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Implementation of Problem-Based Learning in Environmental Chemistry

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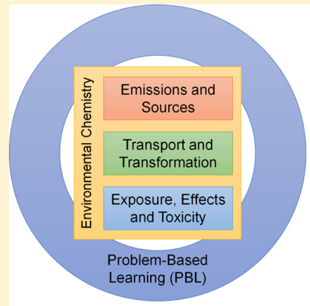
Supporting Information

ABSTRACT: Environmental Chemistry covers a range of topics within the discipline of chemistry, from toxicology to legislation, which warrants interdisciplinary study. Consequently, problem-based learning (PBL), a style of student-centered learning which facilitates the integration of multiple subjects, was investigated to determine if it would be a more appropriate instructional method for teaching Environmental Chemistry than the traditional teacher-centered education model. This article describes the practical aspects of course development and implementation of PBL in a master's level course in Environmental Chemistry. Overall, the results, which were collected from the initial two years of the course, indicated that the students were pleased and found PBL to be an efficient methodology for not only learning, but also acquiring an in-depth understanding of Environmental Chemistry. This is intended as a case-study with the target audience consisting primarily of high school and undergraduate chemistry teachers, but may also be useful for teachers in other subject areas with an interest in student-centered education.



Implementing PBL as teaching methodology in a master level course in Environmental Chemistry, consisting of three main themes.

KEYWORDS: *Upper-Division Undergraduate, Environmental Chemistry, Collaborative/Cooperative Learning, Problem Solving/Decision Making, Student-Centered Learning*

■ INTRODUCTION

"Definitely the PBL. It's a really good way to work!"
"PBL is a very good way for students to study environmental issues. I hope you don't change that."

The two quotes above are course evaluation responses, regarding what should NOT be changed, received from two students after their completion of a 10-week (15 ECTS) master's level course in Environmental Chemistry at Umeå University, Sweden. These responses are indicative of the positive feedback that we obtained from the students after changing the teaching model typically used for this course from predominantly teacher-centered to student-centered by implementing problem-based learning (PBL). In addition to modifying the course to fit the PBL concept, the material, which was originally designed for undergraduates, was adapted to be suitable for master's level education by a teacher team during a course development mission in 2011−2012.

This paper describes the course development process, and the implementation of PBL as a teaching methodology. It also discusses the results and experiences from a student perspective from the first two years that the course was given. It is intended as a case-study for a target audience consisting primarily of high school and undergraduate chemistry teachers, but we believe that it is also useful for teachers in other subject areas with an interest in student-centered education.

The Concept of Student-Centered Learning

Student-centered learning involves teaching methodologies that focus mainly on the learning processes of students instead of the more traditional emphasis on the teacher's teaching efforts.[1,2] For example, student-centered learning generally includes a higher degree of activity and collaboration among students.[3] It also involves inductive learning,[4] an active instructional method whereby students are motivated to learn, and gain the knowledge required to meet the expected learning outcomes of the course by addressing various challenges through asking questions and solving problems.

Problem-Based Learning

Problem-based learning is based on the principle that a student's learning process is aided by the combination of individual intellectual exploration, and the ability to collaborate with others.[4,5] For example, students must first be able to identify problems related to a given situation or scenario. Then, after questions which are relevant to the overall learning objectives have been identified by a learning group, the students should be able to provide possible solutions. In practice, PBL groups consisting of six to nine students complete coursework through physical group meetings. In addition, the students also acquire, process, and compile information, either individually or as a group.

An instructional method closely related to PBL is case methodology or case-based learning. However, in case methodology the description of the situation, i.e. the case, is substantially longer and more detailed than a PBL scenario, and the problem is defined by the teacher, unlike in PBL where the students identify and define the problem themselves.[4]

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There are several benefits of using PBL in chemistry education including enhanced creative thinking ability, self-regulated learning skills and self-evaluation.[6] These are important skills in any educational field, and are especially relevant within Environmental Chemistry, given the subject's complexity and interdisciplinary nature making it suitable for single problems to cover the contents of one or even several weeks of classes, a previously successful approach to combine diverse topics.[7]

Furthermore, the students' understanding of chemistry may be enhanced through PBL, as this teaching method aims to improve their generic learning skills such as collaboration, synthesis, communication and problem solving. In addition, in advanced courses where chemistry may seem rather fragmented to the student, PBL has the potential to link the subject matter to other areas of science as a result of the previously mentioned benefits. Therefore, the advantages of PBL are both broad and subject specific.[8−11]

While a subject like chemistry naturally requires a certain degree of memorization of facts, PBL augments further understanding as it is based on practical applications, which demonstrates to students the variety of ways that chemistry education can be used after training. This facilitates a long-term, in-depth learning process, which is not achieved to the same extent by traditional teacher-centered methods of learning and lecturing.[12,13] This advantage over traditional teacher-centered learning makes PBL ideal for advanced courses, such as those at master's level.

