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Remote Teaching of Chemistry Laboratory Courses during COVID-19

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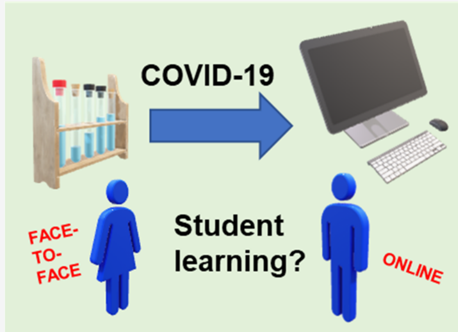
ABSTRACT: This paper describes the transfer from face-to-face education to emergency remote teaching of chemistry laboratory courses in a bachelor's degree in Pharmacy during the COVID-19 pandemic. The virtualization was carried out using videos of each experimental practice and questionnaires containing the experimental data needed. The contents were integrated into the virtual platform Blackboard Collaborate, where tutorials and remote support from the teachers were provided to solve the issues raised. The didactic strategy was very positive: it turned the students into active learners, fostering knowledge sharing and promoting the self-management of their learning process. The teachers acted as guides, raising questions, and provided continuous feedback to the students that contributed to knowledge assimilation and competence acquisition. The teaching−learning process was evaluated through a rubric that graded the reports delivered by the students and a final online test. The impact of this teaching methodology was assessed by comparing the students' marks with those obtained in the conventional on-site education before the pandemic and feedback from the students via surveys. This study provides a unique experience on how a traditional instruction can be adapted to remote teaching in analytical chemistry laboratories, providing new tools that can be used in future pandemics or in other settings.



KEYWORDS: *Second-Year Undergraduate, Distance Learning/Self-Instruction, Problem Solving/Decision Making, Analytical Chemistry*

■ INTRODUCTION AND LITERATURE BACKGROUND

The framework of this study is the global COVID-19 pandemic, during which severe constraints to many activities, including educational activities, were imposed by most of the governments across the world.[1,2] This led to the closure of universities and colleges, and hence to the suspension of face-to-face teaching, affecting about 85% of the enrolled students worldwide. As such, all teaching activities moved to online/remote teaching−learning. In the context of the theoretical lessons, virtual platforms facilitated the delivery of contents via video conferences and recorded presentations.[3] Online educational platforms, like Blackboard Collaborate, allow lecturers to share notes and multimedia resources with students and even to conduct face-to-face online teaching. Such tools were already used in prepandemic times. Yet, chemistry and pharmacy degrees, among others, are purely experimental sciences, with laboratory practices being essential for the students.

Despite that online technologies work well for knowledge building in theoretical courses, they have strong limitations for developing students' practical skills. Furthermore, laboratory courses in science disciplines require an active participation of the students in the teaching−learning process to acquire competences such as hands-on training of the laboratory material, resolution of problems, pharmaceutical control, and so forth, and they may struggle later in their professional lives.[4] It is well established that instrument handling (i.e., buret, pipet, analytical balance, etc.) cannot be replaced by online learning as "experimental skill and human interaction are extremely important for the practice of chemistry".[5] Thus, experiments play a crucial role in chemistry education,[6] but the effect of hands-on chemistry laboratories on students' knowledge still involves investigation and better understanding. According to Domin,[7] four main types of laboratory instruction can be identified in chemistry education depending on whether the approach is deductive or inductive and if procedures are developed by the students or the instructors: expository (traditional), inquiry,[8,9] discovery, and problem-based. Hofstein et al.[10] reviewed the inquiry-type style in chemistry laboratories, which is based not only on "hands-on" but also on "minds-on".

The strategies explored to deliver laboratory courses in the field of sciences can be classified into four types: face-to-face laboratories, virtual laboratories, home study kits, and remote-control laboratories. Among them, virtual laboratories are the most frequently associated with online courses. The term "virtual" typically refers to computer simulations that allow the learner to interactively explore several scenarios in a completely safe environment. Many instructors described it as a good means to teach students (especially the novice), since it reduces extraneous cognitive load, and therefore allows for greater focus

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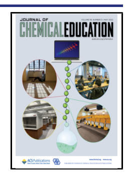

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Figure 1. Schematic representation of the steps followed for the virtualization of the laboratory.

on specific tasks and skills.[11] Nonetheless, very few studies have focused on comparing students' performance in hands-on and virtual laboratory courses, particularly in the field of chemistry.[12,13] In contrast to the virtual laboratory, the remote-control lab allows students to carry out real experiments on real samples in real time and in a safe way. They are employed for different purposes: (i) to allow observations of natural phenomena or experiments; (ii) to carry out measurements; (iii) to manipulate instruments or physical objects in experiments; (iv) to facilitate collaborative work at a distance.[14] However, they are still in their infancy in the chemistry field and most of the developed software is in English. Alternatively, students could perform experiments at home using domestic substances or chemicals delivered to them, which offers autonomy and flexibility, though this approach seems more expensive, risky, and less handy.[15,16]

