Designing a drinking water treatment experiment as a virtual lab to support engineering education during the COVID-19 outbreak

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Abstract: The design and deployment of a conventional water treatment experiment, the Jar Test, are presented in a virtual format. It used a low-cost online platform to reproduce the experimental steps and the actual lab setting to empower students with experiential skills. Skills like experimentation, instrumentation, learning from failure, and communication for their professional success. These skills are evaluated in the accreditation criteria for engineering programs of the Accreditation Board for Engineering and Technology. This virtual experience provided one-hundred and sixty-three civil engineering students with the knowledge to perform experimentation at an engineering level, from water sampling campaigns to performing the Jar Test experiment and measuring physicochemical quantities to draw technical conclusions. According to students’ perceptions, the simulation strengthened their capacity for conducting experiments and data collection-processing using virtualized lab instruments. It also consolidated theoretical knowledge to report conclusions according to research findings and enhanced their confidence to perform in-person experiments based on the revised virtual procedure. The results from this study demonstrate that virtual tools could be deployed as a powerful supplement to deliver the practical syllabus when limitations of face-to-face interaction occur. It can also be a blended educational approach since the computer-assisted simulation provides the necessary pre-knowledge that maximizes learning during in-person experimentation.

Subjects: Engineering Education; Chemical Engineering; Civil, Environmental and Geotechnical Engineering; Higher Education

Keywords: Simulation lab; engineering education; ABET instructional objectives; lab instrumentation capability; academic communication skills; psychomotor and learning from failure competencies

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1. Introduction
The Director-General of the World Health Organization declared the novel coronavirus (SARS-CoV-2) outbreak a public health emergency of international concern on 30 January 2020. As a result, the number of infected people with this life-threatening illness increased rapidly, inflicting global challenges to the health, economy, and education systems (WHO, 2020).

Governments worldwide deployed strict measures to control the rapid spreading of the disease (Anzai et al., 2020), such as social distancing, travel restrictions, reinforcement of border controls, isolation, and shutting down trade centers, companies, and educational facilities. However, despite these measures, infections kept rising, and education facilities remained closed (Coluccia et al., 2021; Garcia et al., 2020; Xi Lin & Zhang, 2020; Reuters Business News, 2020; Torres & Sacoto, 2020). This closure affected education in low- and middle-income countries at all levels since the government funding for higher education was reduced. As a result, international mobility was restricted, the number of course enrollments declined, and the traditional educational model of face-to-face interaction experienced an abrupt transition to virtual learning (Almarzooq et al., 2020; Basantes-Andrade et al., 2020; Crawford et al., 2020).

The search for adequate e-resources to deliver the academic content of hands-on courses was crucial (Glasey & Magalhães, 2020), and providing students with real-world interactions as much as possible was a priority (Aristovnik et al., 2020; Jiménez-Sánchez, 2020; Johnson et al., 1995; Junus et al., 2021; Machado et al., 2020; Theoret & Ming, 2020). Nevertheless, computer-assisted resources are not always innovative educational approaches in practical courses. In recent decades, Information and Communication Technologies (ICT) have provided novel didactic strategies to illustrate, simulate, and stimulate real experiences, thus supporting higher education in experiential skills acquisition in a wide field of studies and disciplines. Disciplines like science & technology (Dalgarno et al., 2009; Loftin et al., 1993; Martinez-Jiménez et al., 2003; Yang & Heh, 2007), history using web-based museum tours (Wang et al., 2009), and medicine (Tabas et al., 2005). Virtual environments also demonstrate industrial production processes (Dominguez et al., 2018) and illustrate engineering field trips or fieldwork (Seifan et al., 2019). In engineering studies, the illustration of conventional physics and chemical reaction experiments using web-based simulation tools was common in developing countries (Bell & Scott Fogler, 1996; N. D. Finkelstein et al., 2005; Domingues et al., 2010; De Jong et al., 2013). However, in the Ecuadorian context, online labs have not been widely incorporated into experiential teaching practices, mainly due to insufficient teacher training in digital-pedagogical competencies and limited access to technological resources. Challenges were overcome during the pandemic, teachers explored the potential of different e-tools for the devising of support materials to reinforce students’ experimental skills and impart the content of hands-on courses. Among the alternatives, the application of cost-free simulation resources, readily available on the Internet, did not fully address a broad spectrum of learning objectives and lab instrumentation of engineering-level practicum sessions. While customizing a virtual hands-on lab generally requires a time and cost-intensive approach and not in all instances require strong ICT skills. The benefit gained is tailoring the designed resource to the instructional objectives of the experimentation.

In this way, evidence has depicted that computer-designed simulations have empowered students with essential skills across a broad spectrum of cognitive, psychomotor, and affective competencies necessary for their professional success in solving real-world problems (Balamuralithara & Woods, 2009; Nikolic et al., 2021). According to the ABET criteria, thirteen learning objectives must be met throughout an undergraduate engineering program, whether face-to-face or virtual, regardless of the delivery method (Besterfield-Sacre et al., 2000; Feisel & Rosa, 2005; Felder & Brent, 2003; McGourty et al., 2002; Most & Deisenroth, 2003).

These objectives are geared to strengthen students in their cognitive domain and cover aspects of (1) Instrumentation—an appropriate application of instrumentation, sensors, and software tools (Grimaldi & Rapuano, 2009); (2) Models—to determine the strengths and opportunities of theoretical models as predictors of real-world outcomes. For example, this could entail identifying if a hypothesis sufficiently describes a physical occurrence and developing or validating a connection between measured data and
physical principles (Noguez et al., 2007); (3) Experiment—in order to characterize an engineering material, component, or system, the student designs an experimental approach, choose relevant equipment, and methods, conduct these procedures and evaluate the resulting output (Dominguez et al., 2018); (4) Data Analysis—to demonstrate data collection, analysis, and interpretation competencies, as well as the ability to construct and support technical conclusions (Jamshidi & Milanovic, 2022); (5) Design—to meet customer requirements, establish system specifications from the requirements, and test and debug a bench-lab prototype, system, or process using appropriate resources to satisfy requirements (Domingues et al., 2010). Meanwhile, the two instructional objectives related to the psychomotor domain are (6) Psychomotor—to demonstrate expertise in the selection, modification, and manipulation of appropriate engineering apparatus and resources (Scheets et al., 2005); and (7) Sensory Awareness—to use human senses to collect data and make solid engineering decisions when devising solutions to real-world challenges.

