Evaluating the effectiveness and challenges of online laboratory practices in physical chemistry

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Abstract
Relevance. The COVID-19 pandemic highlighted the necessity of utilizing information technology in higher education, particularly for laboratory practices in physical chemistry.

Purpose. This study aims to explore the characteristics of online laboratory practices, evaluate existing training methods, and determine the effectiveness of various approaches in laboratory instruction.

Methodology. The study employed a combination of basic statistical methods and the Pearson chi-square test to analyze survey data collected from teachers and students regarding their familiarity with, interest in, and preferences for online laboratory practices. Additionally, case analysis was conducted to identify the advantages, disadvantages, and overall effectiveness of online laboratory methods used during the COVID-19 pandemic.

Results. The study reveals differing preferences between teachers and students regarding laboratory practices. Most teachers (88%) favor traditional on-site laboratory work, while a significant portion of students (70%) prefer online methods. Familiarity and interest in new technological tools were assessed, showing that 94% of professors are unfamiliar with virtual laboratories, though 80% wish to learn more, and 47% actively use them. Among students, 95% are unfamiliar with virtual labs, but 88% want to learn more, and 77% see virtual labs as beneficial.

Conclusions. The paper discusses challenges in integrating modern technology into physical chemistry labs and suggests that the findings could aid educators in adapting to new teaching conditions and improving educational quality monitoring.

Keywords: virtual laboratory; remote learning; teaching methods; information technology; COVID-19.

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Introduction

The coronavirus pandemic has affected education systems in virtually all countries. Educational institutions around the world, including the Republic of Kazakhstan, have switched to distance education through the creation of an electronic information educational environment. As a result, all face-to-face practices, including lecture, practical and even laboratory practices were moved to an online environment [1]. New active and interactive forms of teaching based on such principles as technology, differentiation, innovation, inclusion of students in intensive direct or indirect educational interaction, open new possibilities in the organization of teacher-student relationships and in the nature of their activities [2]. In particular, in the teaching of chemistry, this approach can contribute to increasing the level of knowledge acquisition, skills to apply them, the development of students' abilities to integrative and creative thinking, the formation of skills to solve problem situations [3-6].

As a rule, practical chemistry skills are more easily learned when conducted physically in real laboratory conditions. And although the laboratory practices are an integral part of any chemistry program, it is at the same time the most complex component for distance learning [7]. Although many practical science strategies supporting online and distance learning have been developed and studied in the past [8], until recently online teaching of laboratory practices in general, and chemistry in particular, it has been used infrequently by us and abroad [9-11]. However, with the advent of the COVID pandemic and mandatory social distancing, many institutions of higher learning are opening up to online learning in this area as well, and are now addressing the practical aspects of providing a suitable laboratory component.

The remote-controlled lab allows students to conduct real-time experiments on real samples in real time. They just do it safely in a browser at a distance. However, the vast majority of such remote laboratories are not in the natural sciences. Of the 355 remote-controlled laboratories analyzed, fewer than five were used for teaching chemistry and biology, while the majority were devoted to engineering (64%) and physics (36%) [12]. A virtual laboratory is a computer program that allows you to simulate a chemical process on a computer, change the conditions and parameters of its conduct. When performing virtual laboratory work, a student operates samples of substances and components of equipment that reproduce the appearance and functions of real objects. In a virtual chemical laboratory, you can perform a separate experiment, for example, to demonstrate a specific property or phenomenon, as well as virtual laboratory work. Detailed review and classification of virtual chemical laboratories for training are presented in the literature [13].

Of all the chemical disciplines, physical chemistry is the most multifaceted and complex science. Probably, this explains the fact that the most famous laboratories Chemistry Experiment Simulations, VirtLab, ChemLab, Crocodile Chemistry 605, Virtual Chemistry Laboratory, Dartmouth ChemLab represent works mainly on inorganic, general and organic chemistry, and there are practically no dedicated virtual laboratories on physical chemistry in the market of educational products. Of course, universities as far as possible create virtual laboratory work on physical chemistry, taking into account their specific, most often to work with their own students. However, from both a technical and a methodological point of view, the level of such development is very diverse, and the use and development prospects are limited to a relatively small number of users and, as a result, a lack of a commercial perspective [14].

The analysis of strengths and weaknesses, opportunities and shortcomings of the implementation of online content in education requires careful assessment at a level that is specific to the group concerned. Thus, the purpose of this study was, using feedback received from teachers and students regarding online teaching of laboratory work in physical chemistry, to determine the features of such practices, analyze existing training practices and ultimately determine the effectiveness of the different methods used.