During the COVID-19 pandemic, educators in chemistry/science were in a particularly tough position since they were challenged to carry out classes online, not only theoretical but also practical. Hence, they were suddenly committed to shift experiments and laboratory activities to an online environment. These changes pose new problems for both teachers and students: they should be used to ICT tools, tune their teaching plans accordingly, and rapidly adapt to this novel online method.[17] A few studies have recently reported their experience in response to the COVID-19 crisis. Some of them reoriented the courses to support students' development of experimentation skills and scientific practices relevant to the conventional course.[18,19] Assignments ranged from problem-based projects to computer-based animations, simulations, and demonstrations, including team and individual work. For example, at Rice University, students were instructed to use a virtual-based simulation activity on an electrochemical cell.[20] Many teachers recorded and shared their own videos about hands-on and laboratory experiences, performed at home, by using everyday-life materials.[21] Others requested the students to preview experiments via open-access courses, such as MOOCs, where video demonstrations could be watched. Some undergraduates were given a literature project and asked to prepare a short presentation.[22] Other students conducted experiments via virtual platforms, such as MLabs, which offers on-screen experiments and interactive simulations.[23] One organic chemistry teacher even created a gamification alternative: "choose your own adventure within the institution's learning management system".[24] Other means developed to familiarize students with practical aspects of chemistry during remote learning include written protocols supported with photos, provision of mock data, live interactive demos, simulations, etc.[25−31]

The aim of this paper is to share our experience in the virtualization of laboratory experiments of Chemistry courses in the degree in Pharmacy during the COVID-19 pandemic. The strategy comprised first the visualization of open-access videos and tutorials recorded by the instructors, followed by filling a questionnaire including questions related to the research, and experimental data delivered to solve each practical case/practice. All the materials were integrated into the virtual platform Blackboard Collaborate, where remote support from the teachers was provided to solve the issues raised. In this way, and as a unique approach, student independence is promoted, similar to the degree of autonomy required in a practical laboratory. The teaching−learning process was evaluated by a rubric that graded the reports delivered by the students and a final test. The impact of this methodology was assessed by comparing the students' marks with those obtained in the face-to-face education. Despite previous studies on undergraduate chemistry laboratory courses describing their experience during COVID-19 pandemic,[18−28] very few of them analyzed the teaching−learning process from the students' point of view, and, to the best of our knowledge, it is the first time that the comparison between face-to-face and remote teaching achievements is applied to practical lessons in this field. We expect that our experience will shed more light on the emergency remote teaching of experimental courses.

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■ PROBLEM DESCRIPTION

Aims of the Study and Research Questions

The general aim of this article is to share our experience in adapting a face-to-face chemistry laboratory to an online environment. It should be noted that due to the emergency pandemic situation, traditional teaching was suddenly switched into remote, online settings, with few skills and resources available at that moment. Other aims are (1) to evaluate the effect of virtualization on the students' knowledge; (2) to evaluate its effectiveness in ensuring the continuity of the teaching−learning process; and (3) to provide alternative ways for skill training from home. In particular, the study explores the complements of physical experiments brought in with videos, tutorials, questionnaires containing fictitious data equivalent to those obtained in the laboratory, and remote support from the teachers for providing skill trainings. A schematic representation of the steps to deliver laboratory practices remotely is depicted in Figure 1.

To test whether virtualization tools have an impact on the education, particularly on the students' acquisition of competences and performance, the learning outcomes for a control group in 2018−2019 (before-COVID, full on-site modality) have been compared with those obtained during 2019−2020 (throughout COVID, remote learning). The two groups received the same teaching hours, and in both cases the attendance to the laboratory lessons was mandatory.

The main idea was to find out how well the students assimilated the information delivered and if they were able to solve practical cases like those encountered during the practices, and also to assess the students' level of satisfaction with the developed methodology and to find out if it promotes students' autonomy.

The specific goals of this research are summarized below:

- Assess the benefits and drawbacks of remote lessons compared to face-to-face teaching in the context of practical courses.
- Evaluate the potential of remote teaching for the acquisition of practical skills within the context of higher education.
- Raise the students' motivation for learning the course contents through a flexible and attractive environment.
- Boost students' capacity for discussion, critical thinking, making decisions, and problem resolution.
- Promote both autonomous and collaborative work among students.
- Preserve the quality of traditional means of laboratory teaching at the university level in the context of the COVID-19 pandemic.

