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Problem-Based Learning in Science Education

Achievements, Pitfalls and Ways Forward, 2nd Edition

Edited by
Laurinda Leite and Luís Dourado

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Guest Editors

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About the Editors

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Preface

This volume is a reprint of the 2nd edition of the Special Issue “Problem-Based Learning in Science Education: Achievements, Pitfalls and Ways Forward”. It deals with problem-based learning (PBL) in science education and aims to complement the 1st edition of this Special Issue.

The motivation to edit a 2nd issue lies in two main reasons: firstly, the call for the 1st edition was so successful that some papers could not be included in the 1st edition; secondly, we felt that it was important to broaden the scope of PBL by gathering and putting together more and different pieces of research on the theme. We believe that, together, the two reprints offer a good view of the state of the art of research on PBL in science education, in both face-to-face and digital environments, or in environments including digital technologies.

The 1st edition aimed to fill an existing gap in the specialized literature on science education, as there was no known collection of articles on the topic. The 2nd edition expands and strengthens that collection of papers on PBL, which is a student-centered, active methodology that acknowledges problems (that should be or seem to be real) as starting points for learning.

The target audience of this reprint is science education researchers, science teacher educators, post-graduate students, and schoolteachers. It presents a set of 11 papers reporting research performed by authors who work in different countries and used diverse research and or teaching methodologies. The research concentrates on a relatively wide range of educational levels, from school to initial science teacher education, and acknowledges both qualitative and quantitative paradigms.

Globally, the papers included in this 2nd edition of the reprint of the Special Issue reinforce the idea that PBL is a valuable approach for both science teaching and learning, and initial science teacher education, and also for developing students’ and prospective teachers’ competences. However, the authors point out some difficulties that may depend on the problems or vanish if teaching approaches improve and the school curricula become more consistent with the spirit of PBL.

The editors are grateful to: the papers’ authors, as without them this Special Issue would not be possible; Kathy Zhao for the invitation and her trust in the editors; the reviewers for their key contribution to the final quality of the papers; and MDPI staff for their cooperation during the submission, review, and publishing processes. Finally, the editors would like to acknowledge the Research Centre on Education (UID/01661), Institute of Education University of Minho, a FCT/MCTES-PT R&D Unit funded through national funds, to which they belong.

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Guest Editors

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Article

Understanding and Designing Variation in Interdisciplinary Problem-Based Projects in Engineering Education

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Abstract: In various problem- and project-based traditions, interdisciplinarity is part of the definition, and there have been a few conceptualizations of interdisciplinary projects. However, with the increasing application of interdisciplinary projects, it is necessary to develop a more varied understanding. A recent study in a PBL context defines four interdisciplinary project types, and this article aims to develop a conceptual understanding that can inform the design of project types. To design interdisciplinary project collaboration, it is necessary to understand the characteristics of the disciplines involved. In the literature, we identified three major dimensions: knowledge, culture, and approach to learning, all of which play a role in the understanding of problems and collaboration. Furthermore, it is important to understand the move from the disciplinary to the more interdisciplinary project types. In this regard, problem design and team collaboration are chosen areas to exemplify the complexity of this move. As an outcome of this paper, a conceptual framework is developed combining the three dimensions of disciplinary understanding with the interdisciplinary project types. This creates an understanding of what to take into consideration in a design process moving from disciplinary to interdisciplinary projects, especially in the design of problems and interdisciplinary project collaboration.

Keywords: PBL; interdisciplinary learning; interdisciplinary projects; problem- and project-based learning; design of interdisciplinary projects

1. Introduction

PBL is in many ways a confusing acronym. It can stand for problem-based learning, project-based learning, practice-based learning, or play-based learning. One way to distinguish the problem and project approaches has been by using the PjBL acronym, which stands for project-based learning (Graham, 2010). However, the confusion has always been there in the literature and was reinforced during the 1990s when Aalborg University (AAU) declared that their pedagogical model was problem- and project-based learning, as students identify and analyze problems to be solved in their team-based projects (Kolmos & de Graaff, 2014; Kolmos et al., 2004). Instead of arguing on a level of curriculum practices, de Graaff and Kolmos tried to move the discussion beyond the territorial discussions to emphasize that PBL should be seen as sets of learning principles guiding the framing of the curriculum (de Graaff & Kolmos, 2007).