Nonetheless, it has been suggested that the minimally guided instructional approach used in PBL is less effective and less efficient than guided instructional approaches used in teacher-centered and other more traditional educational activities.[14] Even though this statement has been subject to debate,[15,16] it illustrates that the value of PBL is under discussion and context-dependent. It is beyond the scope of this article to elaborate on educational debates regarding the advantages and disadvantages of PBL. However, we have considered the challenges in implementing PBL during the course development process, and the suitability of this approach with regard to the degree of difficulty and content of the course.

Constructive Alignment

An important concept associated with PBL is constructive alignment, devised by John Biggs.[17] Constructive alignment is based on constructivist learning theory and the importance of the learner's activities in creating meaning, which has been described by, e.g., Cobb[18] and Loyens et al.[19] This implies that the course objectives (in this case mainly the expected learning outcomes), the teaching/learning activities (in our case with an emphasis on PBL), and the examination (here, a written exam and individual report) should be linked.[17] The interlinked relationships among the objectives, teaching/learning activities and examination are often visualized in a triangular fashion (Figure 1).

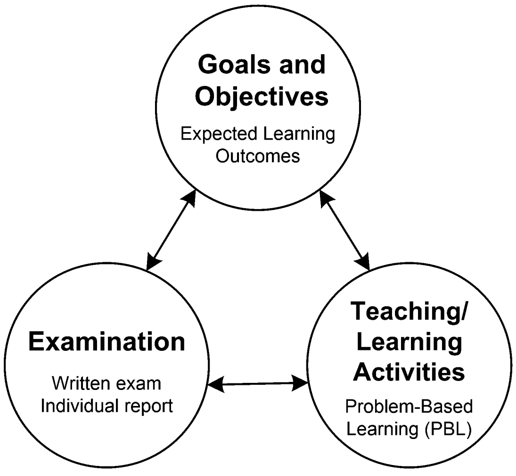

Figure 1. Constructive alignment and the interrelations between goals and objectives (e.g., expected learning outcomes), teaching/learning activities (in our case with an emphasis on problem-based learning), and examination (for instance, written exam and individual report). Based on Biggs[17] and Fink.[20]

■ CURRICULUM DESIGN

A course development team consisting of five university teachers created the curriculum with the goal of complying with the constructive alignment concept, i.e., to focus on linking the course objectives (the expected learning outcomes), the teaching/learning activities, and the examination. We carefully considered the general literature on PBL available at the time and the advantages and disadvantages of PBL in relation to the subject topic, level of the course, and the expected student group. Since there is a lack of PBL procedures specifically applied to Environmental Chemistry courses in the literature, we hypothesized that PBL would be a suitable learning method for the interdisciplinary content of the subject topic (Environmental Chemistry) at the master's level, and that the teaching/learning activities would benefit from intense collaboration among students with various backgrounds, ranging from chemistry to biology.

The master's level course in Environmental Chemistry is given annually, and in English. Although the subject content was in itself a driving force to introduce student-centered learning methods, the declining number of students over a number of years opting to take the focal course, provided additional motivation for this transformation. The majority of students attending the course are graduate students or on equivalent level of studies, admitted to the master program in Chemistry or from other disciplines and courses of study.

The main objective was to create a high-quality and rewarding master's level course of 15 ECTS in Environmental Chemistry, which would simultaneously encompass numerous disciplines and several complex theory blocks. The choice of methodology, student-centered learning with an emphasis on PBL, has consequently been used for this course, as well as in a related 15 ECTS course in Environmental Analytical Chemistry.

Course Content and Organization into themes

The course covers a wide range of topics including chemical structure and function, sources and emissions, distribution, transformation and fate in the environment of organic and inorganic substances, as well as their human health and environmental effects. The course also introduces methodologies and legislation regarding risk assessment of hazardous compounds in the environment.