According to what is detailed above, we present the results of a pilot experience about the design and implementation of a simple but efficient approach for remote teaching of practical chemistry concepts adopted as a compulsory emergency measure during almost the entire second semester of 2019/2020. Our challenge was 2-fold. We needed to create new laboratory materials (videos, tutorials, fictitious data, etc.) for remote teaching and we had to deliver them in a virtual setting which was completely new to both students and instructors. During the emergency, most videos were created without any prior planning. Consequently, teachers who lacked online teaching experience found themselves making their own videos with no time to learn.

The following research questions were raised: (1) How do students perceive learning chemistry online at the university level? (2) Is it possible to deliver practical contents via online platforms like Blackboard Collaborate? (3) What are the effects of the virtualization on the students' performance? (4) Do teaching videos and tutorials have a positive impact on the courses they are used? (5) What are the difficulties of the proposed methodology from the students' and the instructors' point of views? (6) Is the active participation of the students encouraged?

Course Characteristics and Student Cohort

The proposed methodology was implemented during 2019−2020, within the framework of "Analytical Techniques", an annual compulsory course of the second year of the degree in Pharmacy at the University of Alcalá (Madrid, Spain). It comprises 12 ECTS (9 theoretical and 3 experimental), with a cohort size of 50 students. Detailed information about the course is included in the Supporting Information.

Research Methodology

Following the steps described in Figure 1, a suitable space within the Blackboard Collaborate was first built, easy to handle for both teachers and students. The teachers prepared all the material to be delivered and arranged the students in small workgroups (4−5 people). Students were provided with all the instructions and a schedule with the activities to be performed. Then, the teachers explained the practical contents via video conference. Students read individually each practice and visualized the videos and tutorials. Subsequently, they started the collaborative teamwork guided by the instructors. They gathered to exchange ideas, analyzed the questions/problems to be addressed, and distributed the work so that each student took a role. The laboratory reports were elaborated in a cooperative way using the fictitious data provided, and were delivered through the platform within 1 week. The teachers provided continuous support to answer students' questions. A tutorship was arranged the last day to solve the issues raised. Following the schedule, teachers and students met again through the platform to share the results obtained, present the solution to their peers, and demonstrate the acquired knowledge. The learning outcomes were evaluated by a rubric that graded the reports delivered by the students and a final online test. A final session was organized to assess the results of the teaching−learning process, in which the students reviewed the work carried out, evaluated their functioning as a team, and provided feedback. A survey was conducted to inquire about the level of satisfaction of the students and the difficulties encountered.

■ DESIGN AND IMPLEMENTATION OF THE VIRTUAL LABORATORY

The course "Analytical Techniques" includes a laboratory of 3 ECTS. It entails practical lessons (36 h) where students develop experiments to apply the theoretical concepts acquired during the lectures plus 30 h of laboratory-related independent work. The goal is to initiate the students in the methodology of the analytical process and make them skilled for the evaluation of analytical results. Teamwork and familiarization with the instruments and devices commonly used in an analytical lab are competences that should be attained.

The virtualization of the laboratory experiments was performed using the Blackboard Collaborate, which contains folders where different contents can be uploaded, a video conference/chat option where live presentations can be

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delivered, a grade center where students can deliver their work to be assessed, a message/announcement area for communication among teachers/peers, and an assessment section where tests and surveys can be performed.

Six laboratory practices, to be developed during the second semester of the academic course 2019/2020, were virtualized and are listed below:

- Analysis of sulfates by turbidimetry.
- Analysis of sodium and potassium by flame photometry.
- Conductimetric titration of acids.
- Separation of compounds by high performance liquid chromatography.
- Analysis of mixtures by molecular absorption spectrophotometry.
- Determination of paracetamol by cyclic voltammetry.

Students were arranged into small teams (4−5 people) and were provided with instructions and a detailed schedule with the activities to be carried out, the resource/tool that should be employed, and the hours for each activity. The time outline is summarized in Table 1.

Table 1. Time Outline of the Proposed teaching−learning Methodology

Activity	Resource/Tool	Hours
Preparation of the material to be delivered and distribution of the students in workgroups	YouTube, Adobe Premiere, Power Point, Microsoft Word, Blackboard Collaborate	40 (teachers)
Presentation of the contents by the teachers	Video conference/ Blackboard Collaborate	1
Individual reading of each laboratory practice	Laboratory Notebook/ Microsoft Word	6
Individual visualization of videos/tutorials	YouTube/Blackboard Collaborate	6
Individual reflection and analysis	–	2
Teamwork/Brainstorm guided by the teacher	Blackboard Collaborate	2
Collaborative analysis of the questions/problems to be addressed	Blackboard Collaborate	1
Elaboration of the reports and delivery	Laboratory Notebook/ Blackboard Collaborate	15
Tutorship	Video conference/ Blackboard Collaborate	1
Presentation of the solutions among groups	Video conference/ Blackboard Collaborate	3
Assessment	Rubric and Online test/ Blackboard Collaborate	2
Final session	Survey/Blackboard Collaborate	1

The first task was the explanation of the laboratory practices by the instructors. All sessions were recorded, so that students could access them whenever necessary. They could also ask the instructors for further assistance at any time.

