Research Article

Integrating Virtual Tools Into the Face-To-Face Teaching of Undergraduate Analytical Chemistry

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At the National University of Luján, traditional classroom-based instruction characterized the analytical chemistry courses. However, in response to evolving educational needs, a transition to hybrid education combining virtual and face-to-face activities is occurring. In this context, some questions arise: Can all face-to-face activities be replaced by virtual activities? What benefits does the inclusion of virtual activities bring to the curriculum?

Reflecting on the experiences gained during the virtual instruction period that occurred due to the pandemic, the teaching group recognized the value of integrating virtual and face-to-face components. In a comparative assessment of teaching tools, the consensus emerged that a blended approach is crucial for effective analytical chemistry education in the current educational landscape. The findings indicated that, for theoretical lessons, a hybrid approach with face-to-face sessions complemented by asynchronous virtual tools proved to be advantageous. This allowed students the flexibility to review lessons at their convenience. Regarding practical work, a preference for face-to-face instruction was noted, as it facilitated hands-on experience in laboratories with real equipment and samples. However, it was found that the simulation software for gas and liquid chromatography equipment allowed the incorporation of valuable experiences for the study of both methodologies without extending the time required to carry out the practical work or requiring new inputs.

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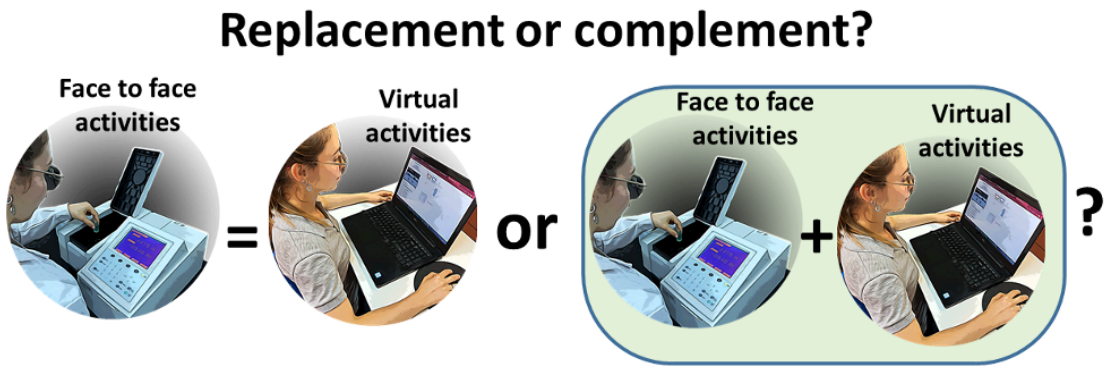
Graphical Abstract



Introduction

At the National University of Luján, Argentina, analytical chemistry courses traditionally followed a classroom format, given the emphasis on intensive practical training within their curricula. Graduates from these courses are expected to possess knowledge and skills applicable to implementing instrumental techniques, requesting analytical determinations from third parties, interpreting analytical results, and demonstrating proficiency in laboratory procedures, instrument operation, data analysis, and error identification[1]. Additionally, adherence to quality, safety standards, and sustainability principles in the laboratory is integral to their education. Achieving these objectives is heavily reliant on hands-on laboratory practices[2][3].

Both virtual and face-to-face education in analytical chemistry present distinct advantages and drawbacks. Virtual education offers the flexibility of remote learning, eliminating the need for physical presence, reducing travel-related constraints, and accommodating diverse schedules. This mode of instruction can leverage technology to simulate laboratory experiments, fostering a dynamic and interactive learning experience. However, drawbacks include potential challenges in replicating the hands-on, tactile nature of laboratory practices virtually, limiting students' direct engagement with real equipment and samples. On the other hand, face-to-face education in analytical chemistry allows for hands-on experiences, immediate feedback, and direct interaction with instructors and peers, promoting a collaborative learning environment. Nevertheless, it may pose logistical challenges such as commute