Later, the challenge-based learning approach, which is another active learning pedagogy, has won territory in the style of, and with many overlaps to, both problem- and project-based learning (Doulougeri et al., 2024). Challenge-based learning requires a link to the global sustainability challenges, which is not necessarily a requirement in problem- and project-based learning as the problem here can be both disciplinary and social. Thus, there are overlaps in the approach to the problem for both traditions (Martin & Bombaerts, 2024).

The origins of the two founding PBL curriculum models and principles at McMaster/Maastricht and Roskilde/Aalborg have been studied in a PhD thesis by Virginia Servant, where the deeper historical details are explained (Servant, 2016; Servant-Miklos et al., 2019). Basically, the story is that during the period of establishing reform universities in the 1960s and 1970s, several universities were born with new pedagogical ideas. These universities were based on a theoretical and critical trend where research should be applicable for society and maybe even create a more equal society (Borgnakke, 1983; Hultengren, 1979; Illeris, 1974). These prominent educational models were developed at McMaster and Maastricht, mainly within medicine, and at Aalborg and Roskilde University, within a broad range of disciplines, including engineering.

As these new pedagogical concepts gained popularity, the curriculum and learning practices also became more varied, and many of the original PBL concepts overlapped. During the 1990s and the 2000s, examples of implementations emerged in the literature, ranging from implementing a single smaller project in a course to more institutional implementations (Chen et al., 2021). To categorize these variations, there are examples of the categorization of project types. De Graaf and Kolmos defined three types based on the relation between the discipline and problem: the assignment-based project, the subject project, and the problem project, ranging from disciplinary focus to societal focus for the problems (de Graaff & Kolmos, 2003; Kolmos, 1996). A related framework for understanding the variation in student projects also defines three project types: knowledge and techniques, knowledge and techniques with a relation to the real world, and the interdisciplinary and societal project defined by the students (Helle et al., 2006).

During the last 10 years, sustainability- and mission-driven universities have been on the agenda. More and more research and designs on examples of interdisciplinary projects have been published (Bertel et al., 2022; MacLeod & van der Veen, 2020; Routhe et al., 2021; Van den Beemt et al., 2020; Winther et al., 2022). Also at Aalborg University, new project types started to emerge, and, based on empirical studies, a new framework of problem-based projects was developed based on the scale of interdisciplinarity, ranging from disciplines to broad interdisciplinarity, and the scale of team constructions, ranging from single teams to teams in networks with multiple teams working together (Kolmos et al., 2024).

The categorization is based on the practices at Aalborg University and is not necessarily valid for interdisciplinary projects at other universities with different curriculum structures. However, at least it gives a first language to distinguish between different projects and learning outcomes. The discipline project is the one we most often see applied in the engineering curriculum and, more seldom, the inter-team project, which covers several project teams working together within the program (Kolmos et al., 2024).

For the interdisciplinary project, we have found inspiration in the discernment between the narrow and broad interdisciplinary approaches (Klein, 2010). The narrow interdisciplinary approach is the one most often used in engineering education and reported in the literature. The broad approach is what, in principle, leads to the challenge-based learning approach with a focus on climate change, sustainability, and the 17 UN goals. Also, for the narrow and broad interdisciplinary collaboration, there are the two dimensions of single team and multi-teams in the network. Sonnenberg-Klein and Coyle (2024) have identified three challenges with this framework of interdisciplinary projects. The first identified challenge is very important, as there will always be differences/variations in the combinations of engineering/science programs. Indeed, what is emphasized here is that even the narrow interdisciplinary approach will imply more discerned aspects in the design of the projects (Sonnenberg-Klein & Coyle, 2024). The second and third challenges are about different educational and pedagogical systems and how the core pedagogical ideas saturate the entire curriculum. Unlike many other studies that focus on interdisciplinary programs and differentiate by major and minor (Knight et al., 2013; Lattuca et al., 2013), our approach has been project-focused. The disadvantage of focusing on interdisciplinary programs might be that they create just a new community of practice, and students do not learn to collaborate across the programs or disciplines. (Figure 1).