The remaining objectives contribute to the cognition realm and are an influential component of the affective domain. These instructional objectives are: (8) Learn from Failure—to determine whether failures were caused by poor equipment, codes, construction, procedure, or design, and then re-engineer effective corrective actions, (9) Creativity—to demonstrate adequate levels of independent thinking, creativity, and real-world problem-solving abilities (Altalbe, 2019), (10) Safety—to identify and responsibly address health, safety, and environmental hazards associated with technological processes and activities (Viitaharju et al., 2021), (11) Communication—to be able to communicate effectively with a targeted audience about laboratory work, both orally and in writing, at levels ranging from executive summaries to detailed technical reports, (12) Teamwork—to work proficiently in groups, including establishing individual and shared accountability, assigning roles, duties, and tasks, tracking progress, meeting deadlines, and incorporating individual contributions into a final project (Naukkarinen & Sainio, 2018), and (13) Ethics in the Laboratory—to follow the highest ethical standards, which include reporting findings objectively and interacting with integrity.

The present research aims to describe the process of virtually designing, coding, and implementing one of the water-treatment experiments required for the training of civil engineering students, “The Jar test experiment.” However, no evidence was found in the literature of the design and implementation of virtual simulations in conventional water treatment processes. In addition, a comprehensive evaluation of two essential aspects of applying these digital-pedagogical resources has not been addressed. These aspects should cover students’ perceptions of the use of the platform and a quantitative evaluation of student performance according to the instructional objectives of experimentation. In particular, we analyzed the students’ self-assessment of hands-on learning outcomes, such as analyzing and interpreting data to state technical conclusions, solving real-world problems, and their capacity to conduct experiments and follow safety protocols to test water quality parameters. Furthermore, we evaluated the students’ acquisition of competencies established in the ABET instructional objectives, such as “Experiment, psychomotor, instrument, learning from failure, and communication” skills.

This research is an initiative of the Faculty of Geosciences Engineering (FICT) at the Polytechnic University ESPOL in response to the need to provide students with experiential skills during physical distancing restrictions due to the COVID-19 outbreak using a virtually designed simulation. The findings of this study will validate the usefulness of computer-based simulations in hands-on engineering courses and report the experience of an Ecuadorian public university in designing & implementing a virtual laboratory experiment as educational support to further impart experiential knowledge from home.

2. Methodology
This work shows the designing stages to create a virtual lab of the “Jar Test,” based on the flocculation and coagulation processes as one of the steps to produce drinking water, traditionally performed in a face-to-face lab. This Jar Test process is the most common in conventional drinking water treatment.
Figure 1 summarizes the stages to build, simulate, validate, and deploy the virtual lab experiment. The first stage consisted of constructing the lab facility and equipment to familiarize the students with the lab work environment. Then, physical and chemical phenomena related to water treatability were coded in the simulation-coding stage. Finally, the validation stage involved collecting feedback from developers and users during follow-up meetings to improve the virtual experiment’s draft versions. The virtual lab was deployed in the first semester of 2020 (1S-2020) using the university’s learning management system (LMS) and the institutional website. One hundred and sixty-three civil engineering students from 1S-2020 were surveyed using questionnaires to understand their perceptions regarding their learning experience using the virtual lab setting. Meanwhile, during the second semester of 2021 (2S-2021), thirty-three students enrolled in the practical course were selected to assess the accomplishment of the instructional objectives proposed by the ABET accreditation board using written lab reports and practical workshops as evaluation instruments.

2.1. Constructing stage
The online platform was CoSpaces Edu, a low-cost online tool with an intuitive interface and supporting materials to assist developers in the constructing and coding stages, such as tutorial videos and forums. In addition, CoSpaces Edu provided three options to create virtual environments and lab equipment. The first option was the “environment” feature, where several sceneries, such as a classroom-type space, could be selected.

The most useful option in this constructing stage was the “library” feature, where objects were readily available in different categories, e.g., characters, animals, nature, transport, and other items useful for laying common classroom features. Placing avatars was important to role-mimic the instructor interacting with the students. Also, building blocks of regular shapes in 2D or 3D models were attached, rotated, and scaled to build the lab equipment. Some of the most important lab equipment, such as the multiparameter, turbidimeter, and the flocculator, were built piece by piece using these building blocks that could be joined, attached, or texturized by left-clicking the objects and selecting the features. When equipment design was time-consuming because of complex shapes, the “upload” feature permitted importing 3D finished objects as .obj, .fbx, .mtl, and .zip archives. Also, uploading other compatible files with this online tool, like images, videos, and audio, was possible. Thus, they could be reproduced during the execution of the virtual lab.
2.2. Simulating-coding stage

The online tool was equipped with a visual block-based programming language so that people with basic or no prior knowledge of programming language could code. It was important to add labels to the objects to be programmable. This block-based language contained nine family functions accessed with the “code” option: (i) transform, (ii) actions, (iii) events, (iv) control, (v) operators, (vi) items, (vii) data, (viii) functions and (ix) physics. Within the “transform” function, moving and rotating objects and setting a time counter were possible. These functions were useful, for example, to simulate both slow and fast agitation through the paddle stirrers of the flocculation apparatus. The “action” function allowed setting the opacity of an object, either showing or hiding it, displaying multiple-choice questions, and allowing avatars to convey information. It was possible to initialize a programming sequence with the triggering feature of an object in the “events” function. Also, there was a function to display external online resources like videos and website information. The “control” function was useful for repeating actions several times. The “operators” function contained logical operators such as if, or, and, false, true, and not. Combined with the “data” function, these operators were useful for assigning logical properties to a variable to accumulate a numerical value permitting grading questionnaires and assessing the understanding of the experimental virtual method. The “item” function allowed to detach objects from avatars or characters and edit object characteristics such as labels and physical properties. The “physics” function permitted moving and spinning objects with set velocities. This latter function could have been used to simulate contaminants settling; however, the “move” option in the “transform” function was the most intuitive.

Running a hands-on virtual lab session required the synergy of several coding functions. First, the online supporting material was revised to code the non-intuitive sequence of simulations. The “help” option has a drop-down menu where complex questions are responded to by a global community of block-based programmers sharing problem-solving experiences and know-how procedures.

2.3. Validating stage

Active engagement along the design process of the virtual labs was required. The stakeholders, such as lecturers, lab technicians, teaching assistants, and developers, attended weekly follow-up meetings. The collected feedback during the meetings was valuable for rapidly improving the construction and simulating-coding stages. In addition, the virtual meetings permitted the development of a practical virtual platform aiming to positively contribute to the building knowledge process and strengthen the experiential competencies of the students. The design process of a single virtual lab space required approximately three weeks.