Students were provided with a laboratory notebook that described in detail each practice, including the objectives, theoretical background, reagents, experimental procedure, presentation of the results, and in some practices annexes with guide levels fixed by legislation. They were also provided with links to videos freely available online, usually on YouTube, demonstrations of characteristic chemical reactions and instrument functioning, as well as instructional videos recorded by the teachers showing the development of each practice. As an example, screenshots of videos recorded by the teachers are shown in Figures 2, S1, and S2. The videos provided context to help understanding and to introduce new terms. English subtitles were included (Figure 2) since some students had difficulties with the specific vocabulary in a foreign language. Besides, videos could be watched at any time, as many times as required, and could be paused, allowing students to take notes, memorize the new vocabulary, reflect about the new concepts, comprehend new methods, and so forth. Overall, they were more effective and more engaging than using print materials alone.

In addition, students were provided with specific tutorials about the software of the instruments (spectrophotometer, liquid chromatograph, etc.), as well as screen cast tutorials recorded by the teachers showing the basis of the techniques employed in the practices and how to carry out data analysis and present the results.

For each practice, the teachers designed a questionnaire with preliminary questions related to the basis of the experimental techniques, the instrument to be selected for a specific measurement, the role of the different parts of an instrument, etc., and numerical exercises about the preparation of solutions. It also included fictitious data like those obtained in the practices, that enabled students to carry out the complete data analysis and treatment (i.e., plot the calibration curve, get the calibration equation, calculate the concentration of an analyte in a sample, compare the results with levels fixed by legislation, etc). A representative example of these questionnaires is depicted in Figure 3. All the above-mentioned material was uploaded to the Blackboard Collaborate. After the individual reading, reflection, and visualization of the videos and tutorials, students were ready to start the online collaborative teamwork guided by the instructors.

The reports were filled in teams and delivered through the Blackboard within 7 days. The teachers offered continuous support to solve the issues raised. Individual and team live tutorships were arranged through Blackboard to put forward any doubts and misunderstandings about the contents. The teachers served as guides and posed questions that were collaboratively answered by the students, but never explicitly provided the solution to the problems/queries of the questionnaires. The last day, the students presented the solutions to their peers, and the instructors promoted critical thinking, discussion, and debate among different groups.

To assess the learning outcomes, a numeric grade was assigned to the reports delivered by means of a rubric (Table 2) that represented 40% of the practical course mark. As can be observed, the rubric was designed to highlight the integration of the collaborative work and the student participation (i.e., contribution to discussion, questions raised, response to teacher's feedback, level of engagement, etc.). The attitude of the students toward their peers and teachers, and whether they took an active role in the teaching/learning process and completed the assigned tasks with punctuality were also assessed. Besides the organization of the delivered tasks, the preparedness and correctness of the answers provided, the justification of the response to the preliminary questions, as well as the resolution and discussion of the numerical problems were considered.

The other 60% of the mark corresponded to an online test developed via the Blackboard Collaborate, which comprised questions and numerical problems related to the knowledge acquired during the practices and the elaboration of the

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Figure 2. Screenshots of the videos recorded by the teachers for the practice "Analysis of sulfates by turbidimetry".

DETERMINATION OF PARACETAMOL IN PHARMACEUTICAL PRODUCTS BY CYCLIC VOLTAMMETRY, REPORT

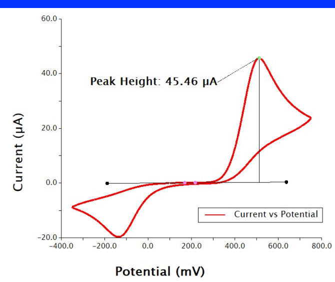
PRELIMINARY QUESTIONS (10 points)

1. Indicate the parameter (s) that is/are monitored during cyclic voltammetry and draw the shape of the applied potential as a function of time (5 points)

2. Calculate the amount of paracetamol (in mg) needed to prepare 100 mL of a 1 x 10^{-3} M solution in buffer. MW, paracetamol = 151.16 g/mol (5 points)

PRESENTATION OF THE RESULTS (10 points)

1. Report the values for the cathodic peak potential E_{pc}, the anodic peak potential E_{pa}, the cathodic peak current i_{pc}, and the anodic peak current i_{pa} from the cyclic voltammogram obtained in part 1 (3 points)
Assume that you perform the CV measurements, obtaining the following cyclic voltammogram.