Considering this very broad content, the course was divided into three more specific themes: (1) Emissions and sources; (2) Transport and transformation; and (3) Exposure, effects and toxicity. Each theme was assigned to one teacher for the coordination of its development and execution, i.e., one teacher at a time was responsible for instructing the students. During

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Table 1. Relating the Three Themes to Expected Learning Outcomes and Teaching and Learning Activities

Expected Learning Outcome Number	After the Course the Student Should Be Able To	Themes[a]	Main Teaching and Learning Activities	Main Form of Examination
1	**describe** and **discuss** the general principles for legislation on chemicals, focusing on the European chemicals legislation REACH	1–3	PBL	Written exam
2	**describe** the main emission pathways of chemicals	1	PBL	Written exam
3	**determine** and **justify** the difference between diffuse and point sources	1	PBL	Written exam
4	**describe** and **assess** the influence of chemical properties on transport, accumulation and transformation processes in humans, animals and the environment	2	PBL	Written exam
5	**describe** and **analyze** different uptake routes for chemicals in acute and chronic exposure	2, 3	PBL, Case study	Written exam
6	**assess** and **justify** concepts and models for studying the biological effects of chemicals	3	PBL	Written exam
7	**explain** and **justify** choices of methods for risk assessment of chemicals	1–3	PBL, Case study	Written exam
8	independently **analyze** and **assess** environmental chemistry issues and research results	1–3	PBL, Case study, Project assignment	Individual report and oral exam
9	orally and in writing **present** and **communicate** environmental chemistry issues and research falling within the content of the course	1–3	PBL, Project assignment	Individual report and oral exam

[a]The themes are 1, Emissions and sources; 2, Transport and transformation; and 3, Exposure, effects and toxicity.

the months before the start of the course, the course coordinator regularly convened these teachers to discuss their teaching plans.

Within each of the three themes, the students worked primarily according to the PBL method and this study will therefore focus on the results and experiences of PBL as the main teaching methodology. In addition, the student-centered learning was integrated with a few traditional lectures, as well as a series of scientific talks by invited speakers which highlighted research areas linked to the course content. At the end of the course, the final examination consisted of a written exam, as well as a written and oral report on individual project assignments.

Objectives and Expected Learning Outcomes

The expected learning outcomes (Table 1) were defined in relation to the course topic using constructive alignment principles in terms of the activities of the student: describe, discuss, determine, justify, assess, analyze, explain, present and communicate (highlighted in bold in Table 1). These skills were then exercised using PBL, and evaluated in the examination phase by a written exam, a four-page written individual report of the project assignment and an oral presentation of the individual project.

In defining the expected learning outcomes, the objective was twofold: to cover different levels of complexity in learning, as described by the Structure of Observed Learning Outcomes (SOLO) taxonomy,[21] and to identify progression in the students' ability to understand the material in comparison to previous courses within the master's program in Chemistry. We also aimed to develop multistructural and relational expected learning outcomes rather than unistructural ones. Approximately half of the expected learning outcomes were linked to one specific previously defined theme (e.g., nos. 2–4, and 6, Table 1), whereas the other half (nos. 1, 5, and 7–9) covered more than one of the course's themes.

■ EXECUTING THE COURSE

Introducing Student-Centered Learning to the Students

The students were introduced to the concept of student-centered learning and PBL by a 90 min introductory lecture and a group discussion on the first day of the course. The teacher of the first theme then discussed the organization of the group work with the students. In addition, a series of guided questions on operational principles (Table S1) which addressed student opinions on topics such as individual and team work, and group member interactions, was filled in and subsequently discussed within student groups with the intention of establishing the expectations of each student from a number of perspectives. The purpose of discussing operational principles was not to force the students to reach an agreement on each topic mentioned, but rather to make them aware of differences and similarities of the individual attitudes within their student group toward specific PBL methods.

Group Meetings

At the first group meeting of the course, the coordinating teacher acted as chairperson, but this task was soon handed over to the students. In fact, during each PBL group meeting, the group assigned one student member as chair and another as secretary. These were rotating positions as new students were selected for these tasks at each meeting throughout the course. The responsibility of the chair was to ensure that the members of the group followed the procedures, joined the discussion, and that the group discussions remained within the topic defined by the expected learning outcomes. The secretary was responsible for taking notes, and posting them on the web-based learning platform used throughout the course.

The responsibilities of the coordinating teacher were to (1) observe the group discussions and be available as a discussion partner if the students' work faltered, (2) keep track of the defined expected learning outcomes of the course and provide additional instructions if the students' focus shifted from that, and (3) ensure the topic areas of each theme were sufficiently covered (as defined by the expected learning outcomes), and provide additional information to the students for the topic areas that were not. Overall, the coordinating teacher avoided interfering, if possible, with the students' PBL work. The triggering act for the teacher to intercede with the students work could for example be if the teacher considered that too much time was spent on discussing sidetracks (i.e., issues not directly related to the expected learning outcomes) or issues related to how to organize the work.