2.4. Deployment stage

The virtual lab experiments were deployed in the Virtual Classroom, the institutional LMS that supported the teaching experiments by organizing the course-related materials. The virtual lab experiments were also uploaded to the faculty website (http://www.fict.escpol.edu.ec/ies/coagulaci%23%23n-fioculaci%23%23n), where links and QR codes were available. Evaluating the usefulness of these new academic resources as being fundamental for educators to improve them continuously was crucial. Therefore, feedback was collected from one-hundred and sixty-three senior-level civil engineering students enrolled in the Drinking-Water and Water Treatment practical course. The survey aimed at obtaining information regarding the perception of the virtual lab’s contribution to the development of learners’ experiential capacity, challenges to engaging in virtual classrooms, and achieving three learning outcomes: understanding the experimental procedure, analyzing and interpreting data, and reporting conclusions.

It was essential to enquire about the number of times the students accessed the virtual lab and whether the educational experience with this resource was enjoyable or not. Students were asked to share if they felt confident performing experimentation in the real lab after utilizing the virtual lab. The following questions were asked to the students:
• How would you rank the contribution of the virtual lab to enhancing your experimentation skills?
• In your opinion, what are common challenges found in engaging in virtual classrooms?
• How would you perceive your understanding of the experimental procedure using the virtual lab?
• How do you think the virtual lab has contributed as a support learning material?
• How useful would you consider combining virtual didactic material (virtual lab session + lab guide + online videos) for learning virtual experiments?
• How would you appraise the teacher’s performance during the virtual session to couple the technical know-how with the virtual tool?
• How would you describe your performance in the virtual lab practicum regarding your capacity to conduct experiments?
• How would you perceive your performance regarding your capacity to analyze and interpret the data?
• How would you perceive your capacity to state conclusions using engineering judgment?
• How often did you access the virtual lab to understand the experiment’s instructions, concepts, and procedures?
• If you would need to experiment in the real lab, how confident would you feel about performing it based on what you learned during the virtual lab session?

Moreover, two virtual lab deployment scenarios were tested to see which one influenced student learning before or after the face-to-face lab experience. Lab reports and workshop grades from two academic terms (1S-2020 and 2S-2021) were compared to discriminate student performance under these two situations, (1) Real-simulation: students with prior interaction with the in-person water treatment lab before the pandemic (2S-2019) and students who enrolled in the hands-on drinking water treatment course in 1S-2020, and (2) Simulation-real: 2S-2021 students enrolled in the course who first used the computer-assisted lab session prior to the face-to-face real laboratory interaction.

The assessment instruments selected to measure the ABET instructional objectives were:

• Surface water sampling report to measure objectives such as experiment and communication.
• Workshop on lab equipment calibration to assess objectives such as psychomotor, instrumentation, and learning from failure.

3. Results

3.1. Constructing and design
The virtual lab facility was scaled using architectural information from the real laboratory. The online platform had a measurement sensibility of ± 0.12 m when stretching blocks to shape. Therefore, the elements constructed with the building block tool were reproduced at scales approaching the actual dimensions. For example, the real laboratory building size is 7.50 m wide and 7.70 m long, whereas the virtual lab dimensions, were 7.44 m wide and 7.66 m long. On the other hand, common lab and office items were retrieved from the platform library as a time-saving option over the constructing stage period.

The working areas of the actual lab setting were reproduced along with the laboratory equipment and materials used to measure water quality indicators. In the flocculation area, there was the Jar Test apparatus equipped with four channels to carry out the coagulation-flocculation process, as shown in Figure 2. In the measurement area, one could find the spectrophotometer that measures ions in a water sample.

Familiarizing students with existing facilities and equipment is important since civil engineering is a hands-on degree program. In addition, some students conduct research related to water treatment issues in their undergraduate dissertations or as part of the faculty’s research projects.
Therefore, providing them experience in a virtual laboratory workspace during pandemic times could help prepare them to design and conduct physical-chemical measurements.

These simulation-based tools have been applied in the last two decades as a new pedagogical and logistically effective approach in engineering programs with the expectation that it could potentially empower, reinforce, and extend the complex skills needed to succeed in the real world (Baher, 1999; Balamuralithara & Woods, 2009; Molina et al., 2021; Serrano-Aroca, 2015). Nevertheless, virtual tools should not be assumed to replace immediate and vivid academic experiences in most cases; instead, this digital tool supports students’ scientific and engineering training (Corter et al., 2011; Feisel & Rosa, 2005). Furthermore, some studies reported that real-time interactions in education are more effective at consolidating learning. However, computer-based simulation has been proved to be a powerful, supportive resource for preparing students by reinforcing the pre-knowledge to maximize learning and fostering assertive interaction between teachers and students (Hodge et al., 2001; Seifan et al., 2019).

The Jar Test flocculator, a complex device, was unavailable in the library. Thus, it was constructed by attaching building blocks and customizing the equipment features, as displayed in Figure 3. The flocculator is used to agitate the water samples with different hydraulic flow systems to remove contaminants, such as organics, colloidal, and suspended particles. Performing the flocculation experiment is essential for civil, chemical, and environmental engineers working in the water treatment industry to set hydraulic velocity gradients to reproduce the operational conditions of a treatment plant on a bench-lab scale and understand the role of the coagulant, chemical, or natural substances that remove contaminants.

Figure 2. A) Virtual flocculator and B) virtual spectrophotometer constructed on the online platform.
The Jar Test experiment measured basic water quality variables such as pH, electrical conductivity, dissolved oxygen, and turbidity using the multiparameter and turbidimeter. The turbidimeter was constructed similarly to the flocculator by assembling the building pieces (Figure 4). The interesting feature of this equipment was the visualization of the measurements, whereby images designed in jpg format files were displayed as results on the equipment’s screen after each measurement. Reproducing the laboratory devices with carefully crafted details such as measurement options responded to the goal of showing the equipment handling, thus facilitating the learning process and proper operation of the equipment (Awad & Corless, 1997; L. Finkelstein, 1994; Mallalieu et al., 1994; Pyatt & Sims, 2012). As a result, students could recognize materials and reagents and develop skills such as data collection, analysis, and interpretation from experimental findings to solve real-world problems in the water treatment field (Bisantz & Paquet, 2002; Flack & Volino, 1999; Rasteiro et al., 2009; Williamson, 1953). Similar results were pointed out, where virtual simulations supported students in establishing a relationship between measured data and underlying biochemical principles of the fermentation process. At the same time, embedded graphs of bacterial growth, dissolved oxygen availability, productivity, and nutrient consumption stimulated engineering intuition to conclude process optimization in terms of cost and time (Seifan et al., 2020).

Awareness of working in a safe laboratory space was essential. Thus, safety signs were introduced by placing some around the virtual scenario. Although this was a virtual session, maintaining safety standards was essential during the experiment to avoid accidents in a real laboratory environment. The usefulness of online laboratories in improving safety culture has been seen in advanced-level engineering labs and elementary practical courses (Zendler & Greiner, 2020). Furthermore, computer-based lab tools are reported beneficial for students to get routine work...
done while gaining confidence to avoid incidents and being used for illustrative and safety training purposes (Viitaharju et al., 2021).