time and the need for dedicated laboratory facilities[4][5][6]. Striking a balance between these modalities, harnessing the strengths of each, could yield a comprehensive educational approach that combines flexibility with practical, experiential learning in analytical chemistry [3][7][8]. However, some questions arise that must be answered: how do we integrate both modalities? How can we assess if their integration was successful? In an attempt to answer these questions, we decided to make a comparative evaluation of the pedagogical tools implemented during the pandemic period (March 2020 to December 2021), selecting the most appropriate ones for teaching analytical chemistry in classroom conditions, considering the advantages of face-to-face and virtual modalities. The opinions of the students and the experience of teachers were considered, who made a critical evaluation considering factors such as complementarity or redundancy of each activity and the importance of the knowledge provided by virtual practices that were complementary.

Course Description

Analytical chemistry II and instrumental analytical chemistry are included in the curricula of Food Engineering and Biological Sciences, respectively. They are four-month courses taught in the fifth and seventh semester of each degree course, respectively, the first has a weekly load of 6 hours (96 total hours) and the second of 4 hours (64 total hours). In analytical chemistry II there are 10 practical activities, and in instrumental analytical chemistry 6. In the last 6 years, the average number of students taking the subjects was 21 in analytical chemistry II and 5 in instrumental analytical chemistry, with small variations over the years. The teaching group responsible for both subjects consists of two professors and five teaching assistants.

Traditional Analytical Chemistry Lessons

Historically, analytical chemistry courses in our university have been taught face-to-face. The theoretical lessons consisted of classroom activities where the teacher explained the contents assisted with the most appropriate didactic resources for each case, such as the blackboard, slides or videos. The teacher encouraged the students to participate by suggesting solving problems, answering doubts and questioning the audience. Students were also encouraged to read specific bibliographies. In the practical lab work, students prepared their samples, operated the equipment (in those cases in which due to the greater complexity, they were operated by the teachers), obtained and treated the analytical data to obtain results. All practical work was complemented by solving problems and questions. During the course,

there were two classes that differ from the rest. The first and the last; the first consisted of the theoretical explanation of the fundamentals of the analytical process and included the resolution of exercises. In the last class, a workshop was held where students must present a problem related to their future professional field. This problem had been assigned to them beforehand, and its resolution was done as a group. The practical work performed were shown in Table S1 and the practical work guides could be found in the supporting information (SI). The guidelines for practical work are inspired by the protocols that, according to the standards in Argentina, analysts must follow. We understand that by using them, there is no opportunity to learn how to decide in case the conditions do not match those described by the protocols. It might be interesting to involve students in the creation of a protocol.

Each analytical methodology studied was evaluated in written exams. The mid-term evaluations inquired about the fundamentals and practical details of each methodology used in the practical work, while the final evaluations included more theoretical aspects of the analytical methodologies as well as applications or methodological variants different from those implemented in the practical work.

The university's virtual classroom (Educativa™, virtual campus 14) was used as a means of asynchronous communication with students and as a means of accessing or sending files.

Online teaching modality

In the online teaching modality, the theoretical lessons were given in asynchronous format and consisted of slide presentations with audio or video explanations prepared by the teachers. In order to replace practical work, asynchronous activities included questions and problems with experimental analytical data processing, videos of experiences carried out by the teachers, and analytical instrumentation simulation software with free access and available on the Web were offered. Weekly synchronous meetings were held through platforms (Zoom® or Google Meet®) where teachers explained, solved exercises, and answered questions. The activities performed were shown in Table S1 and the guides could be found in the SI. The virtual practical activities made it possible to demonstrate the theoretical principles and certain applications of analytical methodologies. However, the learning objectives that required face-to-face attendance, like the acquisition of individual skills necessary to perform in an analytical laboratory, were not achieved. These skills could only be acquired through the development of hands-on-experimental activities, such as the treatment, preparation and analysis of samples and standards, as well as the observation and handling of equipment, which allowed recognizing them in their totality, understanding their components, care and dimensioning the complexity of their use.