2. Represent the calibration plot and obtain the calibration graph and the analytical figures of merit (3.5 points)
Assume that you have prepared all the standard solutions and measured the peak height of the cathodic peak. The data that you should obtain are reported in the following table.

C (paracetamol), M	I (μA)
1 x 10^{-6}	0.04
1 x 10^{-5}	0.365
1 x 10^{-4}	4
1 x 10^{-3}	25

3. Report the concentration value obtained for the sample in percent recovery, considering the value reported by the manufacturer (3.5 points)
Assume that you take an aliquot of the sample of the pharmaceutical preparation (apiretal) and dilute 10 μL of apiretal with 100 μL of buffer to fit it into the linear range of the calibration plot obtained in 2. Data: MW, paracetamol = 151.16 g/mol. Concentration of paracetamol in Apiretal= 100 mg/mL

Figure 3. Questionnaire prepared by the teachers for the practice "Determination of paracetamol by cyclic voltammetry".

laboratory reports. To set up the exam, the teachers prepared several question pools: one for multiple-choice questions, one for essay questions that required an answer in a short paragraph, and five for fill-in the blank questions, each comprising one type of numerical problems. The test comprised 40 questions: 36 from the multiple-choice pool (correct answers scored 0.1 points, unanswered questions did not score, incorrect answers deducted 0.03 points), 2 from the essay, and 2 from the fill-in pool (correct answers scored 1 point, unanswered or incorrect answers did not score). Random draw option was chosen for all

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Table 2. Rubric Used to Assess the Work of the Students during the Lab Practices

	Exemplary (9–10)	Effective (6–9)	Minimal (4–6)	Unsatisfactory (0–4)
Attendance and level of engagement (10%)	Attends all of the sessions.	Skips one session without justification.	Skips several sessions without justification.	Skips several sessions without justification.
	Contributes to initiate discussions, offering insightful ideas.	Regularly makes meaningful contributions to discussions.	Contributes to discussions when prompted.	Rarely contributes to discussions or offers ideas.
	Always responds to the teacher's feedback.	Frequently replies to the teacher's feedback.	Seldom offers ideas or responds to the teacher.	Never replies to the teacher's feedback.
Attitude and teamwork activity (10%)	Consistently exhibits a positive cooperative attitude toward teachers and classmates.	Generally shows a positive, supportive attitude toward teachers and classmates.	Sometimes shows a cooperative attitude toward teachers and classmates.	Seldom shows a cooperative attitude toward teachers and classmates.
	Always takes an active role in the team.	Frequently takes an active role in the team.	Sometimes participates actively in the teamwork.	Scarcely participates in the teamwork.
Report format and punctuality in the delivery (5%)	The format is clear, concise and readable. Provides all the calculations and the final result. Systematically completes all the tasks on time.	The format is clear and readable but too extensive. Provides all the calculations and the final result. Usually completes the tasks on time.	The format is readable but not clear enough. Provides only some calculations and the final result. Sometimes delivers the tasks late.	The format is not clear and some formula are not readable. Provides only the final result. Delivers the tasks late.
Response to preliminary questions (35%)	Addresses all the questions correctly. Justifies the responses well with own ideas.	Addresses most of the questions correctly. Justifies the responses without own ideas.	Addresses some questions correctly. Does not justify the responses.	Seldom replies to the posed questions. Does not justify any response.
Resolution and discussion of numerical problems (40%)	Solves all the problems correctly. Expresses the results properly with the corresponding significant figures. Discusses all the results obtained well.	Solves most of the problems correctly. Expresses the results properly with the significant figures. Discusses some results well.	Solves some of the problems correctly. Expresses the results with significant figures. Does not discuss the results.	Solves the problems inadequately. Expresses the results with significant figures. Does not discuss any result.

the pools. An example of the multiple-choice question is shown in Figure 4. A link to the exam was released to all the students simultaneously. The timer was set for 2 h. The students had unlimited attempts, and if they left the exam for any reason, they could continue again. Questions were presented one at a time, and backtracking was prohibited, to prevent students from returning to previous questions they had failed to answer. All these measurements were taken to avoid dishonest behaviors, and their effectiveness can be corroborated by the comments performed by the students and the numerical grades obtained, as will be discussed in the following section. The score of the test was directly included in the grade center, so that after careful check by the teachers, the students were able to visualize their marks and the test failures.