Materials and Methods

As part of this study, a one-time questionnaire was used to compile a statistical representation of the features of online laboratory exercises in physical chemistry at the university during the COVID-19 pandemic. The purpose of the study was to analyze the existing organization of the educational process, during which students perform laboratory work, assess the effectiveness of approaches that would contribute to the development of active cognitive activity of students, involving them in creativity and autonomy in solving scientific and practical problems, as well as forecasting the most effective methods of their further conduct for the successful development of students' planned skills.

Two sets of questionnaires were prepared for the survey: one for professors and one for students. Each questionnaire consisted of 25 questions. When posing closed questions, the respondent was asked to choose a suitable answer from the list of proposals. Depending on the purpose, the closed questions allowed for a single or multiple choice. The open questions in the questionnaire allowed the survey participants to formulate their own detailed answer, which allowed them to learn new ideas that could be missed. The types of questions alternated. Some questions were common to both groups of respondents, some questions were designed specifically for each type.

Questions for teachers related to their approach to the application of different online laboratory techniques, the frequency of their use of interactive learning opportunities, the reasons for choosing the approach used, and the pros and cons of conducting experiments in this way. The questionnaires for students were dominated by questions about the usefulness of certain methods of conducting laboratory, offered by teachers, about the advantages and disadvantages of distance learning, touched upon technical issues.

18 teachers and 80 students were involved in teaching/studying physical chemistry in Korkyt Ata Kyzylorda State University. They were invited to take part in the experiment. Owing to the quarantine restrictions imposed by the pandemic, all communication took place...
online. Participation in the study was entirely voluntary for both teachers and students. They were aware of the data that needed to be collected, the purpose of the collection and the way the processing was done according to ethical standards. The respondents could refuse to participate in the research at any stage. The answers were anonymous. A total of 95 responses were received from two groups of respondents (17 from teachers and 78 from students). Both sexes participated in the monitoring, the age range ranged from 19 to 25 for students and from 30 to 60 for teachers.

The study was mixed, the data were coded and analyzed using basic statistical methods, but individual cases were also analyzed. To establish a link between the characteristics of respondents (sex, age, position, i.e., teacher or student) and such parameters as “familiarity” and “interest” in new methods of online teaching of laboratory physical chemistry, a statistical analysis was conducted using one of the most popular statistical criteria, the Pearson chi-square.

**Results**

**Methods used in online laboratory teaching**

Figure 1 presents respondents’ answers to the question about the preferred method of teaching laboratory practises (full-time or online). As can be seen from the data provided, the opinions of teachers and students differ significantly. While 88% of professors prefer traditional laboratory work in special laboratories, more than 70% of students prefer to work at home. Detailed answers from teachers indicate the impossibility of performing laboratory work personally by students, problems of software and content support of the educational process, lack of personal contact. Many students need constant assistance and supervision from teachers. Among the detailed answers of students as positive aspects of online work indicated work in a more comfortable and less stressful environment, the ability to manage their time, increasing their independence. There were answers about the possibility of doing other work in parallel (for example, when watching a video). Among the negative aspects of online learning, students highlight the insufficient level of digital literacy of some teachers, technical problems (low internet speed, and sometimes its absence), lack of personal communication and social interaction. Similar problems reported by respondents are also highlighted in the works of other authors [15; 16], as well as in the thematic analysis of Kazakhstan’s independent agency for quality in education [17] (Figure 1).

![Figure 1. Respondents' views on the way laboratory practicals are conducted](image)

Variants of the answers are presented in Figure 2. This distribution of answers shows that most teachers are unfamiliar with virtual laboratories, although the majority of respondents (80%) have expressed interest in learning more about this type of training practice, and almost half (47%) would like to use it for their work in the future. It is evident that the lack of application of virtual laboratories in the laboratory workshop is due to both purely technical issues and the lack of digital literacy, especially among senior professors and teachers.

The advantage of live-stream of laboratory works is a step-by-step review of the real laboratory, so that students can visualize the entire experimental process and its components with the help of video [18]. But on the
technical side, it can be a little difficult to organize broadcasts, while the work, filmed in the usual laboratory conditions based on video, has become a good alternative to performing laboratory work (42% of teachers use them). The idea of video lab work is not new, there are many modern video software products that allow diversity of material feed [16]. In addition, it is possible to set different specific measurement parameters for different groups of students, so that the theoretical and analytical parts of the work students perform independently.