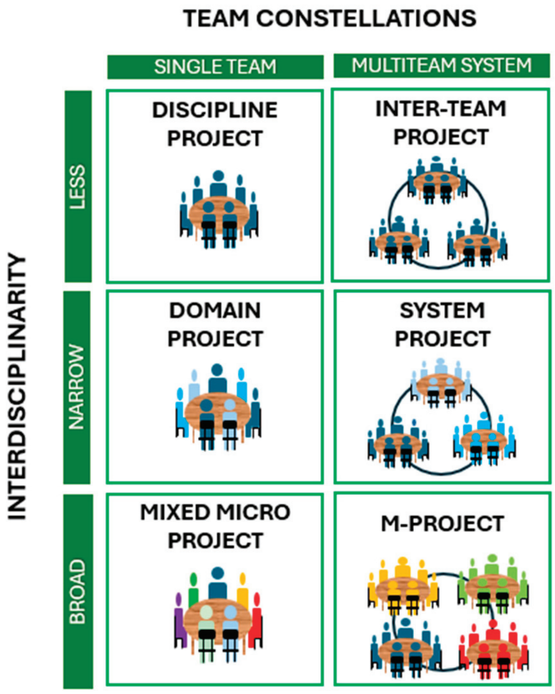

Figure 1. Model of project types (Kolmos et al., 2024).

The six project types will most likely require a variation in the design of a disciplinary and interdisciplinary PBL curriculum. Interdisciplinarity is collaboration between two or more disciplines. Research indicates that students do have issues transforming their collaborative skills learned in a disciplinary project to be applied in interdisciplinary projects (Kolmos et al., 2024).

The project type model opens for further elaborations. First, the model only implicitly touches upon the diverse nature of disciplines, and variables needed to understand the interacting disciplines. It is important to understand what a discipline is to understand the interdisciplinary collaboration with a focus on learning to work in and on boundaries. Secondly, the project type model does not indicate what is happening in the movement from the disciplinary to the broad interdisciplinary, considering the PBL process. A hypothesis is that we approach the core aspects of problem design and collaboration differently, with increasing interdisciplinarity. Such variations are important to take into consideration in the curriculum design.

Therefore, for the design of interdisciplinary projects, we need to ask the question: how can we understand the involved disciplines and the movement from disciplinary to interdisciplinary projects in a PBL context?

In the following, we approach this question in two parts. In the first part, we focus on the understanding of disciplines, and a conceptual model is presented to reflect on disciplinary characteristics. In the second part, specific aspects of PBL such as problem design and collaboration are used as examples of the variation in the PBL approach when moving from disciplinary to interdisciplinary projects. Building on the literature, these combined conceptual models form a base for the further design of PBL curricula and practice, as well as further empirical studies. The developed framework stands as a hypothesis and, thereby, further development of empirical data and tools is needed.

It is necessary to understand the specific characteristics of the involved disciplines, and it is necessary to understand the differences in the approach to problems and the collaborative patterns that saturate the team approaches. An understanding of the different approaches to problem analysis, problem solving, and team collaboration might be helpful for academic staff designing the problem-based projects and for students to understand and develop their collaboration in the project teams. There are many more variables in the design process that are important in the pedagogical and cultural collaborative practices that determine the collaboration processes. However, this might be a start for designing variation in the interdisciplinary curriculum.

