indicated “I do not use AI”, which corresponds to 39.7% of non-users plus 12-15% who may have skipped this item.

Table 4. Table of connectivity of benefits and frequency of use of virtual laboratories by respondents

Advantages of virtual laboratories	Yes, regularly	Yes, sometimes	Rarely	No, but I plan to try	No, I don't use it	Total
Safety of conducting experiments	87(73.1%)	164(54.8%)	100(41.7%)	102(21.7%)	33(4.5%)	486
Economy of material resources	69(58.0%)	154(51.5%)	104(43.3%)	91 (19.4%)	25(3.4%)	443
Availability at any time	103(86.6%)	211(70.6%)	141(58.8%)	127(27.0%)	34(4.6%)	616
Visualization of complex processes	97(81.5%)	197(65.9%)	105(43.8%)	104(22.1%)	26(3.5%)	529
Possibility of multiple repetition	92(77.3%)	165(55.2%)	93(38.8%)	95(20.2%)	23(3.1%)	468
Individual pace of learning	66(55.5%)	112(37.5%)	55(22.9%)	68(14.5%)	12(1.6%)	313
High interactivity	60(50.4%)	99(33.1%)	51(21.3%)	47(10.0%)	12(1.6%)	269
Simulation of dangerous or expensive processes	69(58.0%)	101(33.8%)	46(19.2%)	52(11.1%)	17(2.3%)	285
I don't use AI	0(0.0%)	3(1.0%)	114.6%	262(55.7%)	679(92.0%)	955
Total	119	299	240	470	738	1866

Table 4 shows a cross-sectional analysis of benefits by frequency of use (regularly, sometimes, rarely, no, but I plan to try, no, I don't use it), with percentages calculated within each use group for comparison.

The percentages in the table are calculated from the total number of respondents who indicated the corresponding frequency of use of virtual laboratories (regularly, sometimes, rarely, no, but I plan to try, no, I don't use it).

The analysis of the table shows that respondents who regularly use virtual laboratories are more likely than other groups to note various advantages of them, in particular, availability at any time. However, given the multiple nature of the respondents' answers, it is advisable to interpret the results obtained as a trend. A similar trend is also observed among respondents who use virtual laboratories sometimes and rarely. In general, it can be stated that with an increase in the frequency of use of virtual laboratories in the educational process, the number and variety of advantages recognized by teachers increases.

Given the multiplicity of respondents' responses, statistical testing of the relationship was not conducted; the analysis was conducted at the descriptive level using absolute and relative indicators. Analysis of Table 4 demonstrates a monotonic decrease in support for each benefit from regular to non-users.

According to the results of calculating the Spearman's rank correlation coefficient between the frequency of use of virtual laboratories and AI simulations and the indicator of availability of educational resources at any time, a statistically significant inverse relationship of medium strength was found ( $r_s = -0.601$ ;  $p < 0.0001$ ). This indicates that teachers who regularly use virtual laboratories and AI simulations differ statistically significantly in their assessment of availability at any time compared to those who rarely or do not use them at all.

For all categories of teachers, the following advantages were found to be widespread in terms of the frequency of use of virtual laboratories in the educational process: availability at any time and visualization of complex processes. Therefore, it can be argued that these advantages are obvious even for those categories of respondents who do not use and plan to use virtual laboratories.

Among those teachers who regularly use virtual laboratories, the advantages associated with individualization of learning (individual pace of learning, high interactivity, and modeling of dangerous or expensive processes) are the most significant in organizing the educational process. For respondents who plan to or do not yet use virtual laboratories in the educational process, these advantages are not yet obvious, and are realized by teachers only over time, with their systematic use. For all categories of teachers, the following advantages were identified regarding the frequency of use of virtual laboratories in the educational process: availability at any time and visualization of complex processes. Therefore, it can be argued that these advantages are obvious even for those categories of respondents who do not use virtual laboratories and do not plan to use them. The advantages of individualization are most pronounced among regular users and are significantly underestimated by those who have no experience. At the same time, teachers who only plan to implement WL see more advantages in them than those who do not currently use them.

### 4.3 Barriers to Implementation

The survey identified key barriers to the implementation of virtual laboratories in education. The three most significant are: unstable Internet connection (18.0% of respondents), technical problems (14.9% of respondents), high cost of licenses (14.5% of respondents). Difficulty of use (4.5%) and lack of training (8.5%) are relatively minor, suggesting that technical self-efficacy is less constrained than external factors. The sharp asymmetry between the perception of barriers among active and passive educators indicates a significant underestimation of the real difficulties by those who have not yet practiced VL. Regular users ( $n=119$ ) most often cited poor internet connection (46.2%), lack of Ukrainian content (37.0%), and technical problems (31.1%). Among occasional users, these concerns remained prominent, but with varying intensity. In contrast, those who plan to use or do not use virtual labs reported significantly lower barrier experiences, with most categories below 10%, suggesting that actual implementation reveals challenges that were not previously anticipated.

