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Problem-Based Learning in Graduate and Undergraduate Chemistry Courses: Face-to-Face and Online Experiences

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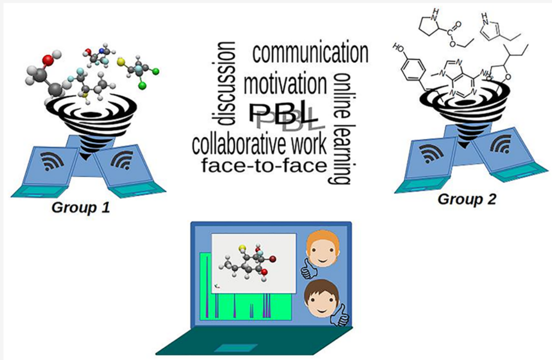
ABSTRACT: The problem-based learning (PBL) methodology has been applied in a set of chemistry courses at the University of Barcelona to determine the main factors that are relevant to a satisfactory application of this educational approach in different contexts (from undergraduate to master subjects). The exceptional situation resulting from the COVID-19 pandemic has also forced us to adapt this methodology from the traditional face-to-face modality to an online version. Thus, the resulting comparative study has allowed us to identify the main aspects of each subject, student background, and modality used, which are relevant to a satisfactory application of PBL. In general, the application of the PBL methodology using Moodle and BBCollaborate as live teaching platforms has a positive impact on student learning and satisfaction. Interestingly, although the face-to-face implementation is preferred to the online modality, students evaluate positively the application of online PBL with respect to the traditional online teaching. Thus, the intrinsic characteristics of PBL, which enhance the learning motivation with suitable problems to be solved in groups, makes this required collaborative work a key point to facilitate student learning.



KEYWORDS: *Problem-Based Learning, Chemistry, Online Learning, Face-to-Face Learning, Undergraduate, Master, COVID-19*

■ INTRODUCTION

Problem-based learning (PBL) is a teaching methodology intended to increase the understanding and knowledge of students on a certain subject by facing the resolution of a practical problem by themselves.[1−3] In traditional teaching methods, students tend to adopt a passive role, with the information mainly flowing from the teacher to them. Usually, the theoretical concepts are first exposed in the classroom and then they are applied in the resolution of the proposed problems. The aim of solving problems is not merely to apply the theoretical concepts but also to better understand them through their use. In complex problems, the resolution arises from a sequence of simple steps. The choice of each step is derived from a decision-making process between different alternatives, which are derived from the problem definition and the results obtained in previous steps. When the problems are directly solved by the teacher, the student follows the exposed solving path, often getting the impression that it is self-evident. In this scenario, students are not forced to think deeply after each step about the different alternatives and the choice of the best one.

PBL stimulates the active role of students by involving them, in a collaborative way, in the problem resolution. It consists basically in proposing a problem and, after some initial guiding, letting students lead the way to solve it autonomously within a reasonable time. Students can access to information sources at their disposal, a valuable opportunity to improve skills in information management and selection.[4−6] During the resolution of the problem, the students have the assistance of teachers, whose task is to discuss the questions raised that could help solving the problem but not to solve it directly. This assistance is helpful in two senses: to provide some guidance to the students and to avoid their demotivation if they feel that they are in a dead end. An important aim is that PBL sessions should be able to engage both the brilliant students and those who have more difficulties.[5]

PBL can be easily applied to work in groups. It promotes collaborative learning peer-to-peer, where students teach each other through discussion. Besides, it helps to develop oral

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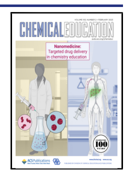

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Table 1. Main Features of the Face-to-Face PBL Implementation

subject	degree	type of subject/credits	students	PBL working groups	number of PBL problems	duration of each session (h)	time between sessions	evaluation
Computing Resources (CR)	Chemistry	compulsory second semester 6 ECTS	20−30	6	6	2	1/2 week	oral presentation and report
Physical Chemistry II (PCII)	Chemistry	compulsory fourth semester 6 ECTS	70−80	13	1	1	consecutive days	related questions in the final exam
Spectroscopy and Laboratory Techniques in Organic Chemistry (SLTOC)	Organic Chemistry Master	compulsory 6 ECTS	20−30	6	6	2	1 week	oral presentation, report, and final exam
Heterocyclic Chemistry (HC)	Organic Chemistry Master	elective 3 ECTS	20−30	6	6	1	1/2 week	oral presentation and related questions in the final exam

communication and leadership skills, which will be needed in future situations.[5,7−9] The PBL process can be divided into four different stages. In the first stage, students identify what they need to know to solve the problem. At this stage, the teacher clarifies doubts and promotes discussion about the different hypotheses of possible solutions. In the second stage, students, individually, search for information. In the third stage, students join all the information and again, in a collaborative way, discuss about possible strategies to solve the problem. Effectiveness of group-based learning is enhanced by facilitating the interaction between the group members, e.g., by planning intermediate working group sessions to clarify doubts, promoting discussion about theory concepts related to other subjects of the study (which contributes to the curriculum integration of subjects and modules), etc. And finally, in the last stage, the students prepare the solution, that can adopt different formats (oral presentation, report, portfolio, etc.) according to the instructions of the teacher. Grading the students work should include, in addition to the correctness of the problem-solving procedure and results, an evaluation of the individual contribution of each member of the working group. This can be done by a peer-to-peer evaluation, where each of the members marks the contribution of the teammates.[3]