2. Disciplines in the Context of an Integrated PBL Curriculum

The PBL curriculum model covers a range of elements and has often been related to a management of change agenda, which includes an alignment among elements, e.g., learning outcomes, student learning, assessment, academic staff qualification, and the selection of content (de Graaff & Kolmos, 2007). The principle of alignment has dominated curriculum development together with the importance of assessment (Biggs, 2003; Gibbs, 1999). Without alignment in the curriculum and especially including assessment in the alignment, the students might be demotivated for learning. Most of the curriculum models address the system level; however, for interdisciplinary projects, there needs to be a model closer to students' learning, such as an alignment among learning outcomes, student learning processes, and assessment, as some of the most important curriculum elements to address.

What has been characteristic for PBL curricula is the learning of both content and generic competences (Habbal et al., 2024). This is also what is often characterized as an integrated curriculum, which has often been used as a concept to develop new interdisciplinary programs. Because of the focus on missions and sustainability, there is a greater demand for interdisciplinary research and teaching, which requires the ability to connect different disciplines (Drake & Burns, 2004). According to Drake and Burns (2004), the ideas of an integrated curriculum and integrated engineering are part of a larger movement in higher education that dates to the 1990s and aims to create links within the curriculum.

According to Drake and Burns (2004), the ideas of an integrated curriculum and integrated engineering are part of a larger movement in higher education that dates to the 1990s and aims to create links within the curriculum. It can be connections between disciplines, professional practices, or generic skills like collaboration and project management (Froyd & Ohland, 2005; Kysilka, 1998).

Drake and Burns emphasize that there is variation in the types of integration by describing multi-, inter-, and transdisciplinary approaches (Drake & Burns, 2004). Earlier, Kysilka (1998) also points out that there is not just one definition of an integrated curriculum, but in fact this is a question of a continuum or scale ranging from separate disciplines to interdisciplinary and total integration. In both Drake and Burns' and Kysilka's understanding, the degree of integration also includes the notion of students as learners ranging from receivers to doers/decision makers/creators and independent investigators (Kysilka, 1998). Drake and Burns emphasize project-based learning as a pedagogy to meet both the interdisciplinary and the transdisciplinary approach (Drake & Burns, 2004; McIntosh, 2023).

A very good example of integrated engineering is to be found at University College London (UCL). Here, integration is defined as the integration of skills into the curriculum, the relation to practice mirrors the disciplines in a multidisciplinary approach, and problem-based projects are used as one of the key teaching and learning approaches (Mitchell et al., 2021). The integration of skills and their relation to practices mirror the principles for a problem-based project curriculum, which is characterized by students working with authentic problems in project teams (Kolmos & de Graaff, 2014).

To practice an integrated curriculum, the curricula structures differ according to the institutions, and the national and international regulations. The most dominant variation in curriculum structures is the elective curriculum versus the predefined programs. The elective system allows students, normally within limitations, to choose courses from other disciplines. An example is the Harvard system, which does have some compulsory credits but, on a large scale, lets the students create their own curriculum (Habbal et al., 2024).

Opposite to this type of curriculum, we find the more fixed program, where nearly all credits must be taken within the discipline. That does not necessarily mean that it is less interdisciplinary. On the contrary, many programs have several credits from other disciplines; however, these might be taught more in an applied mode, e.g., like the teaching of mathematics or business economics in engineering. In this way, the academic staff wipe out the knowledge boundaries, and the students have fewer opportunities to learn to collaborate across the disciplinary boundaries as they participate in courses with all the same students.

So, maybe students are participating in an interdisciplinary program, but they do not learn to collaborate across the disciplines. They learn to understand different disciplinary aspects and understand the problems in a broader context if this is made explicit to them. Following these considerations, a critique of the integrated curriculum approach is that students are not really identifying themselves with the combined disciplines in a program, and the learning is getting too instrumental (Brewer, 2002). Other concerns are that the integration of generic competencies ends up vanishing if these are not explicit learning outcomes in the formal curriculum followed by assessment (Holgaard & Kolmos, 2019). To understand interdisciplinary collaboration from both a knowledge and generic competence perspective, we must understand what constitutes a discipline.