3.2. Coding stage

The processes of agglomeration of colloids and other pollutants into denser masses are carried out in large volume basins in water treatment plants. However, this purification process can be studied on a laboratory scale using the Jar test apparatus. Learning from this experiment empowers students to associate operational variables, such as coagulant dose, mixing energy, sedimentation time, and physicochemical water indicators, to maximize the removal efficiency of colloidal suspended matter, resulting in a lower turbidity value.

The students were instructed to prepare a 1 L volume of water sample per flocculator channel. Since the flocculator assembled in the virtual space is equipped with four channels, students could perform dosing with up to four different concentrations of an alum-coagulant stock solution to identify the optimal dose. These simulated actions were essential to show the students the initial steps of the Jar Test experiment and contributed to the development of their experiential skills.

The simulation of water flow regimes in the Jar Test equipment involved adjusting the period of the paddles. When setting longer periods, the water velocity gradient seemed slow so that students could discriminate between the key concepts of rapid and slow agitation based on the experiential observations being assisted by questions. For example, hydraulic velocity gradients influence the processes from the distribution of chemical coagulant to the floc formation. Fast mixing at short times resulted in a homogeneous distribution of the chemical reagent in the water sample. In contrast, bigger flocs are formed during the slow mixing at longer times, and the mild agitation prevents their breakage. Therefore, the size of the flocs was exaggerated for academic purposes to observe floc formation at an early stage.

Furthermore, contaminants should be larger for more accurate visualization of colloid electrostatic neutralization and agglomeration processes to form flocs with higher densities. Settling processes were simulated by moving the flocs downward while the supernatant liquid became lighter as the contaminant matters were removed. Virtual lab platforms open up opportunities to emulate, illustrate and explain challenging physical-chemical phenomena, invisible to the naked eye, as these occur rapidly at the micro- or nanoscale (Feisel & Rosa, 2005; Ong & Mannan, 2004).

Several studies have demonstrated that interactive simulated laboratories related to multivariable physicochemical phenomena outperform real experiments where modification of operating
conditions involves a higher cost of materials, reagent availability, logistical challenges, effort, and time (Domingues et al., 2010; Dominguez et al., 2018; Nippert, 2002; Ramirez et al., 2020). For example, it was reported that the use of an online simulation instead of a real laboratory environment helped students to acquire sound conceptual knowledge to design complex science-based systems and components, as the virtual tool provided a complete laboratory experience with multiple possible scenarios and reagents with no runout, all without additional logistical effort or material purchase cost (N. D. Finkelstein et al., 2005).

The students were able to observe the results of the measurements on the equipment screens, as observed in a face-to-face lab experience. The results obtained in the virtual lab were analyzed to determine the optimal dose of the chemical coagulant. The selection had to be justified in terms of optimization and efficiency of the reagent, practicing their engineering judgment. In addition, the simulation of the experiment included the calibration process of the turbidimeter against standard formazin standard solutions of 20, 100, and 800 NTU. Before testing the turbidity removal efficiency, it was validated with a 10 NTU formazin standard solution. The nephelometric method was the mechanism for turbidity measurement. Thereby students were taught to clean the turbidity sample vials to remove fingerprints and ensure the lid of the measuring compartment of the turbidimeter was closed to avoid interference from external light during measurement.

The positioning of the cameras around the laboratory facility helped reinforce the data collection skills, as the camera displayed the result of the measurement of the water quality parameters on the equipment screen, prompting students to understand the correlation between the operating conditions of the process and the design output.

4. Discussion
The design process of the virtual lab was monitored twice a week through virtual meetings held with the laboratory teacher, where adjustments were suggested to successfully deliver academic content in the best way possible, acknowledging the online platform’s capacity.

The student’s perception of the contribution of this virtual laboratory in providing hands-on laboratory content was evaluated using a survey with a five-point Likert-type scale. The scale ranged from excellent, good, neutral, and fair to poor. In addition, students self-assessed the acquisition of experimentation skills after the virtual experience according to ABET accreditation criteria. In the first question, the students ranked the contribution of the virtual lab from excellent: “the virtual platform contributed effectively to strengthening my know-how capacity, mandatory for my engineering education” to poor, which means “the virtual platform did not contribute substantially to strengthening my know-how skills, essential for my engineering training.” Of 163 participants, 60.1% perceived the contribution of the virtual lab as excellent-good in improving their experiential capacity, as displayed in Figure 5; most of these students reported they made the most of this lab by preparing themselves in advance by reading the experimental procedure and being in tune with the synchronous hands-on lab session.

On the other hand, only 3.1% of the participants perceived the virtual lab as a non-substantial contribution, fitting into the “poor” category. The reason behind this perception could be linked to common challenges identified by students in virtual classrooms as an impediment to understanding the experiment procedure. These challenges were the instability of the internet connection, frequent exposure to home distractors, no vivid and real lab experiences, no real interaction, and additional ones shown in Figure 6. Another reason students stated not finding the virtual lab engaging was the struggle to revise concepts and experimental guidelines before the synchronous class. These findings shed light on students’ performance in the virtual lab practicum regarding their capacity to conduct experiments with the support of the prepared learning material that has been designed to be successful if these are reviewed in advance.
Figure 5. Student survey results regarding the appreciation of the Jar Test simulation as e-learning support material (1S-2020 results). Question 1: How would you rank the contribution of the virtual lab to enhancing your experimentation skills; 2: How would you perceive your understanding of the experimental procedure using the virtual lab; 3: How do you think the virtual lab has contributed as a support learning material; 4: How useful would you consider combining virtual didactic material (virtual lab session + lab guide + online videos) for learning virtual experiments; 5: How would you appraise the teacher’s performance during the virtual session to couple the technical know-how with the virtual tool.

Figure 6. Word cloud the students’ perception of the most common challenges in engaging in the e-lab sessions.
Regarding the student-teacher interaction during the synchronous lab session, students’ questions focused on the science behind the experiments. For example, establishing or validating a relationship between measured data and underlying physical-chemical principles taught concepts in theoretical classes, rather than understanding the usability of the online tool interface. It was also inquired how the virtual lab could facilitate three learning outcomes: (1) understanding of the experimental procedures, (2) strengthening capacity for analyzing and interpreting data, and (3) elaborating conclusions, as shown in Figure 7.