So far, PBL methodology has been successfully applied to both laboratory[10−12] and theoretical[13−16] chemistry subjects. It has been demonstrated that it enhances students' motivation and at the same time improves several important skills such as autonomy, collaboration, critical thinking, oral communication, and self-evaluation among others. However, the COVID-19 pandemic forced many on-site universities to switch suddenly to an online teaching model because the education authorities decreed that almost all classes had to be held online. It represented a huge challenge and effort for students and teachers to adapt to the new situation. Lectures had to take place mainly in a new environment, which in most cases was not tested extensively. Fortunately, many higher education institutions already had at their disposal learning environments to assist distance teaching, like Moodle,[17] but some drawbacks can be highlighted: (1) teachers and students had generally little experience with the required distance learning software; (2) additional software was necessary in order to adapt the teaching material and classes to the new environment; (3) lack of experience of a majority of faculty members teaching a distance course; (4) teaching and learning online makes personal interaction more difficult; and (5) a special commitment is necessary to set a daily routine to follow the courses and deepen into the taught concepts. Although in less extent compared to the most common face-to-face PBL, there are also studies focused on virtual PBL. Some of them were developed before the pandemic situation, for instance, as part of virtual courses.[18,19] In other instances, as is our case, virtual PBL appeared as an opportunity to engage students in an active-learning methodology during the lockdown.[20]

This study aims to explore the experience of applying PBL in a variety of subjects of the Chemistry Degree and Organic Chemistry Master of the University of Barcelona (UB). The teachers involved in this experience have been working together as a PBL team since 2018. Each one of us has applied individually the PBL methodology in our subjects, first in a face-to face version and later in a virtual environment, although the results derived from the individual PBL experiences have been discussed together in the team from different points of view: suitability of the methodology according to the subject, easiness in its application, acquirement of skills, achievement of the learning outcomes, and satisfaction of students among others. The sudden change to virtual teaching allowed for a direct comparison of the results derived from PBL experiences obtained in two different periods and, therefore, two different PBL modalities: before (face-to-face) and during the COVID-19 lockdown (virtual PBL).

■ BACKGROUND

During the last years, a general growing disaffection and apathy of the students regarding attendance and participation in traditional face-to-face classes has been observed. This is particularly worrying in the case of problem classes, which are key for students to assimilate and learn how to apply theoretical content. Traditionally, students are provided with a collection of problems that they should solve individually. Therefore, problem classes should be dedicated to solving selected problems and all the doubts and difficulties that students may have encountered. In practice, only a reduced number of students do the problems before the lessons, which has a highly negative effect in their learning.

In the faculty of chemistry, the implementation of PBL has been considered as a way to involve students more actively in their own learning and to get students to meet the objectives of the teaching plans in terms of the number of non-face-to-face hours (autonomous and tutored work) considered necessary to achieve the learning objectives.

To have a broader view of the effect of implementing PBL, four different subjects were chosen (see Table 1). This selection includes different types of subjects (compulsory versus elective), different group sizes, and students in different stages (degree versus master).

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Table 2. Deficiencies Found in Traditional Learning (left) and Expected Improvements with the Use of PBL Strategy (right)

General • Lack of autonomous learning. • Traditional problems don't compel students to work on them thoroughly. • Students are not used to cooperative group problem solving and tend to give importance only to the final solution. • Little use of the teaching resources and the additional material in the virtual campus. • Passive attitude of the students. Little involvement in problem solving.	• Facilitate the discussion of problems in groups. • Increase discussions with teachers. • Increase students' curiosity and motivation to solve real problems. • Use of other resources to study and obtain information. • Improvement of grades, with a lower rate of fails.
CR specifics: • Many students have not previously used a command-based programming language or molecular construction programs • Difficulty solving problems that require the use of various algorithmic programming structures.	• Develop more complex programs to integrate several programming structures in a single exercise • Design codes that will be applicable to solve relevant chemistry problems. • Combination of molecular visualization with programming tools to analyze relevant molecular properties. • Motivate students to use programming to solve chemistry problems.
PCII specifics: • Inefficient response of the students regarding the identification and resolution of training problems. • Difficulties following the subject (mainly Mathematics and Physics at a basic level).	• Improve the level of student involvement with the subject. • Clarify concepts of the subject through teamwork.
HC specifics: • Classes that list different methods of synthesis are boring.	• Improve retrosynthetic analysis of different targets through team working. • Students are compelled to think about practical aspects of a synthesis other than the chemical reactions involved.
SLTOC specifics: • Heterogeneous profile of previous knowledge, making it difficult to adjust the degree of difficulty of the problems to the needs of all students. • Most students are used to assign NMR spectra, but they have no experience in processing data.	• Carrying out complex problems requiring the use of additional resources and information that may allow each student to adapt the effort according to their previous knowledge. • Integrate "traditional problems" in a format that can incorporate more transversal skills.

The two Chemistry Degree subjects analyzed, Computing Resources (CR) and Physical Chemistry II (PCII), are both compulsory first- and second-year subjects, respectively. At this stage, especially in the case of CR, the students' background has still an important effect on student learning and some efforts need to be carried out to homogenize the level of the class. Two subjects from the Organic Chemistry Master were chosen: Spectroscopic and Laboratory Techniques in Organic Chemistry (SLTOC, compulsory) and Heterocyclic Chemistry (HC, elective). In master subjects, on the other hand, the great challenge is dealing with students having different academic CV or coming from different disciplines. This problem is more pronounced in SLTOC, due to the compulsory nature of the subject. A complete contents index for all the subjects can be found in the Supporting Information.