The examinations were designed to be solved individually and virtually. For the resolution of the written mid-term exams, it was allowed the use of the didactic materials used in the course. Several questions were created for each topic and each question was randomly distributed among the students to minimize the possibilities of information exchange. Each statement was sent in an individual e-mail and after receipt of the answer the next question was sent. The final exams were conducted orally synchronously using virtual platforms and consisted of an integrative evaluation of contents. For its development, a short text was sent by e-mail that stated an initiating topic consisting of an analytical problem related to the professional field of each career. Students were allowed to elaborate on their answers for 30 minutes. After that time, the exam consisted of a presentation by the student and questions from the teachers on that or other topics included in the syllabus.

The virtual classroom was used as a means of asynchronous communication and of accessing and/or sending electronic materials. Videos were shared through the YouTube® channel (https://www.youtube.com/channel/UCNOrAatXVruVV4v_m83idjA).

Hybrid modality

Once we evaluated the two modalities in which the course was delivered, we decided to extract the most valuable aspects from each modality. The teaching group, considering their experience and the opinions of the virtual students, evaluated the face-to-face and virtual activities, comparing advantages, disadvantages and possible complementarity, in order to improve the teaching process through a hybrid regime. The flow of tasks performed is shown in Figure 1.

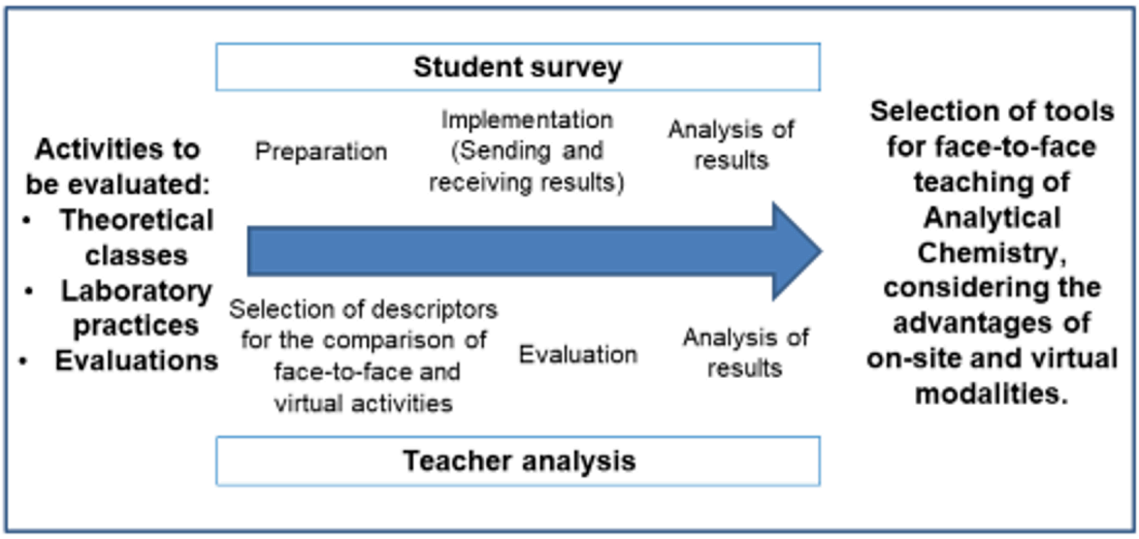


Figure 1. Flow of tasks performed for the evaluation of face-to-face and virtual teaching activities to be implemented in a face-to-face regime

Student survey

This survey was conducted among students who took the courses in the years 2020 - 2021 using the online software Google Forms®. The questions were generated considering all the pedagogical tools implemented in virtual teaching, [9][10] and the preferences in the different teaching activities compared to face-to-face teaching. The question asked about synchronous virtuality, asynchronous virtuality or their combinations. Finally, students were asked about the most efficient examination modality to demonstrate the acquired knowledge. The survey and informed consent were carried out with the endorsement of the Bioethics Committee of the National University of Luján. These documents are available in SI. All students who completed analytical chemistry II (n: 36) and instrumental analytical chemistry (n: 13) during 2020 and 2021 were invited to complete the survey. Thirty responses were received (61% response rate). Responses were analyzed as a whole, without discriminating by subject or career.