A final session was arranged to assess the results of the teaching–learning process, in which teachers and students reflected about the work carried out and provided feedback. An anonymous survey was conducted to inquire about the level of satisfaction of the students with the online chemistry learning, their teamwork, and the difficulties encountered during the teaching–learning process. The students were able to value the new developed methodology. Some of the questions posed in the survey are listed below:

- Do you like online chemistry lab lessons? If so, what you like most?
- What was the most difficult during the online lessons?
- Which features of the online classes would you change if they had to be delivered online again?
- Which of the resources/tools used do you consider more useful?
- How would you rate videos as a learning resource? What format and length make them more effective?
- Do you think the online lessons are more difficult or easier than the face-to-face ones?
- Do you consider remote teaching an adequate methodology for delivering laboratory courses?
- Do you think the developed methodology is useful for fostering the interest and motivation of the students?
- Rate your overall level of satisfaction with the teamwork and the applied methodology from unsatisfied to very satisfied
- How would you rate the work of your peers from 0 to 10?

■ RESULTS AND DISCUSSION

The first evident outcome is that it is feasible to adapt the face-to-face laboratories to remote teaching in emergency situations such as pandemics, and that it is possible to deliver practical contents via online platforms like Blackboard Collaborate. The experience has served as a basis for the application of these methodologies to the blended learning modality adopted during the course 2020-2021.

To assess the impact of the developed methodology on the students' acquisition of competences and performance, their marks were compared with those of a control group that had face-to-face lessons during 2018–2019, and the results are shown in Figure 5. 100% pass rate was obtained in 2019-2020 with remote teaching compared to 70% obtained in the former course with face-to-face modality. This demonstrates that online teaching was beneficial for acquiring knowledge and contributed to the development of student's cognitive competences including critical thinking and problem-solving skills. It also had a positive effect on student's motivation, since the tools

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Description	The following exam consists on 36 short theoretical questions and 4 problems related with the contents of the lab practices
Instructions	For the theoretical questions, select an option (a,b,c or d). Each correct answer scores 1.6 points
Questions	40
Points	10
Attempts	21

1. Multiple choice: The role of $BaCl_2$ in the turbidimetric determination of sulphates in water is:

Points: 0,1

a.	Act as a blank sample for the calibration curve.
b.	Initiate the precipitation of $BaSO_4$.
c.	Initiate the precipitation of Na_2SO4.
d.	None of the above.

Figure 4. Example of the online test with multiple-choice question for implementation in online-teaching platforms such as Blackboard Collaborate.

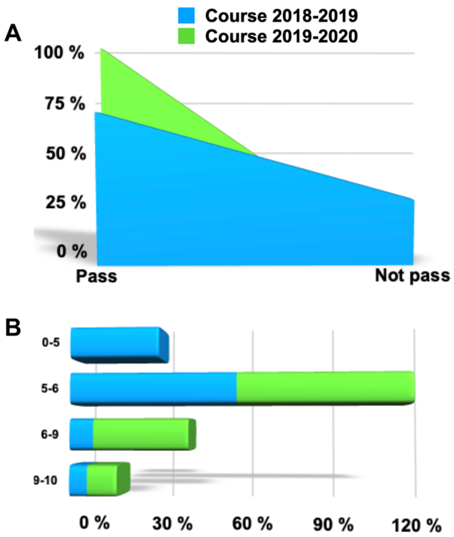

Figure 5. (A) Distribution of the students that passed and failed the laboratory practices during the academic course 2018-2019 and 2019-2020 (right). (B) Distribution and comparison of the marks obtained by the students during those academic courses.

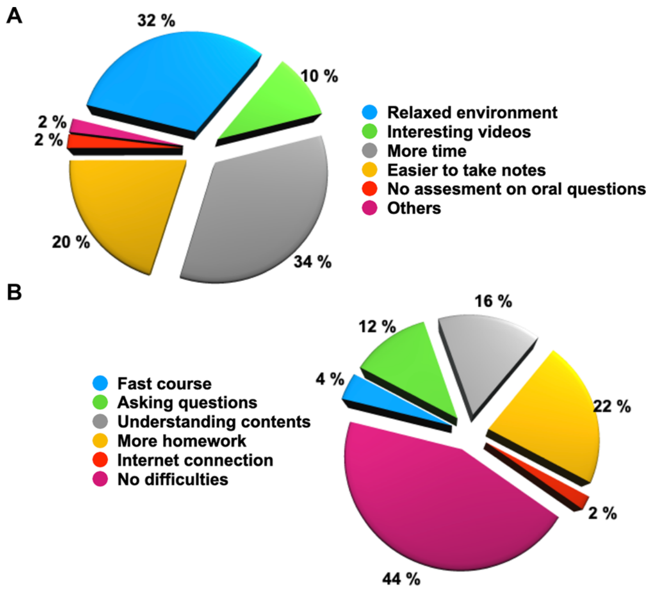

Figure 6. Distribution of the students' responses to survey questions: (A) "What you liked most about online learning?" (B) "What was the most difficult during the online sessions?"