The goal of implementing PBL in the CR subject is to make it easier for students to analyze, solve, and program practical problems within the field of chemistry, while at the same time being able to understand the power of a programming language. Different PBL problems were developed to deal with molecular construction and visualization, and with the realization of a Python program for the calculation of different molecular properties, such as the identification of functional groups or the calculation of relevant distances. The application of PBL in CR has not implied a reduction of the syllabus. However, PBL sessions have been introduced in exchange for exercise sessions and the elimination of a continuous evaluation test.

Acquiring knowledge at a basic but at the same time rigorous level (first-principles) about the atomic and molecular structure is important in the chemistry studies. This is the main goal to be achieved in PCII, in which the contents of quantum chemistry and spectroscopy complement each other. Given the great difficulty that this subject presents for the

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students, it is considered that the most appropriate here is to place the PBL activity toward the end of the course, once the students have already reached a certain degree of maturity on the most fundamental contents (postulates of quantum mechanics and their application to important physical systems that admit analytical solution). The PBL activity is focused on solving spectroscopy problems. The application of PBL in PCII has not involved a reduction of the contents.

Heterocycles are a very important class of organic compounds, because of their widespread presence in natural products or synthetic derivatives (drugs, organic materials, etc.). In HC, the students are expected to reach a medium level of knowledge of the structure, reactivity, and preparation of the most common heterocyclic systems (see the syllabus for this course in the Supporting Information) that will allow them to understand and solve the problems related to heterocycles they will face during their professional development. The PBL activity is focused on the part of the syllabus that concerns the methods of synthesis of the most common heterocycles (pyridines, diazines, quinolines and isoquinolines, pyrroles, indoles and furans, and thiophenes) and requires a certain skill in retrosynthetic analysis. Although different students work on different heterocycles, the skills on retrosynthetic analysis required are the same. The contents of the traditional course were reorganized (see Supporting Information, Section S3) to better fit the PBL activity. Also, because more time is needed for PBL than for traditional teaching, the discussion of the reactivity of pyrroles and indoles, which is very similar, was condensed into one unit, saving time. If more sessions were to be devoted to PBL, furans and thiophenes could be treated together with pyrroles and indoles, and the chemistry of pyridines and diazines can also be discussed together. The PBL activity is designed as a way to make students work on problems concerning the synthesis of heterocycles.

SLTOC is a subject that brings together different aspects that are important for the initiation of the students for research. One of the blocks of the subject is devoted to strengthening and deepening students' knowledge of the most common spectroscopic techniques in organic chemistry, basically by solving problems. One important task for organic chemists is to analyze the reactions carried out in the laboratory and characterize all the products and byproducts obtained. In this context, it is important that students have a high degree of autonomy in structural determination and the PBL methodology is envisioned as an appropriate tool to reinforce these skills. Along with the PBL sessions, students were asked to solve one or two challenging problems, based on real samples from different research groups from the Organic Chemistry Department. Additionally, other new aspects for the students, such as NMR spectra processing and data treatment, that are difficult to address in traditional problems could also be included in a PBL strategy. The implementation of PBL implied the realization of a smaller number of problems but the development of the classes allowed for addressing problems of greater complexity.

Despite the different nature and contents of each subject, there was a common scenario that motivated the use of the PBL strategy: passive attitude of the students during the sessions, especially in the problem-solving ones; little dedication to autonomous work; little use of the teaching resources provided by the teacher and available in the virtual campus; and little experience in collaborative work. Table 2 summarizes all the deficiencies (common and specific) detected by the teaching team in the traditional learning of the subjects. In the same table, we have summarized the improvements expected as a result of the change in methodology.

■ METHODS

Even though there are obvious differences between these subjects, three of them (CR, SLTOC, and HC) have in common a reduced number of students in class (between 20 and 30), very appropriate for collaborative work in a PBL context. PCII, in contrast, is an overcrowded subject (70−80 students) that requires an especial effort for managing collaborative work. PBL experiences were designed to be developed in 3−4 teaching sessions. In general, the number of students in the PBL working groups was about 3−6 in order to encourage collaborative work. This implied 6 working groups in all the subjects except for PCII, which had 13 working groups.

As mentioned in the introduction, the role of the teacher in the PBL method is to facilitate the learning process rather than to provide knowledge. First of all, the teacher has to prepare a collection of problems so that the resolution covers the concepts to be taught. This is one of the most difficult and time-consuming parts of the PBL process, since all problems must be equivalent in terms of learning outcomes. In addition, problems should be based on real cases to catch the attention and increase the motivation of students. Once the problems are delivered to students, the role of the teacher is to clarify doubts and to facilitate discussion about the different hypothesis between the students. Finally, the teacher has to evaluate the success of resolving the problem and the acquired skills and competencies.

The following section will explain in detail how PBL has been implemented in each of these subjects, first in a face-to-face modality and, subsequently, how it has been adapted to online requirements during the pandemic period. In all cases, the PBL experience was continuously followed by the PBL team: the activities were discussed between us before the implementation, when PBL was first applied in one of the subjects the rest of the team attended the activity as neutral observers, and afterward the team gave feedback to the corresponding teacher, followed by discussions to improve the experience. However, it has to be mentioned that the design of the methodology was markedly influenced by the curriculum of the degrees.