Figure 2 showed student preferences for the different didactic activities varied for each type of activity. Most students (43%) preferred face-to-face + asynchronous virtuality for theoretical lessons due to the availability and accessibility of lessons (90%); interaction with teachers (80%), greater convenience (70%), interaction with peers for group study (50%) and travel time and/or cost (50%). Regarding laboratory practices, most students preferred face-to-face format, since they preferred working in a

laboratory with real instruments and equipment (95%), better acquisition of knowledge and skills (90%), and better interaction with teachers (60%). Regarding the usefulness of the didactic tools used during isolation in the development of the practices, the following were highlighted: use of equipment simulation software (80%), solving application problems on concepts studied (70%), questionnaires and study guides (65%) and videos of laboratory experiences (60%). Only 15% highlighted the usefulness of critical reading of scientific work. Finally, the preferences in the examination mode were varied and there was no significant difference among the different condition since they preferred the possibility of consulting teachers about the statements (55%), connectivity problems or complications in assembling and/or sending the files with the answers on time (50%), more comfortable in the way they were assessed (48%), higher concentration (45%) or exam type more adequate with subject content (40%). Only 26% justified the chosen modality by indicating that the statements were usually easier to solve.

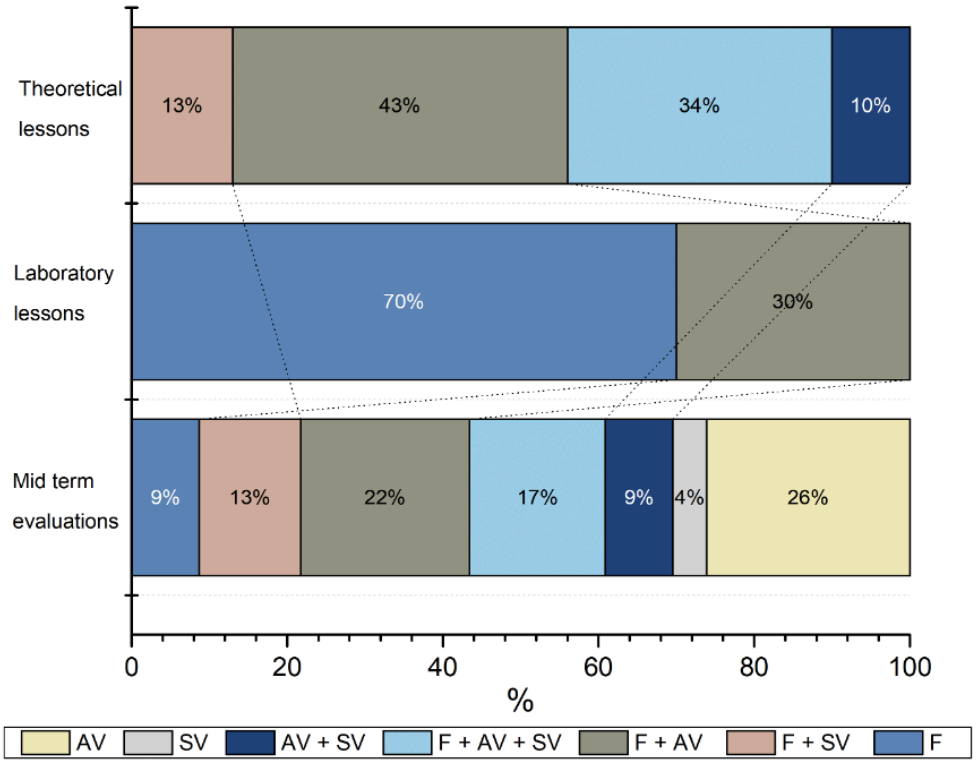


Figure 2. Students' preferences for the different teaching modalities implemented in analytical chemistry courses. Ref: AV: Asynchronous virtuality; SV: Synchronous virtuality; F: Face-to-face