The Problem Solving Process in PBL

Each of the three themes was covered by one or two PBL scenarios, depending on the time assigned to it, with each PBL scenario lasting for 1 to 2 weeks. The PBL scenarios were introduced to the students using one-page consisting of a short descriptive text and an image intended to provoke thoughts

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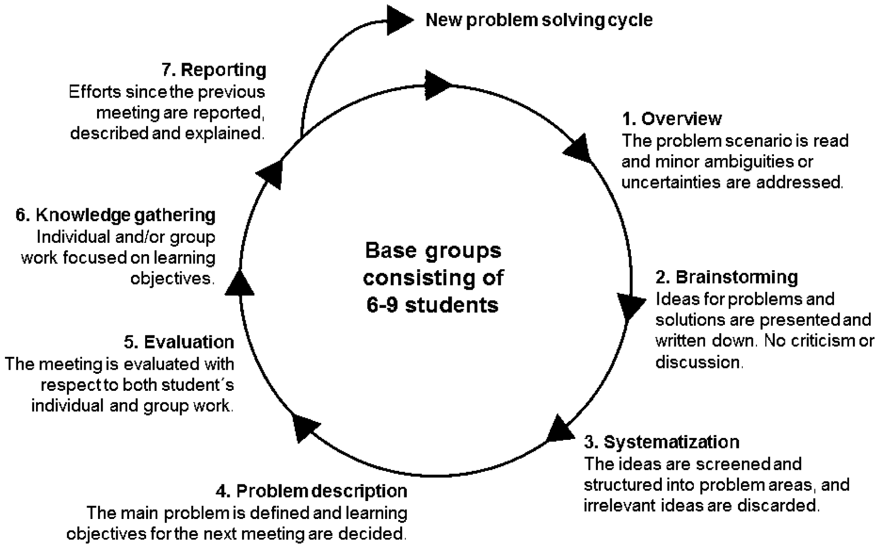

Figure 2. PBL explanation model, adapted from Hård af Segerstad et al.,[22] visualizing the cyclic working procedure of PBL and working order for PBL group meetings.

regarding key issues in the field, such as the handling and environmental impact of chemicals. The associated expected learning outcomes of the current theme were listed at the top of the page with the intention of reinforcing the learning process. An example of a PBL scenario can be found in Supporting Information (Figure S1). Even though the scenario states that the group receives additional documentation in form of an area description of a polluted site in Vietnam, the students have nothing more than the one-page scenario description provided by the teacher for their deliberations. It is the responsibility of the students and the PBL group to identify, gather, and analyze additional information related to the PBL scenario, according to the cyclical approach described below.

A PBL group preferably consisted of six to nine students, and due to the small size of the class in this course during the two years (6 and 9 students, respectively), the entire class constituted one PBL group. To foster collaboration, the students and the coordinating teacher were gathered around a big table rather than being seated in a traditional classroom setting.

The PBL work was conducted following the problem solving cycle shown in Figure 2 and described below:

1. In the **overview** stage, a description of the PBL scenario was handed out and the students were allowed sufficient time (approximately 10 min) to read it, reflect and make some notes.
2. After reflection, each student **brainstormed** and recorded questions, statements, known facts, constraints, and other suggestions on sticky notes, with one item per note.
3. The students placed the notes upside down in a pile on the table, and began the **systematization** process by reading the notes and sorting them into different categories, topics, and processes.
4. Following the systematization, the students utilized a whiteboard to outline ideas and questions brought up during the brainstorming, providing the basis for generating a **problem description** and formulating learning goals to solve the identified problem. These were also used as the foci for discussion at the next group meeting. The students then decided how to delegate the work using the defined learning goals until the next meeting.
5. Before closing the meeting, the students **evaluated** the work conducted during the meeting and reflected on both individual and overall group efforts. In addition, individual self-reflections were uploaded after each meeting by the students on the web-based learning platform, including a summary of what and how each student had learned.
6. In the time between group meetings, the students entered the **knowledge gathering** process in which they worked with their assigned learning goals.
7. As the first task at the next group meeting, each student **reported** the information they had gathered together with their conclusions related to this information, after which the cyclic process was reinitiated with new questions and learning goals being defined.