Of 163 students, a share of 66.7%, corresponding to the excellent-good categories, responded that they were able to associate the experimental methods with the physicochemical concepts of water treatment, as well as collect, analyze, and interpret data allowing them to formulate and support technical conclusions. Strengthening these learning outcomes facilitated the connection between the sciences behind the experiments and the procedures depicted in the virtual lab experiment, which stimulated their engineering judgment to report conclusions. However, it is important to report that a minority of students, 3.8%, failed to meet these learning outcomes even though virtual labs were an online resource that could be accessed anywhere and as many times as the student deemed necessary (De Jong et al., 2013; Potkonjak et al., 2016), learning at their own pace (Garcia-Vela et al., 2020), and thus enhancing the autonomy of the students (Granjo & Rasteiro, 2020).

Most of the participants, 123 students, accounting for 75.5%, accessed the virtual lab platform from one to two times on average to understand the instructions, concepts, and procedures of the experiment, whereas the remaining reported they accessed this resource more than three times to end up mastering instructions, concepts, and experiential competencies. Furthermore, among all

![Figure 7. Students’ survey results on experimentation skills obtained in Jar test simulation (15-2020 results). Question 1: How would you describe your performance in the virtual lab practicum regarding your capacity to conduct experiments; 2: How would you describe your performance in the virtual lab experiments regarding your capacity to analyze and interpret the data; 3: How would you describe your performance in the virtual lab experiments regarding your capacity to state conclusions using engineering judgment.](image-url)
respondents, 50.3% of them agreed that including interactive dialog boxes, audios, and avatars contributed to a more enjoyable experience with the online platform during the virtual experiment, as shown in Figure 8.

Virtualizing the lab facility and customizing the Jar Test simulation was useful as the students could access engineering-level experiments during the most critical time of the pandemic. Interestingly, 74.3% of the survey participants reported feeling confident enough to conduct experimentation under the supervision of a teacher or peer assistant. At the same time, 20.2% of students rated their experiential capacity as robust enough to perform their experiments independently if access to didactic material and replaying the online lab session was granted. Similar results were reported regarding using computer-mediated technologies such as remote labs during the outbreak of COVID-19 in third-year level practical courses. For example, a remote lab permitted undergraduate chemical engineering students to remotely control the laboratory session using virtual tools such as pan-tilt-zoom cameras and Microsoft HoloLens 2 (Bhute et al., 2022). It was reported that >70% of respondents achieved key learning objectives to understand engineering concepts and apply them through experimentation using these online smart technologies. Our approach did not provide learners with real-time views of the lab setting; nevertheless, the construction of the online space allowed the students to advance their experimentation skills and contribute to the intended hands-on learning outcomes.

Figure 8. Discussion based on the results of the student survey (IS-2020 results). A) Time invested by students in the virtual lab to understand the experiment's instructions, concepts, and procedures. B) Contribution of the supporting resources such as dialog boxes, audios, and avatars to a more enjoyable experience during the e-lab session. C) Confidence to perform in-person measurements of water quality parameters and experiments based on the competencies obtained in the online experience.

A) Time students used the e-tool

| Time    | Percentage |
|---------|------------|
| 1-2     | 75.5%      |
| 3-5     | 22.7%      |
| >6      | 1.8%       |

B) Contribution of tool features to an enjoyable experience

| Feature | Percentage |
|---------|------------|
| Agree   | 40.5%      |
| Neutral | 50.3%      |
| Disagree| 9.2%       |

C) Confidence to perform in-person measurements and experiments

| Competence | Percentage |
|------------|------------|
| Complete capacity | 74.3%      |
| Require assistance | 20.2%      |
| Not prepared | 5.5%       |
A more quantitative approach to the virtual lab, as a didactic online support material, was to compare students’ scores when experimenting using the virtual lab before or after the real lab experience. From this perspective, a crucial question arises: when does the virtual lab boost the experiential learning process in the best manner? Before the actual hands-on lab session or afterward? To answer this question, lab grades were collected and analyzed from two groups of students enrolled in the first and second academic terms of the Drinking Water Treatment subject (1S-2020 and 2S-2021). Students from the first academic term; 1S-2020, had experience in a real hands-on lab, and after that, they used the virtual lab (real-simulation), whereas students from the second academic term; 2S-2021, used the virtual lab first and then carried out experimentation in the real lab (simulation-real). This latter scenario occurred while mobility restrictions still applied in the country. Table 1 shows scores of students from two academic activities. The first was the water sampling report and the other was the equipment calibration workshop in the academic terms 1S-2020 and 2S-2021. Both activities aimed to strengthen engineering-level students’ cognitive, psychomotor, and affective competencies. Cognitive competency - experiment and communication: It was observed that higher scores in the report were attained in the simulation-real scenario when the experiment was revised in the virtual lab before attending the field trip (2S-2021). For example, 89.0% of students scored between 90 and 100 in their written reports when the simulation-real configuration class was deployed.

In comparison, only 18.1% of students achieved similar marks under the real-simulation scenario. These findings suggest students were more successful in understanding the guidelines revised in the virtual lab simulation or a virtual class and then practicing in a real setting exercise. In addition, better performance was observed during the face-to-face activity since the students actively participated. Students commented that they could make the most out of the face-to-face activity.

Psychomotor, instrumentation, and learning from failure: Aiming to strengthen “psychomotor, instrumentation, and learn from failure” competencies, an exercise was also devised to test knowledge regarding the equipment calibration necessary to assure reliable data measurement, e.g., equipment calibrated against standard reference solutions. As shown in Table 1, 15.0% of the student group exposed to the real-simulation conditions achieved grades between 60 and 80 marks. When the other student group experienced simulation-real activities, 100.0% achieved assignment scores from 80 to 100. This was a considerable increase in the number of pupils who obtained better scores than those in the cognitive competency experiment and communication. It appears that “psychomotor, instrumentation and learning from failure skills” are easily developed in the stage at which the real field practice is combined with the virtual lab experience.

Table 1. Scores from the water sampling report and equipment calibration workshop from the first semester of 2020 (1S-2020) and the second semester of 2021 (2S-2021) to evaluate cognitive, psychomotor, and affective competencies in engineering-level students

| Academic term                | Number (%) of participants |
|------------------------------|-----------------------------|
|                              | Student’s assignments score | Water sampling written report | Equipment calibration workshop |
| 1S-2020 real-simulation      | 100-80                      | 18%                          | 84%                           |
|                              | 80-60                       | 68%                          | 15%                           |
|                              | < 60                        | 14%                          | 1%                            |
| 2S-2021 simulation-real      | 100-90                      | 89%                          | 100%                          |
|                              | 90-60                       | 11%                          | 0%                            |
|                              | < 60                        | 0%                           | 0%                            |
Feedback from students helped us to understand their learning process better while studying online:

**Being in the lab and listening to the explanation given by the teacher about the proper handling of the equipment and using it by myself gave me confidence. However, confidence is strengthened by practicing more than a couple of times, which is sometimes impossible in a real setting. This is further complicated if I cannot access the lab. However, using the virtual simulation does not allow me to handle the equipment but learn and reproduce the procedure as often as I want.**