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Assessment of activities by the teaching team

Theoretical lessons. The face-to-face and synchronous and asynchronous virtuality modalities were compared, considering the possibility of interaction between students and teachers, the students' preferences and the difficulty of coordinating the activities of synchronous virtuality in a face-to-face mode. Finally, it was concluded that face-to-face and synchronous virtual lessons were equally suitable, although the former was preferred by teachers and students, and the use of videos or slides with audio of each topic was proposed as non-compulsory complementary material. We perceived favorable changes in the students after implementing the face-to-face lessons lessons and the possibility of viewing the recorded classes. Attendance in face-to-face lessons did not decrease compared to previous years, and students participated more actively by answering the teacher's questions and asking questions and showed less concern about taking notes. Besides, since the theoretical foundations were stronger; we have been able to ask them to solve practical situations that they may encounter in their professional lives during exams.

Practical Activities. The comparative evaluation of face-to-face, synchronous, and asynchronous virtual activities was carried out for each practical assignment. For workshops, the same criteria used for theoretical lessons was applied. It was concluded that the workshops covering basic aspects of the analytical process and on the integration of analytical techniques could be conducted in either face-to-face or virtual modality.

The teaching group, drawing from their own experiences, insights from other educators[11], and student feedback, decided to prioritize face-to-face laboratory work. Subsequently, an evaluation was conducted to determine if each virtual practice, whether as proposed or with modifications, could complement the face-to-face activities by addressing theoretical concepts or methodological applications crucial for student training. The possibility of restructuring the laboratory work was considered, ensuring that the total completion time did not exceed the established 4 hours in the subject syllabus. The evaluation details for each practical laboratory work can be found in Table S1.

It was determined that the simulation software for fluorescence, conductometry and gas and liquid chromatography equipment allowed complementary experiences to the hands-on activities, but not the ultraviolet-visible spectroscopy software, being a widely used technique in food quality control laboratories, we considered it crucial that our students not only understood its principles but also become familiar with its practical application. The latter aspect may not have been achieved through the use of a

simulator. While the simulator could serve as a complementary tool, we prefered to focus on both sample preparation, dilution procedures, and the actual operation of the equipment due to time constraints during the class. On the contrary, we decided to use the gas and liquid chromatography simulation software, because they illustrated and improved the understanding of complex theoretical concepts for the students and were valuable for their knowledge of the methodology, while the fluorescence and conductometry software were not incorporated because its contribution is scarce and it required training in the use of the software. The sample preparation and atomic absorption spectrometry videos were considered useful as additional optional material for the students, since they would be able to perform these experiments hands-on in the laboratory. Having videos demonstrating the activities could serve as a valuable tool for providing an overview of the tasks to be performed. This could help optimize time during practical work or serve as a means to review the procedures after completing the practical session and before an examination.

The modifications made in the liquid and gas chromatography laboratory classes were quite similar, in both cases the students operated the simulation software while waiting for the development of each chromatography. To use the simulators, first of all, the students were guided by providing them with the parameters they needed to enter in order to observe the various results obtained under different conditions and to relate them to the theory. The used parameters could be found in the guides in the SI. Then, they were encouraged to change the conditions as they preferred and even suggested increasing the resolution of chromatograms that had very low resolution. In general, the students were able to correlate how the efficiency of a chromatographic run is modified by altering different parameters and how varying them could enhance the resolution.