First Experience: PBL in Face-to-Face Modality

In the first session, the teacher explained how the activity would work, the problems were given to the students, and each group initiated a discussion about how to solve it. Also, in this first session the groups designed a plan to solve the problems and distributed the tasks related to the search of information among the members. Since that moment, students initiated individual work, mainly focused on obtaining the required information. In the following sessions, each member shared the information with the rest of their colleagues in the group, and once all information was put together, they discussed their findings for solving the problem. In most cases, the last session of the activity was used to share the solution to the problem with the rest of the groups through an oral presentation followed by a small discussion with the teacher and the rest of the students.

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Apart from the oral presentation, the PBL activity was evaluated by other means, such as written reports or questions related to the learning outcomes of the problems in the final exam (see Table 1). It is worthy to point that the PBL evaluation can be conditioned by the singularities of the subjects. In the case of the compulsory subjects of the Chemistry Degree, for example, different groups of the same subject are taught along the semester (different teachers and teaching methodologies) and share the same final exam. Master degree subjects, however, do not have this limitation.

In the Computer Resources subject, prior to the implementation of the PBL methodology, the students performed exercises of the different blocks of the subject individually. These exercises were relatively simple, with the aim of understanding the application of the different programming structures. However, more complex exercises that integrated the use of the programming structures of different blocks of the subject were normally not done, so this was the objective of the PBL activity. It started delivering to the students a single Jupyter notebook with the statements of all the different PBL problems. Thus, all students had the problems assigned to the rest of the groups. Although different, all the problems followed the same structure of three sections of increasing complexity. Some of these problems can be found in the Supporting Information, together with the steps needed to solve them.

In the first PBL session, students started building different molecular structures. The second and third sessions were used to develop the program. Depending on the exercise, a Python code should be developed to determine the number of specific functional groups, determine the dipole moment, compute specific intramolecular distances, or to virtually mutate hydroxyl groups into thiol groups for a set of molecules. In the last session, the students made an oral presentation, explaining the different parts of the code responsible for solving each of the problems raised in the three sections of the exercise. The presentation slides were made available to all the groups through the virtual platform. This was helpful for students, since they used their own but also other group's materials to prepare the final test of the subject.

Given the great difficulty that in general PCII presents for the students, the PBL activity was carried out during the last module of the course, which is mostly dedicated to the fundamentals of molecular spectroscopy. In this way, the students show already a certain degree of maturity in the subject. Due to the high number of students enrolled in the subject, the same pedagogical activity was considered for all the student groups. The activity consisted on a series of small problems connected to each other sequentially that illustrate the main concepts of spectroscopy, starting from the electric dipole selection rule and ending in the electronic spectroscopy of diatomic molecules. To solve these problems, the students had to look for information directly made available by the teachers of the subject (lecture notes and other documents in the virtual campus). After the introduction to the activity, students, working in groups, dedicated three consecutive days (1 h sessions) to solve the problems, and at the end of each session, a small general discussion was made. Assessment of the PBL activity was done through questions in the final exam. The experience was positive, although only 3 sessions were not enough for the groups to solve the full set of problems. As these sessions were in consecutive days, the students barely had time to work on the PBL activity outside the class time.

In HC, the PBL activity focused on the synthesis of the most common heterocycles. Its main purpose was to improve the ability of the students to design routes for the preparation of simple, but useful, heterocyclic compounds, using the methods described in the literature. It was decided beforehand that each group of students would be assigned a different set of problems, in order to avoid collaboration between groups. Ideally, all the problems should have the same level of difficulty, to avoid differences between groups. Also, to make them attractive to the students, they were designed to be similar to real-life situations, resembling questions that the students are likely to be asked to solve in their future jobs. Examples of these problems and the steps needed to solve them can be found in the Supporting Information. Most of the problems tackle the synthesis of a marketed compound (Daraprim or Nifedipine, for example), and the students are expected to perform a full retrosynthetic analysis, discussing which of the different methods of synthesis of this type of heterocycle is most suitable. Sometimes they are asked to consider aspects such as availability and price of starting materials and reagents, practicality of the synthesis, etc.

During the first session, the problems were assigned to each group and the students were informed of how the activity would work. Then, the groups started to work, discussing the problem and planning the steps necessary to solve it. The teacher was at hand to solve any doubts that might arise. In the second session, the students continued to work on their problems, with the teacher helping them when needed. In the third and fourth sessions, each group gave an oral presentation discussing the solution of their problems to their classmates. This final activity was designed to allow the rest of the groups to learn about the synthesis of types of heterocycles different from the one they had been working on.

Apart from the final presentation, assessment of the PBL activity was performed through several questions included in the final exam. An average grade of 7.5 out of 10 was our goal, as it would mean that the students have the knowledge required from such a course and it would represent an improvement from courses with no PBL.

Once the activity concluded, the students were asked to fill out a survey about the development of the activity. In general, the students were satisfied (evaluating the activity with a 7 out of 10), though they raised a few points of concern. Although they believed that with the PBL strategy they learn the methods of synthesis of the heterocycles assigned to them more deeply, this was not the case for the heterocycles assigned to other groups. They clearly preferred the presentation of the teacher on these concepts rather than the oral presentations given by their fellow classmates. This can be solved by designing problems for each group that, although different, work the same concepts. Also, the workspace turned out to be important. The students stressed the importance of a comfortable working space to work. All these points were to be addressed in the next implementations of the PBL strategy, during the 2020−2021 academic period.