The most frequently mentioned barriers were: unstable internet connection (18.0% of respondents), technical failures (14.9%), and cost of licenses (14.5%). Infrastructural and economic constraints dominated pedagogical or convenience issues. Difficulty of use (4.5%)

VIRTUAL LABORATORIES IN SECONDARY EDUCATION IN UKRAINE: PREVALENCE, IMPLEMENTATION PRACTICES, TEACHER'S PERCEPTIONS, AND SYSTEMIC BARRIERS

and lack of training (8.5%) were relatively insignificant, indicating that technical self-efficacy is less limiting than external factors.

Table 5 shows the relationship between difficulties (barriers) and the frequency of use of virtual labs by respondents, taking into account the percentages within user groups.

Table 5. Table of the relationship between difficulties and the frequency of use of virtual labs by respondents

Difficulties in using virtual laboratories	Yes, regularly	Yes, sometimes	Rarely	No, but I plan to try	No, I don't use it	Total
Technical problems and failures	37(31.1%)	110(37.0%)	78(32.6%)	42(9.0%)	10(1.4%)	277
Insufficient technical equipment in the school	31(26.1%)	100(33.7%)	61(25.5%)	44(9.4%)	7(0.9%)	243
Bad internet connection	55(46.2%)	124(41.8%)	92(38.5%)	59(12.6%)	6(0.8%)	336
Difficulty in use	8(6.7%)	28(9.4%)	23(9.6%)	18(3.8%)	6(0.8%)	83
Lack of content in Ukrainian	44(37.0%)	88(29.6%)	63(26.4%)	39(8.3%)	5(0.7%)	239
High cost of licenses	38(31.9%)	108(36.4%)	66(27.6%)	49(10.4%)	10(1.4%)	271
Insufficient training of teachers	8(6.7%)	54(18.2%)	40(16.7%)	48(10.2%)	9(1.2%)	159
Pupils' resistance to new technologies	11(9.2%)	14(4.7%)	11(4.6%)	3(0.6%)	0(0.0%)	39
I don't use AI	0(0.0%)	5(1.7%)	13(5.4%)	306(65.2%)	707(95.5%)	1031
Other	1(0.8%)	5(1.7%)	1(0.4%)	2(0.4%)	1(0.1%)	10
Total	119	297	239	469	740	1864

The analysis of the distribution of difficulties by categories of frequency of use of virtual laboratories reveals a clear differentiation between systemic barriers, which are inherent in all groups of respondents, and individual competence difficulties, the significance of which varies significantly depending on the level of involvement of the teacher in the practice of digital learning. For teachers who use virtual laboratories regularly, the dominant obstacle remains unstable Internet connection (46.2%), while the complexity of using platforms and insufficient pedagogical training are the least significant difficulties in this group (6.7% each), which convincingly indicates the formed digital competence of experienced users. It is significant that with the increase in the frequency of use of virtual laboratories, teachers increasingly rarely indicate difficulties associated with the complexity of using tools, insufficient training and resistance of students to new technologies – that is, those barriers that are surmountable through the acquisition of practical experience gradually lose their sharpness.

Instead, the instability of the Internet connection and the lack of Ukrainian-language content are consistently significant for all categories of respondents, regardless of the frequency of use, which allows us to qualify them not simply as “common difficulties”, but as systemic barriers of an infrastructural and linguistic-cultural nature, the overcoming of which does not depend on the level of individual competence or motivation of the teacher and requires appropriate decisions at the level of state educational policy.

For the group of teachers who do not use virtual laboratories, but plan to do so, a relatively even distribution of difficulties between organizational and material and technical factors is characteristic: the high cost of licenses (10.4%), insufficient training of teachers (10.2%), and insufficient technical equipment of the educational institution (9.4%) are almost equivalent in

priority, which indicates the complex and interdependent nature of the barriers that hinder the transition from intention to real practice.

The overall picture of the results shows that most respondents are aware of the significant methodological advantages of using virtual laboratories and simulations based on artificial intelligence in the educational process – primarily the 24-hour availability of educational materials, the ability to visualize complex processes and safely simulate phenomena that are not available in a real laboratory. At the same time, 64.9% of the surveyed teachers do not use these tools in their practice, of which 25.2% declare their intention to start using them in the future - and it is this category that most clearly articulates the need for systematic pedagogical training, expansion of Ukrainian-language content and the creation of favorable organizational and technical conditions for the effective integration of digital technologies into the educational process of a general secondary education institution.