5. Conclusions
It is worth to notice traditional face-to-face lab experiences cannot be easily substituted by computer- or online-based tools (Torres-Díaz et al., 2022). Nevertheless, these online approaches efficiently support the mastery of experiential capabilities in engineering education when access to labs cannot be granted by external issues (Klein & Wozny, 2006; Rafael et al., 2007; Shin et al., 2002; Wheeler et al., 2017), e.g., as preparation tools for in-person laboratory sessions (Dalgaro et al., 2009; Gautam et al., 2016; Martínez-Jiménez et al., 2003; Woodfield et al., 2005). The findings of this study show that virtual tools can be implemented in higher education as a support material to deliver the practical syllabus when face-to-face interaction is limited. Moreover, they can also be deployed as part of a blended educational approach since the computer-assisted simulation provides the necessary pre-knowledge that maximizes learning during in-person experimentation and strengthens the “know-how” capacity, data collection and interpretation skills.

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References
Almorzaq, Z. I., Lopes, M., & Kocher, A. (2020). Virtual learning during the COVID-19 pandemic: A disruptive technology in graduate medical education. Journal of the American College of Cardiology, 75(20), 2635–2638. https://doi.org/10.1016/j.jacc.2020.04.015
Altoibe, A. A. (2019). Performance impact of simulation-based virtual laboratory on engineering students: A case study of Australia virtual system. IEEE Access, 7, 177387–177396. https://doi.org/10.1109/ACCESS.2019.2957726
Anzo, A., Kobayashi, T., Linton, N. M., Kinoshita, R., Hayashi, K., Suzuki, A., Yang, Y., Jung, S.-M., Miyama, T., Akhmetzhanov, A. R., & Nishiura, H. (2020). Assessing the impact of reduced travel on exportation dynamics of novel coronavirus infection (Covid-19). Journal of Clinical Medicine, 9(2), 601. https://doi.org/10.3390/jcm9020601
Aristovnik, A., Keržič, D., Ravšelj, D., Tomžičević, N., & Umek, L. (2020). Impacts of the COVID-19 pandemic on life of higher education students: A global perspective. Sustainability, 12(20), 1–34. https://doi.org/10.3390/su12208438
Awad, S. S., & Corless, M. W. (1997). An undergraduate digital signal processing lab as an example of integrated teaching. IEEE INSTRUMENTATION & MEASUREMENT TECHNOLOGY CONFERENCE, 2, 1314–1319. https://doi.org/10.1109/IMTC.1997.612412
Boher, J. (1999). Articulate virtual labs in thermodynamics education: A multiple case study”. Journal of Engineering Education, 88(4), 429–434. https://doi.org/10.1002/j.2168-9830.1999.tb00470.x
Balakumardarla, B., & Woods, P. C. (2009). Virtual laboratories in engineering education: The simulation lab and remote lab. Computer Applications in Engineering Education, 17(1), 108–118. https://doi.org/10.1002/cae.20186
Basantes-Andrade, A. V., Cabezas-González, M., & Cosillas-Martín, S. (2020). Digital competencies in the training of virtual tutors at the Universidad Técnica del Norte, Ibarra (Ecuador). Formación universitaria, 13(5), 1393–1399. https://doi.org/10.4067/S0718-50062020000500269
Bell, J. T., & Scott Fogler, H. (1996). VicHer: A virtual reality-based educational module for chemical
reaction engineering. Computer Applications in Engineering Education, 4(4), 285–296. https://doi.org/10.1002/SCI1099-0542(1996)4:4<285::AID-CAEE3.0.CO;2-9

Bestefeld-Sacre, M., Shuman, L. J., Wolfe, H., Atman, C. J., McGourty, J., Miller, R. L., Olds, B. M., & Rogers, G. M. (2000). Defining the outcomes: A framework for EC-2000. IEEE Transactions on Education, 43(2), 100–110. https://doi.org/10.1109/13.848060

BHute, V. J., Sengupta, S., Campbell, J., Shah, U. V., Heng, J. Y. Y., & Brechtelsbauer, C. (2022). Effectiveness of a large-scale implementation of hybrid labs for experiential learning at imperial college London. Education for Chemical Engineers, 39(March), 58–66. https://doi.org/10.1016/j.ece.2022.03.001

Bisantz, A. M., & Paquet, V. L. (2002). Implementation and evaluation of a multi-course case study for framing laboratory exercises. Journal of Engineering Education, 91(3), 299–307. https://doi.org/10.1002/jee.2168-9830.2002.tb00707.x

Coluccia, B., Agrusdei, G. P., Miglietta, P. P., & De Leo, F. (2021). Effects of COVID-19 on the Italian agri-food supply and value chains. Food Control, 123, 107839. https://doi.org/10.1016/j.foodcont.2020.107839

Corter, J. E., Esche, S. K., Chassapis, C., Ma, J., & Nickerson, J. V. (2011). Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. Computers & Education, 57(3), 2054–2067. https://doi.org/10.1016/j.compedu.2011.04.009

Crawford, J., Butler-Henderson K, Rudolph J et al. (2020). COVID-19: 20 countries’ higher education intra-period digital pedagogy responses. Journal of Applied Learning & Teaching, 3(1). https://doi.org/10.37074/joljt.2020.3.1.7.

Dalgarno, B., Bishop, A. G., Adlong, W., & Bedgood, D. R. (2009). Effectiveness of a virtual laboratory as a preparatory resource for distance education chemistry students. Computers & Education, 53(3), 853–865. https://doi.org/10.1016/j.compedu.2009.05.005

De Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. Science (80–J), 340(6130), 305–308. https://doi.org/10.1126/science.1230579

Domingues, L., Rocha, I., Dourado, F., Alves, M., & Ferreira, E. C. (2010). Virtual laboratories in (bio)chemical engineering education. Education for Chemical Engineers, 5(2), 22–27. https://doi.org/10.1016/j.ece.2010.02.001

Dominguez, J. C., Miranda, R., Gonzalez, E. J., Oliet, M., & Alonso, M. V. (2018). A virtual lab as a complement to traditional hands-on labs: Characterization of an alkaline electrolyzer for hydrogen production. Education for Chemical Engineers, 23, 7–17. https://doi.org/10.1016/j.ece.2018.03.002

Feisel, D. R., & Rosa, A. J. (1990). The role of the laboratory in undergraduate engineering education. Journal of Engineering Education, 91(4), 121–130. https://doi.org/10.1002/jee.2168-9830.2005.tb00833.x

Felder, R. M., & Brent, R. (2003). Designing and teaching courses to satisfy the ABET engineering criteria. Journal of Engineering Education, 92(1), 7–25. https://doi.org/10.1002/jee.2168-9830.2003.tb00734.x