employed (videos, tutorials, etc.) increased the level of student engagement, as corroborated by their comments in the survey. The increased interest was then reflected in better learning outcomes. Another key factor on improving student's performance was teamwork, since it made problem resolution easier. Besides, students were able to learn from their peers, hence competence achievement took much less effort and time. It should be noted that the curriculum is not grading the hands-on skills. Thus, a small percentage (about 3%) of the students that failed in the face-to-face modality did not gain the skills needed for handling the glassware and equipment. The 100% pass rate is likely masking out this factor, which is one of the main drawbacks of online teaching. Unfortunately, further development of the students in experimental subjects, or the influence of the lack of hands-on skills in superior courses is difficult to be assessed. Yet, from discussions with our colleagues and from our own experience, some lack in pipetting ability, titration skills, equipment handling, etc., were identified in 2020-2021 and 2021-2022 compared with prepandemic times. Note that in our university, face-to-face modality fully restarted in the current academic year (2021−2022). As such, the situation is very complex and requires further study, identifying the key factors and evaluating the influence with a future perspective. Indeed, contradictory results have been reported in the literature about this topic. Some authors[32,33] claimed that virtual chemical laboratories are viable as an effective complementary tool or as an alternative to hands-on laboratories, resulting in better learning outcomes (i.e., cognitive, affective and skill-based) than traditional media, while several publications[34−36] argued that they cannot be used as replacement. The most effective could be to combine virtual laboratories with hands-on laboratories.

Regarding the marks distribution (Figure 5B), a significant increase in the average grade was found upon applying the developed methodology. Thus, in 2018-2019, the percentage of students with the highest grade (9−10) was 6%, and it increased up to 10% with the online learning. Further, the percentage of students with a grade in the range of 6−9 raised from 8% with the face-to-face modality to 32%.

On the other hand, a student survey was meant to identify the level of students' satisfaction with online chemistry lab learning. Starting with a simple yes/no question about whether they enjoyed such laboratory lessons, only 1% answered "no". Students were then asked to write what they liked most. Typical

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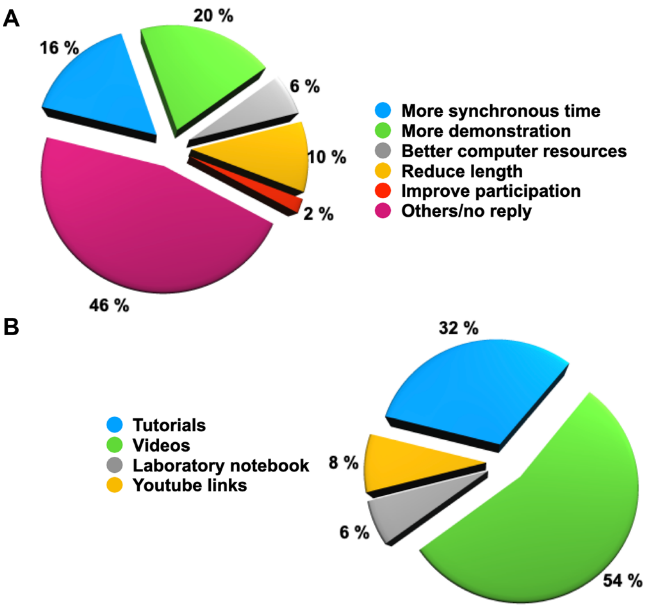

Figure 7. Distribution of the students' responses to survey questions: (A) "Which features of the online classes would you change if they had to be delivered online again?" (B) "Which of the resources/tools used do you consider more useful?"

answers are listed below, and the distribution of the students' responses is displayed in Figure 6A.

- Many interesting videos and interactive homework.
- More relaxed environment compared with traditional lessons.
- Enable to manage time and work more efficiently, since no transportation to the university is needed.
- More time for discussion of the results, due to availability of the online platform.
- Do not have an assessment based on oral questions.
- Easier to take notes and follow.

When students were inquired what was the most difficult during the online sessions, 22% indicated too much homework, 16% problems with understanding the lesson content, 12% the difficulty in asking questions and missing the live interaction with their teachers and classmates, 4% the fast course pace, and 2% problems with internet connection. The rest of the students (44%) did not identify difficulties (Figure 6B).