In the case of STLOC, PBL sessions were programmed for the students to solve complex problems based on real samples from different laboratories of the Organic Chemistry Department, similar to those that most of them will have to synthesize during their final master's thesis. Most of the compounds were organic products of small to medium size, but small biomolecules (peptides and nucleic acids) were also included. In order to cover a wide range of different products, a different problem was given to each group, and to go a little bit further than simple assignment, students were provided with a zip file containing all the spectroscopic data. During the first session, students had to obtain suitable processed spectra (as those shown in the Supporting Information) and start the assignment work. In the second session, they continued with the assignment and discussed the possible compatible compounds oriented by the teacher. During the third and fourth sessions, each group performed an oral presentation to explain the resolution process and give their final solution. Additionally, each group handed in a report, which was also published for all the students. All these contents allowed the students to see how to proceed depending on the nature of the compound, instead on having only their own experience.

The level acquired by the students was assessed in a final exam in which they had to solve a structural determination problem of the same type as in the exams using the traditional methodology. In this way, it was possible to compare the grades obtained with PBL with those of a previous course without PBL. The main objective was to improve the marks of all the students and, above all, to reduce the percentage of students who were unable to solve the problem and pass the course.

As in HC, students were globally satisfied with the PBL experience (evaluating it with a 7 out of 10), but they are used to greater teacher participation in classes and do not value so positively having such an active role in the search for information and problem solving. Moreover, they found the oral presentations time-consuming with little effect on the learning process.

Second Experience: PBL in Online Modality

In the 2020−2021 academic year, due to the COVID-19 pandemic scenario, it was not possible to carry out a face-to-face PBL for most of the subjects. PCII, SLTOC, and HC were taught 100% in the online modality, and only CR could be taught semiremotely. In this latter case, half of the students were in the classroom and the other half at home. However, they changed modality (face-to-face/online) in each consecutive session.

In order to keep the same guidelines, important changes were required to ensure the collaborative work of students in reduced groups and the proper communication with the teacher. For this purpose, the BBCollaborate (Blackboard Inc., versions 19 and 20) platform,[21] accessible to all students through the virtual campus (Moodle platform, versions 3.4 to 3.9 of Open LMS)[17] of the subjects, was used. Generic rooms (with access to the teacher and all students) were created for each session, coinciding with the subject timetable. Additionally, parallel BBCollaborate sessions were created for each one of the PBL groups to provide each group with a virtual space in which to meet and work collaboratively. BBCollaborate sessions corresponding to each group remained open and accessible throughout all the PBL activity. In the class sessions, once all the general aspects had been discussed in the generic room and the problems had been assigned, each group could connect to their own session and work as they would have done in a face-to-face session. Establishing a good communication among the students working in the same group and also with the teacher was in fact the main challenge of online PBL. The teacher entered these classrooms, in turns, to supervise and answer any questions the students had.

CR was the only subject taught in a semiremote mode. Although all generic explanations were given in front of the camera so that both face-to-face and online students could follow it, the PBL sessions were recorded, facilitating asynchronous access to this information. The final oral presentation made by the students of each group was eliminated due to the difficulties encountered in having part of the students in the classroom and the other part connected online. Instead, this session was replaced by a dynamic interview related to the results previously delivered. Questions were directly addressed to the group components either in the classroom or via the BBCollaborate platform for those that were connected online. In addition, students were asked to individually explain the algorithms, programming structures, and main variables used in solving the PBL exercise. As in the face-to-face mode, the works done by the students were uploaded to Moodle so that they were available to the entire class.

PCII was taught 100% online. Considering the previous face-to face experience, the number of sessions dedicated to the PBL activity was enlarged to seven. The first session was dedicated to the introduction to PBL, the explanations on the use of the BBCollaborate environment when working in group, and the delivery of the problems to be solved (six problems, the same for all groups, with some comments of general character on the goals to be achieved). The problems and the steps needed to solve it can be seen in the Supporting Information. In each one of the following six sessions, the groups of students solved one of these problems and, typically, 10−12 min before the end of each session, a student representing one of the groups shared the solution of the selected problem with the other students (the teacher acting as guide and moderator). Just after each one of these sessions, the teacher recorded the solution of the problem in a video of about 15 min so that it was available to the students in a more pedagogical way through the virtual campus.

In the case of HC, in the online implementation, the set of problems was modified to allow each group to work on the six types of heterocycles studied. This time, each team was given a set of six different heterocycles, and a synthesis for each of them had to be designed. This was done in response to the feedback received from the students who took part in the previous face-to-face PBL experience, which stated that the presentations given by their fellows were not an effective way for them to learn about the methods of preparation of a particular heterocycle. In this way, all the groups worked on the synthesis of all the six types of heterocycles studied and presentations, which are time-consuming, could be avoided.

Regarding SLTOC, oral presentations were also eliminated as an evaluation element in the online modality. To share the results of the different groups, a general discussion of the different problems was carried out with the teacher instead.

In all the subjects, evaluation of the online PBL was mainly done through questions related to the learning outcomes of the PBL activity in the final exam.