The most common method of conducting laboratory practices was (71%). Most likely due to the rapid spread of COVID-19 in 2020 and the move of higher education institutions to distance learning, teachers had to adapt quickly to the changes and urgently switch to online learning instead of real laboratory conditions. In some cases, this adaptation took only a few days, and job development was the most feasible option. Analysis of the answers to the detailed questions showed that 88% of the teachers interviewed use combined methods of teaching. This can be a video demonstration of doing laboratory practice, and then handing out tasks with a specific option for each student; working with the Microsoft Excel program, which provides very wide possibilities for computing tasks and processing of graphical dependencies.

The opinion of students about modern methods of online teaching of laboratory and their influence on the perception and quality of the course at the potential introduction are presented in Figure 3.

As you can see, the acquaintance of students with virtual or remote-controlled laboratories is practically absent, although a significant part (from 65% to 88%, depending on the technology) showed a desire not only to familiarize, but also to actively use such methods. Most students believe that new technologies will be useful in the study of physical chemistry, while a small proportion of students (6-8%) pointed to pessimism in every aspect. Approximately the same number of students (4-8%) were undecided in this question. Such results could be expected, given the traditional teaching methods commonly used in laboratory courses, as well as the possible fear of lack of physical interaction and social interaction that is inherent in face-to-face learning [10].

In order to determine which variant of the existing method of teaching laboratory is the most optimal, students were asked “How useful training practices were for you in the study of physical chemistry”. Among the responses (Figure 4) was a surprise response from 21% of the respondents that they do not watch video at all. And very disturbing option “I can not answer” from 32% of students. It seems that they do not pay due attention to the review of the work itself, but only perform the task, applying methods and examples of calculation with a detailed description of the algorithm and references to theoretical material. It is also a positive fact that 15% of respondents said that they started searching for information on the Internet, which indicates the development of students' ability to think and increase their independence. This trend is confirmed by the figures of Kazakhstan’s independent agency for quality assurance in education [17].

Figure 4. Students' opinion on the usefulness of training practices in conducting online laboratory practicals

Detailed student responses indicated that they performed fewer written jobs, such as laboratory reports (13 per cent), and the shift from mostly group work during face-to-face training to individual telecommuting was welcomed by less than 30 per cent of respondents.
Identification of the potential of online laboratory teaching methods

Since new online laboratory teaching techniques had a significant potential for effective dissemination of knowledge through the Internet, it was important to assess the existing difficulties or limitations. To this end, students were asked what technical devices they were using. More than half of respondents (61%) use smartphones, 25% use laptops or tablets, and 8% use desktop computers (Figure 5). At the same time, 6% of students did not answer this question. Since the study did not assess the socio-economic status of respondents, it is possible that students from socially vulnerable groups may have limited access to technology.

It was suggested that, depending on their position (teacher/student), gender or age, respondents were differently acquainted and interested in using modern online laboratory teaching techniques. In order to confirm or refute the suggestion, a number of questions were presented in the questionnaires. Data processing was carried out using the Pearson consent criterion (the chi-square criterion), which evaluates the probability that any observed difference between categorical datasets is random. If p is less than 0.05, then the two variables are independent, whereas if p is greater than 0.05, the variables depend on each other. The resulting p-values are shown in the table.

Table 1. p-Values obtained when calculating the consent criterion for establishing the link “characteristics-parameters”

<table>
<thead>
<tr>
<th>Characteristics of respondent</th>
<th>Familiarity</th>
<th>Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>0.624</td>
<td>0.002</td>
</tr>
<tr>
<td>Age</td>
<td>0.320</td>
<td>0.031</td>
</tr>
<tr>
<td>Position</td>
<td>0.477</td>
<td>0.028</td>
</tr>
</tbody>
</table>

As the table shows, the indicator “familiarity” with modern methods of online teaching is connected with each of the variables under consideration. p-Values for this parameter are greater than 0.05 for all characteristics of respondents, i.e., both teachers and students of both sexes at all ages are not sufficiently familiar with the latest techniques. At the same time, the indicator «interest» in new methods, as expected, does not show any connection with gender, age or position. This means that regardless of the characteristics of the respondents, they all have an interest in modernizing teaching methods, especially at a time when classical learning tools are being upgraded and the use of information technology is taking place.

Discussion

The results obtained make it possible to identify the features of online teaching of laboratory work on physical chemistry during a pandemic; the difficulties encountered by both teachers and students in conducting classes; and identify optimization methods and solutions to existing problems.