Examination and Goal Attainment

Assessment of student learning was based on a written exam covering expected learning outcomes 1−7, as well as the oral and written reports of the independent project assignment performed at the end of the course covering expected learning outcomes 8−9 (Table 2). The final grade, a summarized assessment of the results from these different parts of the examination, was only given after all mandatory components of the examination were completed. A three-point grading scale—Fail, Pass, or Pass with Distinction—was applied.

The student's results were generally good (Table 2), with most of the students passing the exam and completing the individual project assignment. The students performed notably better during the second year of the course with regard to both the average exam score and the number of students passing (all, after re-exam). The variation and range of the exam scores were also substantially smaller during Year 2, which could be the effect of students putting more efforts into their studies that year, or more specifically being better prepared for the written exam.

The written exam comprised six comprehensive questions, which required a problem-solving approach. The questions were designed to cover the three themes and expected learning

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Table 2. Examination Results and Goal Attainment from Years 1 and 2 of the Course

Evaluated Parameters	Year 1	Year 2
	Students, *N*	
Total students registered in the course	9	6
Students who passed the course	6	6
Students taking the written exam	8	6
Students who passed the written exam with distinction	2	2
Students who passed the written exam	2	3
Students who failed the written exam	4	1
Students who passed the re-exam	1	1
Students completing the individual project report	6	6
Students giving the oral presentation	7	6
	Exam Score (max. 60 points)	
Average exam score	27.8	36.0
Exam score span	7.5−43	24.5−46

outcomes 1−7 efficiently and reflect both the complex and interdisciplinary nature of the course topics. Each question could potentially cover more than one expected learning outcome. In the Year 1 exam, all six questions covered 10 points, resulting in a total of 60 points, whereas in Year 2, the maximum score of three of the exam questions was adjusted to make some questions more comprehensive and thereby more efficiently cover expected learning outcomes 1−7. The total exam score was still 60 points. Examples of exam questions are found in Table S2 in Supporting Information.

Students' performances were generally more variable in Year 1, with some students doing very well and two students not even answering all of the exam questions, than in Year 2. To evaluate the success of PBL as a primary instructional method, we assessed the performance of each student on every question with regard to each expected learning outcome. In Year 1, four students failed. Their poor performance on certain exam questions and consequently insufficient total exam score indicated that the expected learning outcomes corresponding to these questions were not achieved. In contrast, in Year 2, the students performed fairly well in all questions, except for one student who failed the exam. This student, however, passed the re-exam shortly after, resulting in a 100% success rate for that yeaŕs course.

EVALUATION AND FURTHER IMPROVEMENTS

Evaluation Survey Results

Overall, the students were very happy with the course, as indicated by their positive responses recorded in the evaluation survey (Table 3). The questions and categories that the students were asked to comment on in the evaluation protocols are provided in Table S3, Supporting Information. They rated the overall quality of the course at 3.8 out of 5 in Year 1. In Year 2, they rated the course 4.3, with excellent scores solely of "4" and "5" for treatment during the class. The students would ideally spend 40 h on the course to match a full time study effort. This was almost reached during Year 1. In Year 2, while the number of hours was lower the exam scores were nevertheless higher and the student's opinions recorded in the qualitative survey section were even more positive than in the previous year (Table 3).

Overall, the students found PBL to be a different and appreciated methodology for learning and acquiring deep knowledge of Environmental Chemistry. In 11 of 12 evaluations, PBL was mentioned when we asked "What should we definitely not change?" One student also mentioned that "I gain a lot of self-confidence and learn how to behave in a group meeting." These results were taken as indications that PBL improves not only students' abilities to communicate and present Environmental Chemistry material in a group setting, but also their ability to collaborate and increases their understanding of group dynamics.

Table 3. Student Categories and Evaluation Results from Years 1 and 2 of the Course

Evaluated Parameters	Year 1	Year 2
	Students, *N*	
Total students registered in the course	9	6
Students who provided answers in the evaluation survey	6	6
Master of Environmental Chemistry course of study	2	3
Chemistry course of study	1	
Erasmus course of study	1	2
Other course of study	2	1
Female	2	1
Male	4	5
Quantitative questions in the survey	Rating[a]	
How do you rate the overall quality of the course?	3.8	4.3
How do you rate, as a whole, the treatment you received as a student during class?	4.8	4.8
	Hours per Week	
How many hours per week (scheduled teaching and work on your own or together with fellow students) have you spent on average on this course?	38	26
Qualitative questions in survey	Positive Answers, *N*[b]	
Was the aim of the course clear to you?	5	5
Did the contents of the course match its aim?	5	6
Did the examinations reflect the contents and the aim of the course?	4	6
Would you recommend this course to a friend?	6	6

[a]Rating is based on a scale of 1−5, in which 1 is the lowest and 5 the highest rating. [b]Categorization (into positive and negative) of the free text answers given by students on the qualitative questions was made by the teacher(s).