2.1. How Do We Understand Disciplines?

For the academic disciplines, it is a widespread understanding that disciplines are social constructions (Abbott, 2002; Yates et al., 2016). A university-based academic discipline is a subset of knowledge that is studied and taught and that shares epistemologies and methodologies. Since the 19th century, disciplines have been institutionalized by university structures with departments, educational programs, professional associations, journals, and conferences, and with that a self-understanding of us and the others. It is about creating an academic identity by participating in a community and sharing knowledge, ideas, and experience; having deep conversations; and creating social relations (Fensham, 2004). It is identity and belonging and a place where you share experiences and language.

The structures of the disciplines are saturated by the institutional structures, which seem to be a basic foundation, and Abbott is especially pointing at the well-established researchers and career structures as some of the barriers for interdisciplinary futures and the cultures that determine habits and practices (Abbott, 2002). But even if the university and scientific structures determine the disciplines and prevent any change, the institutional cultures differ and influence the disciplinary practices and learning. Examples of when electronics should apply PBL during the 1990s at one institution were the arguments that projects were the only way to teach and learn electronics, and at another institution, the arguments were that you could only learn electronics by lecturing and traditional classroom teaching with smaller individual tasks. The learning outcomes and the content were the same.

Together with the epistemological dimension, there is a cultural dimension of disciplines that is not often studied. During the 1980s and 1990s, there was a discourse among UK higher education researchers to talk about disciplines in a language of regimes, tribes, and territories (Becher & Trowler, 2001; Kreber, 2010; Trowler & Kreber, 2009). Their intention was to analyze the changing landscape of higher education in general, where, since the 1980s, we see massification, and orientation to practice, with a requirement of employability and competence focus, which has changed disciplinary practices in many ways. It is argued that disciplinary knowledge influences how researchers work, the focus for the research, the dissemination patterns, and even the personal life (Becher & Trowler, 2001).

A concept like disciplinary practitioners living in tribes with distinctive ways of thinking and practicing is very descriptive for the academic identity approach, or what in broader terms could be called culture. They point at the fact that the disciplines form their own communities with their own practices, which go beyond the professional level as they bring the logic and the values from their work into their personal lives and create identity. Becher has made a study of disciplines at prestigious US and UK universities, and among the disciplines are physics, mechanical engineering, sociology, and law (Becher, 1981). One point from this study is that cultural self-understanding is developed by contrasting one's own experiences to images of others and creating stereotypes. Once stereotypes are created, it takes years to change these images and overcome this in a collaboration.

Universities today look very different from the 1980s when most of this research and conceptualization was developed. Today, there is powerful political pressure to not only contribute to innovation but also to innovate for a greener world to solve some of the climate issues we have. Maybe that is a dream for the technology optimists, but it involves a more mission-driven and interdisciplinary approach to the development of the disciplines. The funding structure has changed to being reliant on external funding from both public and private foundations.

What Becher, Trowler, and Kreber point out in their approaches is that there is more to a definition of discipline than knowledge and the organization of knowledge networks by journals and conferences (Becher & Trowler, 2001; Kreber, 2010; Trowler & Kreber, 2009). The cultural self-understanding has a huge impact on the boundaries that form the discipline. At the engineering faculties at Aalborg University, the physical space is used as office space and for collaborative project teams. In the humanities, the individual approach dominates more, with a tendency to sit at home and think the "big thoughts". The teaching starts at 8:15 at the engineering faculty and 9:15 or 10:00 at the humanities, which impacts the culture.

A disciplinary practice can also be seen in the light of a community of practice (CoP) which is defined by a group of people sharing interests, experiences, or concerns (Wenger, 1999). A CoP is not a formal organization but more like an informal network. It is not a formal, structured organization, and it is not a formal team with common objectives; it is groups sharing ideas, with members who join by interest, and it only lasts if there is commitment from its members. The concept of a CoP has been very valuable as it represents a cultural layer in between the formal structure, formal networks, formal teams, and the individual-driven interest and motivation. Understanding disciplines or how they can evolve can be aided by the theory of a CoP in a variety of ways. However, even a CoP has boundaries.