Regarding the features of the online classes they would change, 20% suggested more demonstration/method introduction, 16% more synchronous time, 6% better computer resources, 10% shortening course length, and 2% improve group participation. The rest of the students provided other suggestions or did not reply (Figure 7A). Among the resources they considered more useful, more than 50% indicated videos, around 32% tutorials, and a few of them YouTube links and the laboratory notebook (Figure 7B). Focusing on the videos as a learning resource, almost 80% rated them with 8 or 9. Students considered videos as a very useful and valuable resource especially for practice. They believed that shorter ones are more effective since they keep students more focused, and that videos made by teachers are more instructive than those found in YouTube or similar channels. Regarding whether online lessons are more difficult than face-to-face ones, almost all replied that the degree of difficulty was similar. Most students considered remote teaching as an appropriate methodology for delivering laboratory courses. All of them agreed that the developed methodology is highly beneficial for fostering the interest and motivation of the students.

72% of the students were very satisfied with the teamwork, and none of them were unsatisfied (Figure 8). Similar results were obtained when they rated their peers: 78% rated them with a mark higher than 8, and none gave a grade of 5 or lower. Finally, when students were asked to express their overall level of satisfaction, 90% answered that they were very satisfied, and only 4% were little satisfied, but none were unsatisfied (Figure 8). One student indicated that a drawback could be unfair assessment since students can cheat during the online tests, although it was carried out in such a way to minimize fraudulent behaviors.

■ CONCLUSIONS AND FUTURE PERSPECTIVES

In this paper we have described our experience of remote emergency teaching of chemistry laboratory courses in the bachelor's degree in Pharmacy. The virtualization was carried out via the platform Blackboard Collaborate, which allowed us to integrate videos, tutorials, and other resources of each experimental practice. The grades of the students and their surveys illustrate that online teaching was beneficial for acquiring knowledge and contributed to the development of students' cognitive competences including critical thinking and problem-solving skills. It also had a positive effect on students' motivation, since the resources employed (videos, tutorials, etc.) increased the level of student engagement. Another factor on

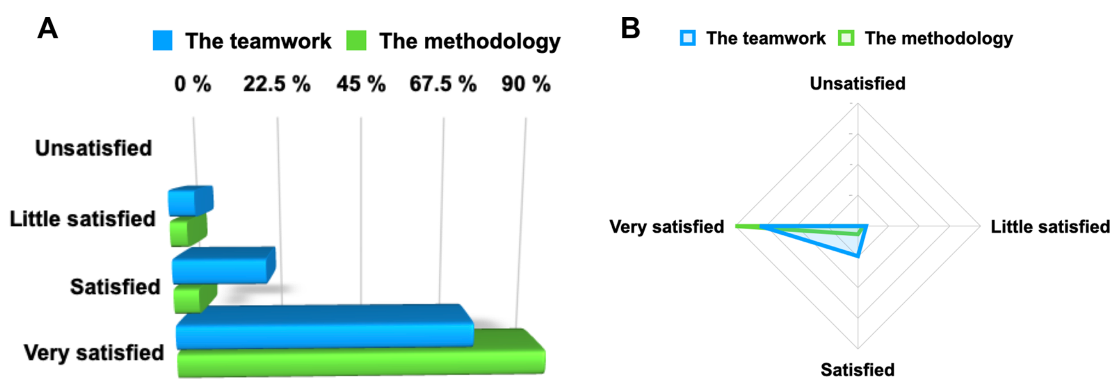

Figure 8. (A) Distribution of the students' responses to the survey rating their overall level of satisfaction with the teamwork and the overall developed methodology. (B) Distribution of the responses.

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improving students' performance was the collaborative work, which made problem resolution easier. Students consider videos as a useful and valuable resource particularly for practical courses. Nevertheless, it is desirable to complement them with other resources such as notebooks. They are beneficial for enhancing comprehension, albeit not enough for students to completely grasp a topic or take in knowledge. Yet, the 100% pass rate attained could be masked by the fact that the curriculum is not grading the hands-on skills. The student survey revealed that 72% of the undergraduates were very satisfied with the teamwork and 90% with the overall developed methodology. Part of this approach has been used in the current academic course that blended virtual and face-to-face environments. In the future, some difficulties pointed by the students including the amount of homework, problems with understanding some concepts, the fast course pace, and the effort in asking questions will be addressed. Novel assessment strategies are required to effectively evaluate students' attributes (e.g., communication skills, reflective practice, teamwork, and collaboration) and demonstrate understanding and acquisition of the competences required for professional life. This study paves the way toward the reflection on the educational strategies that need to be restructured to promote deep learning in an online environment after COVID-19.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00022.

> Screenshots of the videos recorded by the teachers for the practice "Analysis of sodium and potassium by flame photometry"; Screenshots of the videos recorded by the teachers for the practice "Analysis of mixtures by molecular absorption spectrophotometry" (PDF) (DOCX)

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Notes

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