## 5. DISCUSSION

The fact that only 22.4% of Ukrainian teachers regularly or frequently use virtual laboratories, while 64.9% either do not use them at all or only plan to do so, indicates a significant gap between the documented effectiveness of these tools (de Jong et al., 2013; Byukusenge et al., 2022) and real pedagogical practice - and this despite the urgent need for alternative forms of learning caused by martial law. Thus, through the prism of TAM, it reflects the dissonance between the objective capabilities of WL and the subjective perceptions of teachers without experience in their use. This gap is generally consistent with international data on the slow adoption of educational technologies (Tondeur et al., 2017), but is unexpected given a number of enabling factors: free access to the Labster platform for 4.5 million learners, the massive digitalization of the educational process caused by the COVID-19 pandemic (Skvortsova et al., 2025), and the objective need to find alternatives to physical laboratories in the face of the destruction of educational infrastructure. To explain this gap, it is appropriate to consider several interrelated factors. First, a significant proportion of teachers may simply not have sufficient information about the available platforms: 25.2% of respondents who indicated that they “plan to try” virtual laboratories indicate a latent demand that could be activated by targeted information campaigns and methodological education. Second, even being aware of the existence of relevant tools, teachers may experience difficulties with their integration into curricula that meet state standards, while 37.0% of respondents who indicated a lack of Ukrainian-language content indicate that localization of global resources remains extremely incomplete. Addressing this problem requires targeted efforts by the Ministry of Education and Science of Ukraine to prioritize translation and adaptation of high-quality platforms that have proven their effectiveness in a multilingual context, in particular PhET Interactive Simulations.

The most theoretically significant finding of the study is the strong positive correlation between the frequency of use of virtual laboratories and their perceived accessibility ( $r_s = 0.601$ ), which indicates that the construct of perceived usefulness is not a static cognitive formation, but is dynamically formed by direct practical experience. This finding has fundamental importance for the design of professional development programs for teachers: formats based on lectures and demonstrations (“learn about virtual laboratories”) will be significantly less effective than those that involve teachers directly performing laboratory tasks in the role of students (“learn through virtual laboratories”). Accordingly, implementation programs should consistently provide for a

## VIRTUAL LABORATORIES IN SECONDARY EDUCATION IN UKRAINE: PREVALENCE, IMPLEMENTATION PRACTICES, TEACHER'S PERCEPTIONS, AND SYSTEMIC BARRIERS

safe, “trial” familiarization with the platforms without the risk of errors and based on the teaching material well known to the teacher, as well as structured reflection on the pedagogical applications of the acquired experience.

The analysis of barriers to implementation demonstrates their predominantly systemic rather than individual nature, which is fundamentally important for developing appropriate educational policies. Limited access to reliable Internet connections, the shortage of Ukrainian-language content, and the financial costs of licenses cannot be overcome by increasing individual teacher qualifications alone – they require comprehensive government solutions, from prioritizing the restoration of educational networks to forming national partnerships to localize global resources. At the same time, only 8.5% of respondents overall and 6.7% of regular users cited insufficient pedagogical training as an obstacle to using virtual laboratories, which contrasts with Lozova's (2025) finding that 962 Ukrainian teachers were moderately prepared for innovations in STEM education. This discrepancy allows for at least three plausible interpretations: systematic self-selection bias, as the online survey likely overrepresented technologically confident teachers who tend to minimize their own learning needs; the increasing ease of use of modern platforms, as a result of which new generations of educational software require less pedagogical training, adapting to the needs of the user; and finally, the Dunning – Kruger effect, in which teachers may systematically underestimate their own learning needs due to overconfidence in technical competence, which is consistent with the findings of Makransky et al. (2019) on teachers' typical misjudgment of optimal strategies for integrating visual environments. Verification of these interpretations requires the use of objective competence assessment tools in further research. Regardless of the chosen interpretation, this finding suggests that traditional barriers to professional development – lack of time, limited access, insufficient motivation to learn – may be less restrictive for the implementation of virtual laboratories than for other pedagogical innovations.

Comparing the results with international data reveals a distinctive specificity of the Ukrainian context. The level of implementation of virtual laboratories in Ukraine (22.4% of regular or frequent users) is lower than in most developed education systems, although comparable to some data on K-12 institutions. Cruz et al. (2025) record a significant integration of virtual laboratories in a number of schools, while Ndunagu et al. (2023) found that Nigerian university students prefer physical laboratories (49%) compared to virtual ones (21%), indicating global variability in the nature of the implementation of these tools. A fundamental difference in the Ukrainian context is that the implementation of virtual laboratories may be determined here to a greater extent by the forced necessity resulting from the destruction of educational infrastructure, rather than by pedagogical expediency aimed at improving the quality of teaching, which potentially affects the sustainability and depth of such implementation after the end of martial law.