Finkelstein, L. (1994). Measurement and instrumentation science-An analytical review. Measurement, 14(1), 3–14. https://doi.org/10.1016/0263-2241(94)90038-8

Finkelstein, N. D., Adams WK, Keller CJ, et al. (2006). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. Physical Review Special Topics - Physics Education Research, 1(1), 1–8. https://doi.org/10.1103/PhysRevSTPER.1.010103

Flack, K. A., & Volino, R. J. (1999). A series-parallel heat exchanger experiment. Journal of Engineering Education, 88(1), 27–30. https://doi.org/10.1002/jee.2168-9830.1999.tb00407.x

García, P. J., Alarcón, A., Boyer, A., Buss, P., Guerra, G., Ribeiro, H., Rojas, K., Soenz, R., Salgado de Snyder, N., Solimano, G., Torres, R., Tobar, S., Tuesca, R., Vargas, G., & Atun, R. (2020). COVID-19 response in Latin America. American Journal of Tropical Medicine and Hygiene, 103(5), 1765–1772. https://doi.org/10.4269/ajtmh.20-0765

García-Vela, M., Zambrano JL, Falquez DA et al. (2020). Management of virtual laboratory experiments in the geosciences field in the time of covid-19 pandemic. ICIER2020 Proceedings, 1(November), 8702–8711. https://doi.org/10.21125/icierc.2020.1925

Gautam, S., Qian, Z., & Loh, K. C. (2016). Enhancing laboratory experience through e-lessons. Education for Chemical Engineers, 15, 19–22. https://doi.org/10.1016/j.ece.2016.02.001

Glassey, J., & Magalhães, F. D. (2020). Virtual labs – Love them or hate them, they are likely to be used more in the future. Education for Chemical Engineers, 33, 76–77. https://doi.org/10.1016/j.ece.2020.07.005

Granja, J. F. (2016). Enhancing the autonomy of students in chemical engineering education with the LABVIRTUAL platform. Education for Chemical Engineers, 31, 21–28. https://doi.org/10.1016/j.ece.2020.03.002

Grimaldi, D., & Rapuano, S. (2009). Hardware and software to design virtual laboratory for education in instrumentation and measurement. Measurement, 42(4), 485–493. https://doi.org/10.1016/j.measure.2008.09.003

Hodge, H., Hinton, H. S., & Lightner, M. (2001). Virtual circuit laboratory. Journal of Engineering Education, 90(4), 507–511. https://doi.org/10.1002/jee.2168-9830.2001.tb00632.x

Jamshidi, R., & Milonovic, I. (2022). Building Virtual Laboratory with Simulations. Computer Applications in Engineering Education, 30(2), 483–489. https://doi.org/10.1002/caee.22467

Jiménez-Sánchez, C. (2020). Impact of the SARS-CoV2 pandemic on education financing. Revista Electrónica Educare, 24(May), 1–3. https://www.scielo.sa.cr/scielo.php?pid=S1409-42582020000400001&script=sci_abstract&tlng=en

Johnson, S. H., Luyben, W. L., & Talhelm, D. L. (1993). Undergraduate interdisciplinary controls laboratory. Journal of Engineering Education, 84(2), 133–136. https://doi.org/10.1002/jee.2168-9830.1995.tb00160.x

Junus, K., Santos, H. B., Putro, P. O. H., Gandhi, A., & Siswantiang, T. (2021). Lecturer readiness for online classes during the pandemic: A survey research. Education Sciences, 11(3). https://doi.org/10.3390/ES11030132

Klein, A., & Wozny, G. (2006). Web-based remote experiments for chemical engineering education. the online distillation column. Education for Chemical Engineers, 1(1), 134–138. https://doi.org/10.1205/ece60015

Loffin, R. B., Engleberg, M., & Benedetti, R. (1993). Applying virtual reality in education: A prototypical virtual physics laboratory. Proceedings of VRAIS ‘95, IEEE Virtual Reality Annual International Symposium, 1993, 67–74. https://doi.org/10.1109/VRAIS.1993.378261