We considered that the incorporation of the simulation software to the classroom work was very valuable because it allowed demonstrating and improving the understanding of instrumental variables that were only explained in the theory and were important for the knowledge of chromatography. They also perceived greater interest and attention from the students, probably due to the elimination of downtime during the performance of the chromatographies and optimizing the use of time. Previously, these breaks during chromatography runs might have facilitated important conversations. However, using simulations made new situations pop up that didn't come up when doing only hands-on- experiments, which led to a richer discussion, as it not only covered the use of the equipment and the protocols to follow, but also allowed for imagining different scenarios in which various strategies were devised to achieve greater efficiency. Another advantage that we found regarding the incorporation of simulators is

that students can modify variables that they couldn't during hands-on-experiments due to time constraints or lack of necessary resources. We also emphasized the utility of these software tools for acquiring knowledge about chromatographic columns. By using them, students could simulate situations they may encounter and choose the most suitable column for their needs. In addition to meeting the proposed curriculum, this type of activity succeeded in making students more motivated. This became evident through increased participation, likely because they became more engaged in problem-solving and placed more emphasis on possible scenarios in their future professional development. As an example, Table 1 describes the liquid chromatography practical laboratory work before and after the modification.

Assessment of learning outcomes. Considering their experience and that of other researchers [12], the teaching group understood that it was necessary to implement an examination system that included all instances of learning the subject. In the practical activities, the assessment included an interrogation prior to the laboratory experience and the completion of a final report.

The teaching group considered it appropriate to carry out individual mid-term and final examinations with answers to be developed, prioritising questions aimed at assessing understanding, analysis and application of knowledge and avoiding memoristic or repetitive questions. For the selection of the most suitable modality (face-to face or virtual), student preferences, simplicity in the evaluation process (including the elaboration of the statements, student access to the statements, assembling the responses, delivering the resolved evaluations, and correction), and the lower possibility of exchanging information between students or accessing other online sources of information such as artificial intelligence chatbots were taken into consideration [12]. Following the above analysis, it was decided to conduct face-to-face examinations. The mid-term exams were written and asked about the fundamentals and practical details of each methodology used in the practical work. The final exams maintained the integrative oral assessment similar to the one implemented during the isolation.

	Tradicional education	Online education	Hybrid education
Theoretical explanation	Face-to-face only	Virtual (Pre-recorded video)	Face-to face and virtual (Pre-recorded video)
Development of the practical work itself	Students determine the content of sorbate and benzoate in beverages by reverse phase chromatography with isocratic elution and uv-vis detection. They identify equipment components, prepare, load and inject standards and samples, analyze chromatograms and process analytical data. *Activity in waiting times during chromatographies*: Teachers answer theoretical or theoretical-practical HPLC questions. Eventually, doubts on other subjects are answered.	Working with high-pressure liquid chromatograph simulation software, students quantify a mixture of organochlorine pesticides, then modify parameters such as solvent polarity, compare isocratic elution versus solvent gradient, column length and stationary phase particle size. Conclude after each modification.	Students determine the content of sorbate and benzoate in beverages. They identify equipment components, prepare, load and inject standards and samples, analyze chromatograms and process analytical data. *Activity in waiting times during chromatographies*: Working on a simulator, students modify parameters such as solvent polarity, isocratic vs. gradient chromatography, column length, and particle size of the stationary phase. Conclude after each modification.

Table 1. Comparison of the activities performed in the HPLC practical laboratory work

Discussion

Several authors commented on the advantages and disadvantages of distance education [12][13][14]. Advantages included the promotion of autonomous learning, greater independence in managing time and places for learning, and reduced educational costs. Disadvantages included isolation and limitations in students' socialization with teachers and peers, the need for connectivity, availability of electronic

devices, and adequate physical space to perform the activities and achieve the appropriate concentration level.