■ RESULTS AND DISCUSSION

Face-to-Face PBL

Detailed analysis of the activity and of the results obtained in the different subjects allowed us to identify several key factors that are important for its correct development. Probably the most important factor is the student maturity level. Higher levels of motivation and student engagement were observed in master courses, and this may be a consequence of the elective nature of these studies, more in agreement with the preferences of the students, and also of their higher maturity level. In the undergraduate courses, the response was more variable. Another important factor is the number of students in the group, with 20−25 students per teacher (six working groups) being ideal. In this way, the teacher has enough time to interact in a meaningful way with all the groups and assess the progress and performance of each individual student. Larger groups require the assistance of two, or even three, teachers for a correct follow-up. Another important issue is whether to assign the same or different problems to all the groups. In large groups, a single problem for all the class appears convenient, since it facilitates the discussion between the teacher and the students and avoids the need to create a very large number of similar problems, which is time costly. However, exchange of information between groups is difficult to avoid. Two-hour-sessions are preferable to one-hour ones, since the teacher has more time to follow-up the progress of all the groups. The time between sessions is also important. Sessions on consecutive days do not give the groups enough time to work outside of the classroom session, but 2−3 days between sessions is enough time to observe progress in simpler problems. In complex problems, however, weekly sessions are preferable to give the groups more time to work on their own. Assessment of the learning outcome can be performed in multiple ways. However, when students are asked to deliver a written report or to present the results orally to the rest of the class, their performance improves.

As regards the improvements in the learning outcomes, the results obtained were promising. Although only a discrete impact on student grades was observed in undergraduate courses, improvements in student involvement and grades were detected in master courses. For example, Figure 1 shows

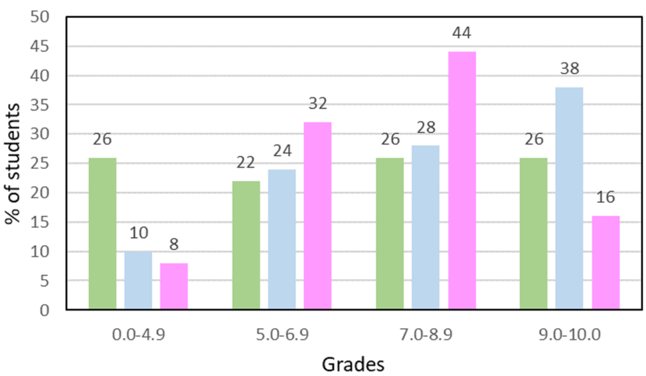

Figure 1. Distribution of students according to the grades obtained in the final exam of SLTOC without PBL (green), with face-to-face PBL (blue), and online PBL (magenta). Maximum grade = 10; to pass the subject, a grade ≥5.0 is necessary.

that better grades were obtained in the final exam of SLTOC when a PBL activity was included. The final exam is graded between 0 and 10 points, requiring a minimum of five points to pass. The graph shows a global improvement in the percentage of high marks (>7) and, more importantly, a marked decrease in the number of students who are unable to solve a traditional structure determination problem (10% versus 26%). These results show that working on this type of problems with PBL allows students to acquire a better level of knowledge and skills, and brings us closer to the ideal objective that all students taking the master's degree should be able to solve this type of problems.

In HC, the effectiveness of the PBL activity was assessed by comparing the percentage of right answers in three different questions directly related to the content taught using PBL. Table 3 shows that, using face-to-face PBL, the percentage of right answers increased to the expected level (approximately 75% of correct answers) compared to when the same content was taught in the traditional way (Table 3, Q1 and Q2). Also, Table 3 shows that online PBL is not as effective, with percentages of right answers well below the expected 75% and relatively close to the results obtained teaching the content in the traditional way (Table 3, Q2 and Q3).

Care must be taken when comparing the results obtained by different groups because the characteristics of a group can greatly influence the learning outcome. However, in all the subjects examined, improvements were observed when a PBL activity was included in the curriculum.

Table 3. Percentage of Right Answers in Three Different Questions Included in the Final Exam of HC (percentage of correct answers expected: 75%)

%right answers	Q1	Q2	Q3
no PBL	68	52	58
face-to-face PBL	79		71
online PBL		60	60

Online PBL

With the COVID-19 lockdown stopping all possibility of face-to-face teaching in March 2020, universities worldwide had to quickly adapt to online teaching. In our case, we decided to take advantage of the situation and study how the PBL strategy could be adapted to online teaching. As explained in the Methods section, we followed the same approach used for the face-to-face PBL, with the important difference that all the sessions, meetings, and discussions had to be held online. This represents a huge challenge, because an integral part of the PBL activity are the discussions between the members of each group and with the teacher. Several drawbacks of performing this activity online were detected:

- Discussion of the problems within the groups and communication with the teacher is more difficult and takes longer. The teachers must enter, in turns, the virtual classrooms created for each group, and this process is slow. In consequence, there was not enough time to discuss all the questions posed by the students, especially in the 1 h period sessions. This was especially critical in PCII, where the number of groups was very large. It was partially addressed using email as a means of communication outside of class hours. Another hurdle is the difficulty of drawing chemical structures quickly and efficiently.
- It is harder to supervise the progress of the students and the involvement and participation of each student in the work of the group. A lot of information about how the groups work is lost because only one group at a time can be controlled by the teacher, whereas, in the face-to face version, the teacher and all the groups share the same classroom and, while discussing the problems with one group, control of the rest of the groups is not lost. Also,

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not being able to see the students, who in most of the cases did not connect their camera, makes things even harder, given the importance of nonverbal communication, which is lost in online teaching. This was partially addressed with a survey in which each student had to evaluate himself/herself and the rest of the group regarding aspects such as participation, contribution or engagement.
- Students working online tend to participate much less and have a much more passive role, which makes learning less effective.
- More evidence for evaluation is available in face-to-face PBL, such as class follow-up, group discussion, or group-to-group discussions.