2.2. Disciplinary Differences

Snow (1990), in his famous essay, *Two Cultures*, is one of the core scientists in describing different disciplines by two approaches: the art and the scientific approach. There are different practices, languages, logics, and realities, and there is a lack of communication, although they live in the same world. Kagan (2009) has developed the two cultures into *The Three Cultures*, pointing out that it is too simplistic just to compare humanities and science, and he has added a third culture, the social sciences (Kagan, 2009). He argues that disciplines vary from each other in nine different dimensions; see Table 1.

Table 1. Selected dimensions after Kagan (2009, p. 101).

Dimension	Natural Science	Social Science	Humanities
Primary interest	Prediction and explanation of all natural phenomena	Prediction and explanation of human behaviors	An understanding of human reactions to events and the meanings humans impose on experiences as a function of culture, historical era, and life history
Primary sources of evidence and control of conditions	Experimentally controlled observations of material entities	Behaviors, verbal statements, and less often biological measures, gathered under conditions in which the contexts cannot always be controlled	Written texts and human behaviors gathered under conditions of minimal control
Primary vocabulary	Semantic and mathematical concepts whose referents are the material entities of physics, chemistry, and biology, and assumed to transcend particular settings	Constructs referring to psychological features, states, and behaviors of individuals or groups, with an acceptance of the constraints that the context of observation imposes on generality	Concepts referring to human behavior and the events that provoke them with serious contextual restrictions on inferences
Dependence on outside support	Highly dependent	Moderately dependent	Relatively dependent
Work conditions	Both small and large collaborations	Small collaborations and solitary	Solitary
Contributions to national economy	Major	Modest	Minimal
Criteria for beauty and satisfaction	Conclusions that involve the most fundamental material components in nature inferred from evidence produced by machines and amenable to mathematical descriptions	Conclusions that support a broad theoretical view of human behavior	Semantically coherent arguments described in elegant prose

Table 1 indicates some of Kagan's dimensions. The knowledge, epistemological, and methodological dimensions are most often pointed at as the main differences. Surely, knowledge and the way knowledge is constructed are very different (Kagan, 2009). Science seeks to explain natural phenomena, e.g., weather, climate change, or cancer, just to mention some. The methodologies for the studies are data, like observations in labs, modeling, and theory building, and the language is a scientific-based language. In social science and the humanities, the intentions are different as the focus is on humans and the human interaction in societies. The methodologies are different, where data are most often collected in the context and not in a lab. The language relates to human behavior or societal structures. The focus is totally different, and the knowledge and actions created within the different focal points are aligned between the purpose, methodology, and semiotics.

What is interesting is that Kagan (2009) also points at other dimensions such as work conditions, contributions to the national economy, and criteria for beauty. It is well known that neither science nor engineering is an individual endeavor. On the contrary, the knowledge constructions are so complex that it is necessary to participate in collaborative work in teams, in departments, or in consultancy. The contribution from science to society contributes to a self-understanding of one's own worth.

2.3. Science and Engineering

In the previous, science is compared to social science and the humanities. However, even in a narrower interdisciplinary approach, it is important to be aware that science and engineering are not the same. Engineering and science are dependent on each other as knowledge and methodologies. There are commonalities in the knowledge constructions, such as cause/effect, scale/proportion, quantitative research approaches, systems/systems models, structure/function, and stability/change (National Research Council, 2012).

There is a close interaction between science and engineering. Engineering has some of its knowledge base in science, and science cannot develop without technology (Arthur, 2009). But there are also differences that influence the knowledge constructions and the culture. In a report from the National Academy of Science on STEM education, eight dimensions are reported as having different approaches (National Research Council, 2012).