However, the students' evaluations indicated that the written exam did not meet their expectations, despite our attempts to define questions in line with the PBL scenarios. For example, students commented in their evaluations that "I think it's better to examine the PBLs, reports, presentations. Written exam does not fit.", and "In this type of PBL course, I think it could be better to have [assignments] instead of an exam". Some students suggested replacing the written exam with a home exam: "It might work equally [well] to have a home exam instead, and with a home-exam there would be more learning opportunities".

Hence, the examination needs further development to better match the students' expectations and comply with the constructive alignment concept while also ensuring that each expected learning outcome is evaluated. This highlights the difficulties in implementing the PBL concept. It also indicates the need for careful review when selecting new educational methodologies.

Observations of Student Work

As the course progressed, we observed an increased understanding of the PBL concept and increases in the effectiveness

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of PBL group meetings. This was expected since the students generally had little previous exposure to student-centered learning due to the limited extent to which this method has traditionally been used by our Department.

On the other hand, an interesting observation was the students' reaction to a teacher choosing to plan his three-day teaching effort in the form of a case study, rather than PBL, because of a preference for case-based learning for that specific topic area. This caused some irritation among certain students, as they found difficulty in switching between educational methods. Furthermore, several teachers observed greater progress in addressing the PBL scenarios in Year 2, which they interpreted as an effect of improved effectiveness and depth of the group work. Whether this observation was an effect of the team of teachers being more experienced in the instructional method the second year and thus better equipped in tutoring the students, or the students being more motivated and actually performing better is difficult to ascertain. Nevertheless, the impression within the team of teachers was that the group composition and level of motivation of individual students appeared to be strongly linked to the depth of the discussions, the collective performance of the group, as well as the teacher's attitude and patience with students.

Student strategies for handling the learning goals and distributing them within the group also differed between the years. In Year 1, the students evenly divided all learning goals among the group, so that no two members were working on the same learning goal. In contrast, in Year 2 the students argued that more than one student (and in some cases all of them) should focus on each learning goal. The communication between the students also seemed to differ between the years. In Year 1, the students made frequent use of the chat function in the web-based learning platform throughout the course, whereas in Year 2, this function was not used at all. However, the students may have communicated with each other between the PBL group meetings using other channels that cannot be registered through the learning platform.

Although dividing learning goals among the group members occurred in both Year 1 and 2 (to a different degree though) and some collaborative efforts between pairs or smaller groups of students were observed, subgroups were not recognized as a problematic issue by the teachers. Neither was nonparticipation, which tends to occur in groups of more than four students.[23] The reporting step in each PBL group meeting (Figure 2) likely counteracted nonparticipation since the students in this step were expected to provide individual reports of the information they had gathered and their conclusions based on that information.

Challenges and Future Remarks

Overall, in this case-study, the students were pleased with the course and found PBL to be an efficient methodology for not only learning, but also acquiring an in-depth understanding of Environmental Chemistry. An identified challenge, which has been taken very seriously by course instructors, was the hesitation by some students regarding their ability to retain and recall course information by working in this problem-based context. To combat this wariness, on several occasions teachers have discussed with the students the purpose of PBL and exemplified by comparing with the approach of a researcher, or a product/method developer in industry.

Therefore, for student-centered learning to be successful in a course at this level, it is important that students are well acquainted with the concept of PBL and sufficiently provided with effective strategies for working and learning according to this method. It is also essential to clearly define the purpose of using PBL as well as the end goals of the course using this method. Another important conclusion is that the teacher team must be well organized, well prepared, and efficiently communicate among themselves for effective implementation of PBL. Furthermore, all participants need to understand the concept of constructive alignment, and accept it as the main teaching method.

There should also be emphasis on defining and evaluating the expected learning outcomes, in order to ensure that the students stay on topic. Finally, it is important for students to combine the group work with opportunities to demonstrate their skills individually throughout the course, in (for instance) examinations, written reports, and oral presentations.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/ed500970y.

Guided questions on operational principles filled in and discussed by the students prior to the PBL work (Table S1), examples of exam questions (Table S2), the evaluation protocols (Table S3), and an example of a PBL scenario (Figure S1) (PDF)

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Notes

The authors declare no competing financial interest.

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