One of the subjects (CR) was taught in a semi online modality, as discussed in the Methods section. In this case, actions such as the introduction of the activity, were conducted satisfactorily using a generic virtual room for students working online. However, once the students started working in groups, a biased supervision by the teacher was detected, since less attention was paid to groups working remotely, mainly because the groups in the classroom monopolized the lecturer. Also, a marked difference in the progress of the different groups was observed, with those working online advancing more slowly than those in the classroom.

The results obtained are consistent with these observations. Figure 2 shows that, under similar circumstances, better learning outcomes were obtained using face-to-face PBL compared to online PBL, in three of the subjects studied. This is also shown in Figure 1 for SLTOC, in which the PBL strategy is applied to the whole subject and makes analysis easier. The percentage of students with high grades (>9/10) markedly drops with online PBL compared to the face-to-face implementation. Nevertheless, the learning outcome is still very satisfactory, when compared to the case when no PBL was used: only 8−10% of the students failed the exam using either online or face-to-face PBL compared to 26% when no PBL was implemented.

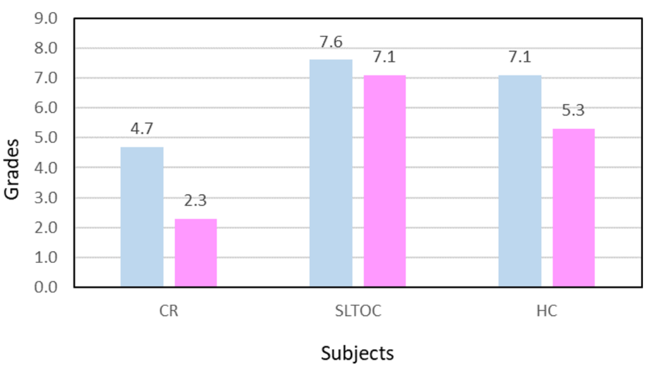

Figure 2. Comparison between the average grades obtained in three of the subjects with a face-to-face PBL (blue) and an online PBL (magenta). These grades correspond only to the learning outcomes related to the PBL exercises (for CR and HC, this represents 10% of the final grade). Maximum grade = 10; to pass the subject a grade ≥5.0 is necessary.

Opinions about the PBL Experience

To obtain the feedback of the students, at the end of each PBL experience, they completed an anonymous satisfaction survey in which they had to evaluate several items. Surveys of the different subjects and experiences have been treated together to obtain general information and also to differentiate the face-to-face and the online modalities.

When asked whether they considered the PBL useful for their learning process, around 50% of the students agreed (grades from 7−10 out of 10), around 32% thought that PBL did not contribute significantly to their knowledge, and only 17% of the students said that PBL did not contribute to their learning process (Figure 3A). A similar rating was observed between the face-to-face and the online experiences. It is surprising that the perception of the students about the improvement of their learning process is more or less the same independently of the PBL modality, when the learning outcomes are clearly better in the face-to-face modality. This is probably caused by the fact that the experience is done every year with different students and, in general, they appreciate this kind of activities and consider them positive for their learning, even the students that have done it online.

When students were asked if they would include more contents of the subject to be worked through this strategy (Figure 3B), again a bit more than 50% of the students answered affirmatively and only 20% said they would prefer the traditional teaching. Here, an important difference between the opinion of students who did the face-to-face PBL or online PBL can be seen. The ones who did an online PBL were the ones more prone to repeat the experience including more contents. This fact points out that the online teaching using traditional learning methods was probably not working satisfactorily. One of the major criticisms of the students regarding the activity (both in face-to-face and online modalities) was that it implied an important workload. However, after the PBL experience, more than 50% of the students would repeat the experience including more contents. This fact reinforces the hypothesis that this type of learning is preferred by the students compared to traditional teaching methods.

Students that did the PBL in online or semiremote mode were also asked about this particular experience. Almost 70% of the students stated that in their opinion the face-to-face mode would have worked better. Only 5% said that PBL in online mode was successful. Here, small differences were detected depending on whether PBL was online or semiremote. More than 77% of the students that coursed the online mode considered that a face-to face PBL would have been better, whereas only 60% of the students in the semiremote mode thought so (Figure 3C). However, when they were asked about the online platform used, 60% agreed that BBCollaborate was a good platform (Figure 3D).

Finally, they were asked to rate the activity in terms of general satisfaction. Almost 70% of the students were satisfied with the experience, regardless of the modality coursed (Figure 3E).

The general opinion of the PBL team is that most of the initial expectations (Table 2) have been fulfilled after these two experiences. Students have been highly motivated during the activity, and working in group has favored discussions within the groups' members but also with the rest of class fellows and the teacher. Through the activity, students have faced more difficult and integrated problems that, after team discussions, have been solved with success. Moreover, if some students had a low level of previous knowledge for a particular subject (as for SLTOC) the team-working strategy allowed these students to achieve a higher degree of comprehension and reach higher