Surely, it will depend on which type of engineering and science we are thinking of. Maybe the differences between biology and biotechnology will not be as significant as, e.g., the difference between physics and production engineering. Engineering is not just one category, as well as science being not just one category. For example, production engineering and civil engineering are much more oriented towards a systems approach, whereas energy engineering and biotechnology are more dependent on a scientific foundation. This must be interpreted in context, and Table 2 shows some more ideal types.

Table 2. Simplified version of comparison of eight dimensions of science and engineering (National Research Council, 2012).

	Science	**Engineering**
Questions and problems	Starts with a question about a phenomenon	Starts with a problem, need, desire, or opportunity
Explanations and solutions	Explanations	Problem solving
Use of models	Models to develop explanations	Models to analyze systems
Investigations	In the field or in the lab	To gain data or to create design requirements
Analyze data	Analyze data for meaning	Analyze data for tests
Mathematics and computational thinking	Fundamental tools	Application for the purpose of design
Evidence	Identifying strengths and weaknesses in reasoning	Best solutions according to design requirements
Evaluation and communication	To colleagues	To customer and colleagues

The questions asked in science and engineering can be very different. Scientists will ask questions to find explanations and causes for certain phenomena, such as what causes cancer or climate change. Engineers will ask questions that are more related to societal problems and will have the character of both understanding the problem and identifying solutions to the problem. Engineers are much more solution-oriented and much more in a creative tinkering process. They are fascinated by solutions that give satisfaction, and there is also an urge for creating things.

The scientific process is different. Knowledge creation in science is in the field, and data are collected to analyze meaning and causes. Models are tools to systematize the explanations. Whereas in engineering, knowledge and data have the aim of identifying design variables, requirements, testing, and to plan implementation. The product is very different; where scientists can be happy with theoretical explanations, engineers are focused on the development of technology. Of course, there is a mix, as engineers need a fundamental understanding of phenomena before developing designs and solutions. Material science is somehow in between the purposes of analyzing, understanding, and developing new materials. It is indeed a discipline that has been raised on the ground of physics, chemistry, and mechanical production.

Within engineering and science, many new interdisciplinary programs have been established according to the development of societal needs. Material science, biotechnology, and nanotechnology are just some of these programs, with historical roots going back hundreds of years, and new disciplines are not established overnight (Bhushan, 2016; Buchholz & Collins, 2013; Bud, 1994; Ferguson, 2006).

At Aalborg University, these programs exist, but the institution has also formed newer programs across Social Science and STEM such as techno-anthropology and design psychology (Christensen, 2014). Design psychology has been closed again and techno-anthropology reduced the number of students due to the high level of unemployment among young candidates, and it witnesses that, without having a market with a strong pull, it is very difficult to establish these programs, and even if these new programs are interdisciplinary, it is questionable whether students learn to collaborate across disciplinary boundaries. New programs might often be looking more into their own boundaries to create a community of practice that can work as an integrated unit.

2.4. Disciplines, Learning, and Generic Competences

There have been established subdisciplines or communities within educational research. Science education is one example, followed by engineering education research, which has specific subjects to study, conferences, and journals, but hardly specific methodology and theories. The theory of threshold concepts is very specific to disciplinary epistemologies, which have more sequential cognitive structures. Barnett et al. (2001) have pointed out that curricula in STEM and humanities vary considerably. He compares the three overall elements in the curriculum: knowledge, action, and the self, and points out that knowledge might be equally important in STEM and the humanities; however, action, and the self differ considerably.

In STEM, action is important, and there is less attention paid to the self and development of identity, whereas in the humanities, the self is more important than the actions (Barnett et al., 2001). Actions can be translated into skills, and the self translates into personal reflection and the development of identity. During the last 20 years, skills and competence have been part of the curriculum, whereas self and personal development has been and still is a more tacit dimension of educational formation and growth.

Sure, all humans need to learn to communicate and collaborate, as this is a basic human capability. However, the context and the culture will create different conditions, even if generic skills are prioritized, integrated into the curriculum, motivated, and learned in different ways in the various disciplines. Coordination actions in a humanity team will be quite different from more strict project management processes in engineering teams that have to work on and deliver a device.