Based on the results of the study, a three-level strategy for systemic intervention is proposed. At the level of state policy and the Ministry of Education and Science, it is necessary to prioritize the restoration of educational Internet networks in areas affected by military actions, expand Ukrainian-language localization of platforms beyond the existing partnership with Labster, form grant programs for the development of national virtual laboratories in accordance with the curricula of the National School of Education, as well as negotiate additional free license agreements with leading platform developers. At the institutional level – the levels of educational institutions and advanced training institutes - it is advisable to include practical master classes on virtual laboratories in mandatory teacher training programs, introduce the positions of school coordinators for digital technologies, allocate targeted IT budgets for the

relevant infrastructure, and create systems for recognizing innovative teachers. At the level of individual professional development, the priority is to provide experiential, practically oriented learning that allows teachers to independently experience the role of a student in a virtual laboratory before implementing it into their own educational process.

Research limitations: 1) Cross-sectional design makes causal inferences impossible. 2) Online recruitment may over-represent technologically confident teachers. 3) Multiple choice limits the accuracy of the assessment. 4) Teachers from occupied and frontline territories were excluded. 5) Social desirability of responses is possible.

## 6. CONCLUSIONS

This study presents the first large-scale empirical dataset on the implementation of virtual laboratories among teachers in general secondary education institutions in Ukraine, revealing a substantial gap between the pedagogical potential of these tools and their actual classroom use. Despite the availability of free platforms, the accelerated digital transformation of education during the COVID-19 pandemic, and the increased need for alternative learning modalities under martial law conditions, only 22.4% of teachers report regular or frequent use of virtual laboratories. In contrast, nearly two-thirds of respondents are either non-users or express only an intention to adopt such tools in the future.

Analysis of adoption patterns indicates that the active user group - comprising 6.4% permanent users and 16.0% frequent users - is not associated with teaching experience ( $r_s = 0.046$ ), thereby challenging the assumption that professional tenure is a key determinant of technological adoption. Teachers primarily perceive accessibility (33.0%), visualization capabilities (28.3%), and safety of the learning process (26.0%) as the main advantages of virtual laboratories. However, pedagogical affordances such as interactivity and self-paced learning are largely realized only through sustained and repeated use, rather than being immediately evident to non-users.

Among systemic barriers, the most frequently reported challenges include unstable internet connectivity (18.0%), licensing costs (14.5%), and technical malfunctions (14.9%). Notably, these constraints persist even among experienced users, indicating that individual professional development alone is insufficient to overcome structural infrastructural limitations.

A key conceptual finding of the study is the strong positive correlation between hands-on experience with virtual laboratories and perceived usefulness ( $r_s = 0.601$ ). This result challenges traditional technology acceptance models by suggesting that perceived usefulness emerges through practice rather than preceding it. Consequently, professional development strategies based primarily on informational or lecture-based approaches are likely to have limited effectiveness. Instead, more impactful interventions should prioritize structured, supported, and reflective experiential engagement with virtual laboratories within teacher training programs.

The findings have important implications for educational policy and practice. For policymakers in Ukrainian education, the results highlight the need for a coordinated, multi-level strategy encompassing: (i) development and stabilization of digital infrastructure, (ii) localization and contextualization of high-quality educational content, and (iii) systematic capacity building of teachers through practice-oriented training and collaborative professional networks. For educational technology developers, the persistence of language and usability barriers underscores the necessity of designing platforms that are fully functional offline,

## VIRTUAL LABORATORIES IN SECONDARY EDUCATION IN UKRAINE: PREVALENCE, IMPLEMENTATION PRACTICES, TEACHER'S PERCEPTIONS, AND SYSTEMIC BARRIERS

optimized for low-resource environments, and equipped with comprehensive Ukrainian-language interfaces.

The study is subject to limitations, primarily related to self-selection bias inherent in online survey methodologies, which may result in the overrepresentation of digitally confident teachers relative to the broader population.

Future research should focus on longitudinal analyses of teachers' pedagogical competencies in the use of virtual laboratories, the integration of learning analytics to assess impacts on student achievement, and comparative studies across different regions and levels of general secondary education. While virtual laboratories demonstrate substantial pedagogical potential – particularly in crisis-affected educational contexts – their sustainable and effective integration depends not on individual initiative alone, but on systemic support, curriculum alignment, and institutionally embedded continuous professional development

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