Physical chemistry is a complex science that has its own characteristics in teaching, especially when performing laboratory robots. No virtual simulators will replace practical exercises, will not solve the problem of formation of purely practical skills. It is not possible to learn, for example, potentiometry or spectroscopy, only from methodical instructions or video demonstrations. Technological possibilities only help the student to independently study and consolidate knowledge on the studied subject. However, in the conditions of social exclusion that have been caused by the spread of COVID-19, effective alternative teaching methodologies in various forms are vital [20-23]. Technology should ensure effective knowledge dissemination, but it is important to recognize any potential limitations and apply the necessary precautions to minimize them [24; 25]. Lack of infrastructure, lack of technical competence or even lack of motivation are the reasons for these limitations. It is necessary to understand not only the effectiveness of new
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methods, but also the students' perception of the inclusion of technologies in promoting learning, especially for science such as physical chemistry, where online methods are rarely practiced.

The results obtained in this work show a high interest and readiness (Figure 2, Figure 3) of the participants in the educational process to adopt the latest techniques. At the same time, it is obvious that both professors and students need not only familiarization with modern technologies, but also training. Of the teachers surveyed, 94% are unfamiliar with the virtual laboratory, although 80% would like to see more details and 47% are actively used for training (Figure 2). Students are more interested in the future application of the latest methods: 77% believe that the use of a virtual laboratory will be useful in the study of the course (Figure 3).

Of course, the design and implementation of such a narrow informational educational environment as a virtual laboratory on physical chemistry is a complex task that requires a special operating base, a team of programmers, teachers and chemical expert, high time and financial costs [26]. However, as practice shows, it is possible to adapt or create within the existing virtual laboratory own laboratory work on physical chemistry, corresponding to the peculiarities of the discipline program. Laboratory work on determination of heat of dissolution, formation and neutralization were created in The Herzen State Pedagogical University of Russia [14], works on spectrophotometry, calorimetry, cryoscopy is successfully practiced in the University of Amrita Vishwa Vidyapeetham, India [27].

Given that 88% of teachers successfully apply combined methods in laboratory (Figure 2), another way to optimize online teaching can be the development of electronic laboratory work, related to the use of Microsoft Excel computing tools. In this case, the main methodical method can be considered stimulation of the search activity of students when working with reference material, conscious performance of calculation tasks with a full understanding of physical-chemical and mathematical processes, the underlying calculations [28]. Excel software is considered an effective tool for studying kinetics in physical chemistry [29]. The implementation of these methods will lead to an increase in the cognitive activity of students, and, consequently, to an increase in the effectiveness and quality of training in general.

Results from a survey of students regarding their attitudes towards existing online laboratory operations and the usefulness of applied practices (Figure 4) showed that they want more interactivity and are interested in using new technologies. Some students (15%) noted an increase in their independence. As disadvantages, indicate physical discomfort and impaired vision from being in front of the computer, as well as a lack of live contact with teachers. Such answers are typical not only for students of Kazakhstan, but also other countries [30-32].

Thus, the experience of conducting online laboratory work in the physical chemistry workshop showed that the combination of virtual and real experiment is the most preferable in which the computer model of the learning process has the auxiliary function of preparing the student to act with real objects. The choice and combination of different modes in a scientifically based proportion will allow the dynamic development of the structure and methodology of physical chemistry teaching on the basis of the most modern achievements of science, technology and methods of cognition.

According to the survey, more than half of the students (61%) indicated that they used a smartphone to access the resource, while a relatively smaller proportion had access to a laptop, desktop or tablet computer. Data collected on the availability of devices indicate that the use of technology-based teaching tools for laboratory work is a viable alternative, given that the vast majority of students had access to devices, which could be used for such purposes. As a rule, many virtual resources used today require support for software that is usually associated with computers, but not with smartphones [32]. In developing online laboratory resources, it would be an undeniable advantage to have applications or programs that are compatible with mobile devices, given that a large number of students prefer to use resources on such platforms.

The analysis of the literature and monitoring results led to the conclusion that in order to optimize the existing methods of online teaching of laboratory work it is necessary not only to develop or adapt virtual resources, search for opportunities to combine different online teaching techniques, but also to choose those that will have minimum system requirements, but can work on mobile platforms.

According to the Kazakh Independent Agency for Quality Assurance in Education, 41% of teachers report lack of necessary technical equipment among professors and students [17]. The lack of special equipment, the general insufficient level of infrastructure provision create huge difficulties in the implementation of new technologies in all universities of Kazakhstan [15]. There are problems with the compatibility of training platforms with operating systems, browsers or smartphones. All this increases the frustration of students and reduces the involvement in the learning process. Obviously, the management of universities will have to solve the issues of financing the necessary infrastructure – the purchase of equipment for the development of new technologies and other types of digital content, services for online consultations and online proctoring.