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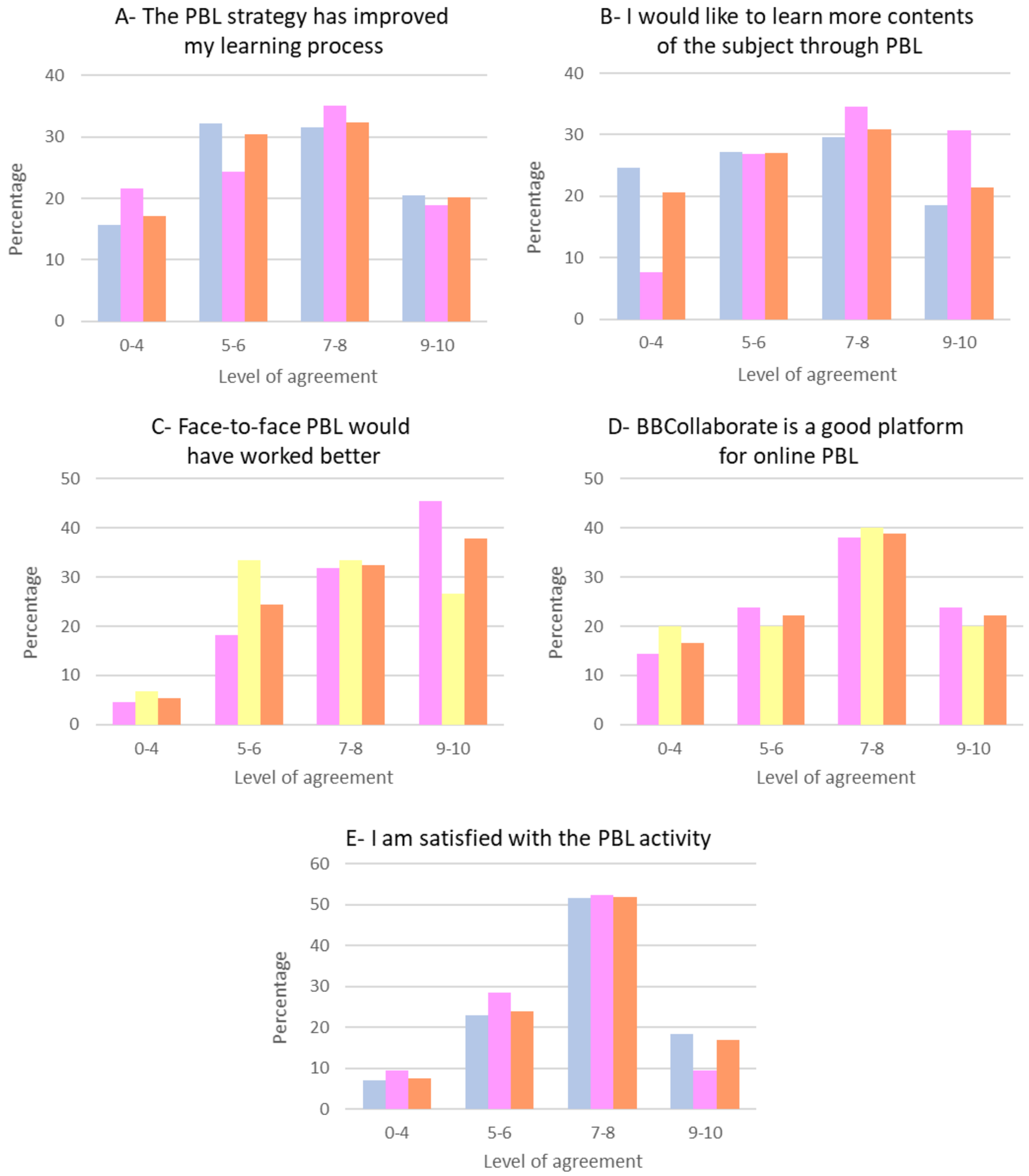

Figure 3. Opinion of students about some key aspects of the PBL experience in different modalities: face-to-face (blue), online (magenta), and semiremote (yellow). Orange bars show the general opinion, independently of the PBL modality.

grades than in traditional teaching methods. In general, a deeper insight into the contents has been achieved and also better grades, especially in the face-to-face mode.

■ CONCLUSIONS

We have studied the implementation of the PBL methodology in four different subjects in the Faculty of Chemistry of the University of Barcelona (in undergraduate and master contexts). These include computer tools in chemistry, physical chemistry, heterocyclic chemistry, and spectroscopic and laboratory techniques in organic chemistry, and we have analyzed the main factors that are responsible for the success of PBL in face-to-face and online formats.

The PBL activities were designed to be developed typically in 3–4 teaching sessions with groups of 3–6 students to encourage collaborative work, independently of the format (face-to-face or online). The implementation of PBL is a way to involve students more actively in their own learning process and, in particular, to increase their learning motivation. In the online modality, the Moodle and BBCollaborate platforms were used.

Compared to the face-to-face implementation, the application of PBL in online format presents some difficulties: (i) discussion about the problems to be solved within the members of the group and communication with the teacher is more difficult and takes longer; (ii) it is harder to supervise the progress of the students and the involvement and participation of each student in the work of the group; (iii) students working online tend to participate less and have a more passive role; (iv) more evidences for evaluation are available in face-to-face PBL, such as class follow-up, group discussion, or group-to-group discussions. However, the teachers' opinion is that, even with these difficulties, better learning outcomes are achieved when PBL is used (even in the online modality).

The comparison of the student satisfaction in both modalities shows that face-to-face implementation is preferred to online implementation, as expected. However, although better learning results were obtained using face-to-face PBL compared to online PBL, students have evaluated positively the application of the PBL methodology in the online version with respect to the traditional methodology adapted to the virtual modality.

Finally, it is worth noting that, in general, students evaluate positively the impact of PBL on their learning process and even suggest that it could be extended to more contents of the subjects.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00741.

Thematic blocks of the different subjects and examples of problem-based learning exercises (PDF)

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Notes

The authors declare no competing financial interest.

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