In this study, students and teachers expressed a preference for face-to-face activities. Students stated that their preference for this format was mainly due to greater comfort and interaction with the teaching group and with their peers. But they also stressed the importance of the availability of recorded face-to-face lessons and the possibility of subsequent viewing (asynchronous virtuality). We preferred face-to-face lessons since the contact with the students allowed us to better assess the degree of understanding of the audience and improve interactivity, which was impossible in asynchronous activities and difficult in synchronous lessons because the students kept their cameras turned off.

The importance of face-to-face practical work in chemistry education has been repeatedly mentioned in literature [15]. The main disadvantage of virtuality is that students did not develop hands-on skills related to technical performance in an analytical laboratory and because they did not have direct interaction with the equipment, they may feel some frustration for not having processed real samples or obtained their own data. Finally, the need for laboratory practice in analytical chemistry will vary according to the field of work of the graduates of a degree program. In food engineering and bachelor's degrees in biological sciences, it will be of vital importance because graduates may work in analytical laboratories and require intensive practical training.

Virtual practical activities are a valuable alternative when: 1. the institutions do not have adequate resources to carry out hands-on experiments, either due to space limitations, lack of instruments or necessary supplies, or when there are no safety conditions for the students[16][17] 2. The experiences require long periods of development [18] 3. Emergency situations arise where students are unable to attend the educational institution. 4. They complement hands-on lab experiments[2][3]. In this sense, we concluded that simulation software can be a very useful complementary tool for the face-to-face laboratory work because it allowed the incorporation of activities that exemplify experimental conditions different from those of the practical work that were not previously included due to lack of time or resources. The integration turned out to be very positive for both students and teachers because they were seen to be better prepared for practical classes and had a better understanding of the topics in those practical exercises where simulators were used. We also value the videos of experiences as complementary resources that are not compulsory. Finally, we decided to use the virtual practical activities designed during the isolation, in special situations such as student absences or unscheduled suspension of classes.

Conclusions

The transition from traditional face-to-face instruction to a hybrid education model, incorporating both virtual and in-person activities, has been a noteworthy evolution in the analytical chemistry courses at the National University of Luján. The exploration of virtual tools during the pandemic-induced shift revealed valuable insights into the strengths and challenges of each instructional modality.

Reflecting on the experiences gained, the teaching group recognized the merit of integrating both virtual and face-to-face components for a comprehensive analytical chemistry education. Through a comparative assessment of teaching tools, it was evident that a blended approach is pivotal in the current educational landscape.

The study found that for theoretical lessons, a hybrid approach with face-to-face sessions complemented by asynchronous virtual components proved advantageous. This allowed students flexibility in reviewing lessons at their convenience. On the practical front, face-to-face instruction remained preferred, providing hands-on experiences in laboratories with real equipment and samples. However, the study demonstrated the effective use of simulation software for gas and liquid chromatography equipment, offering valuable experiences without extending the time required for practical work or necessitating additional resources.

Student preferences, as indicated by a survey, highlighted the importance of a balanced approach, with most favoring a combination of face-to-face and asynchronous virtuality for theoretical lessons. In practical activities, a clear preference for face-to-face formats was observed, emphasizing the significance of hands-on experiences in laboratory settings.

The integration of simulation software into laboratory work was deemed valuable by both students and teachers. It not only allowed for a more engaging and dynamic learning experience but also opened avenues for discussions on various scenarios and strategies, enriching the overall educational discourse. The simulations provided students with the opportunity to modify variables and explore situations that may not be feasible in traditional hands-on experiments.

In conclusion, the hybrid education model, carefully designed by considering the strengths of each modality, emerged as an effective approach for analytical chemistry education. The findings of this study contribute valuable insights into the nuanced balance required to achieve an optimal blend of virtual and face-to-face instruction in the pursuit of comprehensive and engaging learning experiences.

Supporting Information

The Supporting Information is available in the Supplementary Data section of this article and can also be downloaded here. The endorsement of the bioethics committee and the practical work guides are available in the supporting information.

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Declarations

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