Madhava, R. A., Bonoh, P. R. F., Da Cruz Perez, D. E., & Martelli Junior, H. (2020). COVID-19 pandemic and the impact on dental education: Discussing current and future perspectives. Brazilian Oral Research, 34, 1–6. https://doi.org/10.1590/1807-3107BOR-2020. VOL34.0083
Mallilieu, K., Arietos, R., & So'Brien, D. (1994). An inexpensive pc-based laboratory configuration for teaching electronic instrumentation. IEEE Transactions on Education, 37(1), 91–96. https://doi.org/10.1109/13.275183
Martinez-Jiménez, P., S. Climent-Bellido, M., S. Climent-Bellido, M., & Climent-Bellido, M. S. (2008). Learning in chemistry with virtual laboratories. Journal of Chemical Education, 80(3), 346–352. https://doi.org/10.1021/ed080p346
McCourt, J., Shuman J., Basterfield-Sacre M, et al. (2002). Preparing for ABET EC 2000: Research-based assessment methods and processes. International Journal of Engineering Education, 18(2), 157–167. https://www.ije.ie/articles/Vol18-2/JEEE1278.pdf
Molina, R., Orocoa, G., Segura, Y., Moreno, J., & Martinez, F. (2021). KMS platform: A complete tool for modelling chemical and biochemical reactors. Education for Chemical Engineers, 34, 127–137. https://doi.org/10.1016/j.ece.2020.09.003
Most, K. R., & Deisenroth, M. P. (2003). ABET and engineering laboratory learning objectives: A study at virginia tech. In ASEE Annual Conference Proceedings, pp. 1227–1246.
Naukkorinen, J., & Sainio, T. (2018). Supporting student learning of chemical reaction engineering using a socially scaffolded virtual laboratory concept. Education for Chemical Engineers, 22, 61–68. https://doi.org/10.1016/j.ece.2018.01.001
Nikolic, S., Ros M., Jovanovic, K., & Stanisavljevic, Z. (2021). Remote, simulation or traditional engineering teaching laboratory: A systematic literature review of assessment implementations to measure student achievement or learning. European Journal of Engineering Education, 46 (6), 1141–1162. Taylor & Francis. https://doi.org/10.1080/03043797.2021.1990864
Nippert, C. (2002). Online experiments - The results of the online widener laboratories. In Proceedings - Frontiers in Education, Conference, vol. 1, pp. 12–17. https://doi.org/10.1109/fe.2002.1157941.
Noguez, J., Sucar, L. E., & Espinosa, E. (2007). A probabilistic relational student model for virtual laboratories. Lecture Notes in Computer Science, 4511 LNCs(222), 303–308. https://doi.org/10.1007/978-3-540-73078-1_34
Ong, S. K., & Mannan, M. A. (2004). Virtual reality simulation and animations in a web-based interactive manufacturing engineering module. Computers & Education, 43(4), 361–382. https://doi.org/10.1016/j.compedu.2003.12.001
Potkonjak, V., Gardner, M., Collaghan, V., Mattila, P., Guett, C., Petrovic, V. M., & Jovanovic, K. (2016). Virtual laboratories for education in science, technology, and engineering. A review. Computers & Education, 95, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002
Pyatt, K., & Sims, R. (2012). Virtual and physical experimentation in inquiry-based science labs: Attitudes, performance, and access. Journal of Science Education and Technology, 21(1), 133–147. https://doi.org/10.1007/s10956-011-9291-6
Rafael, A., C., Bernardo, F., Ferreira, L. M., Rasteiro, M. G., & Teixeira, J. C. (2007). Virtual applications using a web platform to teach chemical engineering. The distillation case. Education for Chemical Engineers, 21(2), 20–28. https://doi.org/10.1205/cece06007
Ramírez, J., Soto, D., López, S., Akroyd, J., Nurkowski, D., Botero, M. L., Bianco, N., Brownbridge, G., Kraft, M., & Molina, A. (2020). A virtual laboratory to support chemical reaction engineering course using real-life problems and industrial software. Education for Chemical Engineers, 33, 36–44. https://doi.org/10.1016/j.ece.2020.07.002
Rustemier, M. G., Ferreira L., Teixeira J. et al. (2009). LABVIRTUAL-A virtual platform to teach chemical processes. Education for Chemical Engineers, 4(1), 9–19. https://doi.org/10.1016/j.ece.2009.02.001
Reuters Business News. (2020). IMF chief says pandemic will unleash worst recession since great depression. Reuters Business News. https://www.reuters.com/article/us-health-coronavirus-imf-idUSKCN21R1SM
Scheets, G., Weiser, M., & Shearda, R. (2005). Changing a standard telecommunications laboratory to a same-time-different-place virtual laboratory format: Techniques utilized and lessons learned. IEEE Transactions on Education, 48(4), 713–718. https://doi.org/10.1109/13.275183
Seifan, M., Dada, D., & Berenjian, A. (2019). The effect of a virtual field trip as an introductory tool for an engineering real field trip. Education for Chemical Engineers, 27, 5–11. https://doi.org/10.1016/j.ece.2018.11.005
Seifan, M., Robertson, N., & Berenjian, A. (2020). Use of virtual learning to increase key laboratory skills and essential non-cognitive characteristics. Education for Chemical Engineers, 33, 66–75. https://doi.org/10.1016/j.ece.2020.07.006
Serrano-Araoco, A. (2015). Real and virtual bioreactor laboratory sessions by STSE-CLIL WebQuest. Education for Chemical Engineers, 13, 1–8. https://doi.org/10.1016/j.ece.2015.06.004
Shin, D., Yoon, E. S., Lee, K. Y., & Lee, E. S. (2002). A web-based, interactive virtual laboratory system for unit operations and process systems engineering education: Issues, design, and implementation. Computers & Chemical Engineering, 26(2), 319–330. https://doi.org/10.1016/S0098-1354(01)00749-9
Tabas, J. A., Rosenson, J., Price, D. D., Rohde, D., Baird, C. H., & Dhillon, N. (2005). A comprehensive, unembalmed cadaver-based course in advanced emergency procedures for medical students. Academic Emergency Medicine, 12(8), 782–785. https://doi.org/10.1111/j.1553-2712.2005.00107.x
Theoret, C., & Ming, X. (2020). Our education, our concerns: The impact on medical student education of COVID-19. Medical Education, 54(7), 591–592. https://doi.org/10.1111/medu.14181
Torres-Diaz, J. C., Rivera-Rogel, D., Beltran-Flandoli, A. M., & Andrade-Vargas, L. L. (2022). Effects of COVID-19 on the perception of virtual education in university students in ecuador; technical and methodological principles at the Universidad Técnica Particular de Loja. Sustainability, 14(6), 3204. https://doi.org/10.3390/su14063204
Torres, L., & Sacoto, F. (2020). Localising an asset-based COVID-19 response in Ecuador. Lancet, 395(10233), 1339. https://doi.org/10.1016/S0140-6736(20)30851-5
Villahurju, P., Yliniemi, K., Nieminen, M., & Karttunen, A. J. (2021). Learning experiences from digital laboratory safety training. Education for Chemical Engineers, 34, 87–93. https://doi.org/10.1016/j.ece.2020.11.009
Wang, Y., Stash, N., Sambek, R., Schuursmans, Y., Arroyo, L., Schreiber, G., & Gorgels, P. (2009). Cultivating personalized museum tours online and on-site. Interdisciplinary Science Reviews, 34(2–3), 139–153. https://doi.org/10.1177/174327909X441072
Wheeler, L. B., Clark, C. P., & Grisham, C. M. (2017). Transforming a traditional laboratory to an inquiry-based course: Importance of training tas when redesigning a curriculum. Journal of Chemical Education, 94(8), 1019–1026. https://doi.org/10.1021/acs.jchemed.6b00831
WHO. (2020). COVID-19: Public health emergency of international concern (PHEIC) global research and innovation forum: Towards a research roadmap. 

Williamson, C. (1993). Recommendations for the undergraduate physics laboratory curriculum. Physics Today, 6(9), 31–32. https://doi.org/10.1063/1.3061391

Woodfield, B. F., Andrus, M. B., Andersen, T., Miller, J., Simmons, B., Stanger, R., Waddoups, G. L., Moore, M. S., Swan, R., Allen, R., & Bodily, G. (2005). The virtual ChemLab project: A realistic and sophisticated simulation of organic synthesis and organic qualitative analysis. Journal of Chemical Education, 82 (11), 1728–1735. https://doi.org/10.1021/ed082p1728

Xi Lin, B., & Zhang, Y. Y. (2020). Impact of the COVID-19 pandemic on agricultural exports. Journal of Integrative Agriculture, 19(12), 2937–2945. https://doi.org/10.1016/S2095-3119(20)63430-X

Yang, K. Y., & Heh, J. S. (2007). The impact of internet virtual physics laboratory instruction on the achievement in physics, science process skills and computer attitudes of 10th-grade students. Journal of Science Education and Technology, 16(5), 451–461. https://doi.org/10.1007/s10956-007-9062-6

Zendler, A., & Greiner, H. (2020). The effect of two instructional methods on learning outcomes in chemistry education: The experiment method and computer simulation. Education for Chemical Engineers, 30, 9–19. https://doi.org/10.1016/j.ece.2019.09.001