The lack of high-speed Internet, communication interruptions are another problem. According to the results of the respondents in the conducted study slow internet and problems in his work was the main problem (57% of students indicated this fact). Of course, neither students, teachers, or even the management of the university can decide this issue on their own. These problems are being solved at the national level: the development of the Internet, the introduction of optical Internet in remote villages, the creation of 5G-network infrastructure in the country [1].

The results of monitoring within one university (Korkyt Ata Kyzylorda State University) allow to summarize the results with caution, but taking into account the data obtained by other researchers not only in Kazakhstan, but also in other countries, provide an opportunity to highlight common problems and trends in the development of online teaching of laboratory practices, as well as to offer recommendations for further development.
Conclusions
The conducted study allowed to identify the features of online teaching of laboratory practices in physical chemistry and to assess the effectiveness of various teaching methods. It was found that 88% of teachers prefer the traditional on-site laboratory work in special laboratories, and more than 70% of students choose online. 94% of professors are not familiar with the conduct of laboratory work in the virtual laboratory, 80% would like to know more, and 47% actively use for training. Of the students surveyed, 95% were unfamiliar with the virtual laboratory, 88% wanted to learn more and take a laboratory workshop using such technology, and 77% believed it would be useful to study the course, if such training practices are introduced into the training. On the basis of the data presented in the literature and the own results of the survey, it was concluded, that the most effective method for conducting laboratory exercises in remote format is a combined method – a combination of real experiments on modern equipment and virtual laboratory work in a scientifically based proportion.

The proposed assumption about the relationship of personal characteristics of respondents with parameters “familiarity” and “interest” in the application of new technologies was tested using the chi-square criterion. It has been established that there is a link between the variable characteristics of respondents and the indicator “familiarity” (p-value > 0.05), and for the indicator “interest” such connection does not exist (p-value < 0.05).

It is shown that the use of technological means of teaching for laboratory work is a viable alternative, given that the vast majority of students (94%) had access to devices that can be used for such purposes. The article analyses difficulties that may arise during introduction of modern technological means in development of laboratory exercises in physical chemistry.

The materials of the survey can be useful for teachers of laboratory practices in physical chemistry, adapting to the new conditions of professional activity in the field of education, focused on the development of monitoring of the quality of education. The results obtained can serve as an impulse for further theoretical and practical works. The data presented are not sufficient to generalize. In the process of research, new questions and problems have arisen which require further in-depth and serious research.

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Conflict of Interest
None.

References
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Оцінка ефективності та виклики онлайн-лабораторних практик з фізичної хімії

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Анотація

Актуальність. Пандемія COVID-19 висвітлила необхідність використання інформаційних технологій у вищій освіті, зокрема для проведення лабораторних практикумів з фізичної хімії.

Мета. Метою цього дослідження є вивчення особливостей проведення лабораторних практик онлайн, оцінка існуючих методів навчання та визначення ефективності різних підходів до проведення лабораторних занять.

Методологія. У дослідженні використано поєднання базових статистичних методів та критерію хі-квадрат Пірсона для аналізу даних опитування викладачів та студентів щодо їхньої обізнаності, зацікавленості та вподобань щодо лабораторних практик онлайн. Крім того, було проведено аналіз конкретних ситуацій для визначення переваг, недоліків та загальної ефективності методів онлайн-лабораторій, що використовувалися під час пандемії COVID-19.

Результати. Дослідження виявило відмінності у вподобанні між викладачами та студентами щодо лабораторних практик. Більшість викладачів (88%) віддають перевагу традиційним очним лабораторним роботам, тоді як значна частина студентів (70%) віддають перевагу онлайн-методам. Оцінка обізнаності та зацікавленості в нових технологічних інструментах показала, що 94% викладачів не знайомі з віртуальними лабораторіями, хоча 80% бажають дізнатися більше, а 47% активно ними користуються. Серед студентів 95% не знайомі з віртуальними лабораторіями, але 88% хочуть дізнатися більше, а 77% вважають віртуальні лабораторії корисними.

Висновки. У статті обговорюються проблеми інтеграції сучасних технологій у лабораторії фізичної хімії та висловлюється припущення, що отримані результати можуть допомогти викладачам адаптуватися до нових умов викладання та покращити моніторинг якості освіти.

Ключові слова: віртуальна лабораторія; дистанційне навчання; методи навчання; інформаційні технології; COVID-19.