One of the findings we were surprised by was the fact that students who learned generic skills or competencies in disciplinary settings had trouble in both transferring and transforming these skills into interdisciplinary contexts, although it seemed to be easier from disciplines to narrow interdisciplinary contexts than to broader interdisciplinary contexts (Kolmos et al., 2024). The project phases are regarded differently, where social science and humanities (SSH) students emphasize the problem analysis phases to identify the right problem to be solved, whereas engineering students are often very fast in identifying problems and emphasize the solution part. The collaboration between individuals or project teams might become very difficult as the interest and priority of work differ significantly.

These differences are also mirrored in the learning of generic competencies. Structures in the project processes are important for engineering students who work on technology development, while these mean less to many social science students who have critical thinking as a goal. The types of these differences might also explain that students do have difficulties in transferring their generic competencies from a STEM context to a broad interdisciplinary context. Several research projects point out that generic skills are related to the disciplinary contexts in which these are learned.

In a study that compared engineering and business students' attitudes toward learning these skills, significant differences were found. Generally, business students prioritized generic skills higher than engineering students and the motivation to develop these (Chan & Fong, 2018). A similar comparative study presents results from teaching generic skills in physics, history, economics, medicine, and law, which indicate that the disciplinary epistemologies have an important impact in shaping generic skills (Jones, 2009). These findings indicate that skills like critical thinking, analysis, problem solving, and communication are both conceptualized and taught in quite different ways in each of the disciplines. The authors suggest developing a re-disciplined understanding of generic skills (Jones, 2009). The term generic skills is only generic across similar disciplines, and, therefore, they are not always transferable.

Disciplinary differences are also found in doctoral students' learning and appreciation of generic skills, where engineering PhD students prioritized these skills lower in the science field compared to other studies (Sakurai & Pyhältö, 2021). Appreciation is also an element in the motivation for learning, and Jones concludes that there is nothing generic about generic attributes (Jones, 2013). This might be a bit controversial; surely, e.g., collaboration exists in all types of organizations and life conditions; however, theories like the activity theory and situated learning indicate the issue of transfer for generic skills, and it is a relevant question to consider if or how we actually can integrate an element of transformation and recontextualization in the learning of generic skills.

2.5. Framing Interdisciplinary Collaboration

When we investigate the understanding of what defines a discipline, we do not only see the epistemological perspectives, but indeed a broader understanding of disciplines as communities of practice with knowledge sharing, culture, and even pedagogical perspectives. Sonnenberg-Klein and Coyle (2024) are quite right when they have criticized the model for interdisciplinary project types as too general and that even the narrow interdisciplinary perspectives with the domain and system projects will cause issues in the collaboration. As seen with the science and engineering approach (see Table 2), these start out with different understandings of problems and different epistemologies and understandings of the work processes, and maybe even different cultures. When different cultures must work together, it is difficult, as culture is practice and very often tacit. Furthermore, we face a very complex issue, as it is not only the cognitive and the cultural dimensions, but indeed a lot of intertwined dimensions.

Students face issues in a disciplinary collaboration even if they have learned the same disciplinary knowledge, and there are individual issues as well as systemic issues. Vocabularies have different meanings, like Kagan (2009) is mentioning with the meaning of fear and capacity of memory. In psychology, this means something totally different than in biology. Also, the language boundaries create issues where one concept in one language only has one meaning but several meanings in a different language. Not only the language, but also the generic competencies might be prioritized and understood in different ways, and, for example, problems and collaboration might be approached differently. If engineering students do not understand that philosophy students spend a lot of time on the understanding of problems, the engineering students get impatient and vice versa.

All these dimensions influence the communication and collaboration in interdisciplinary teams, need to be considered in a design process, and can be summed up in three dimensions with many subcategories (see Figure 2): knowledge, culture, and learning.

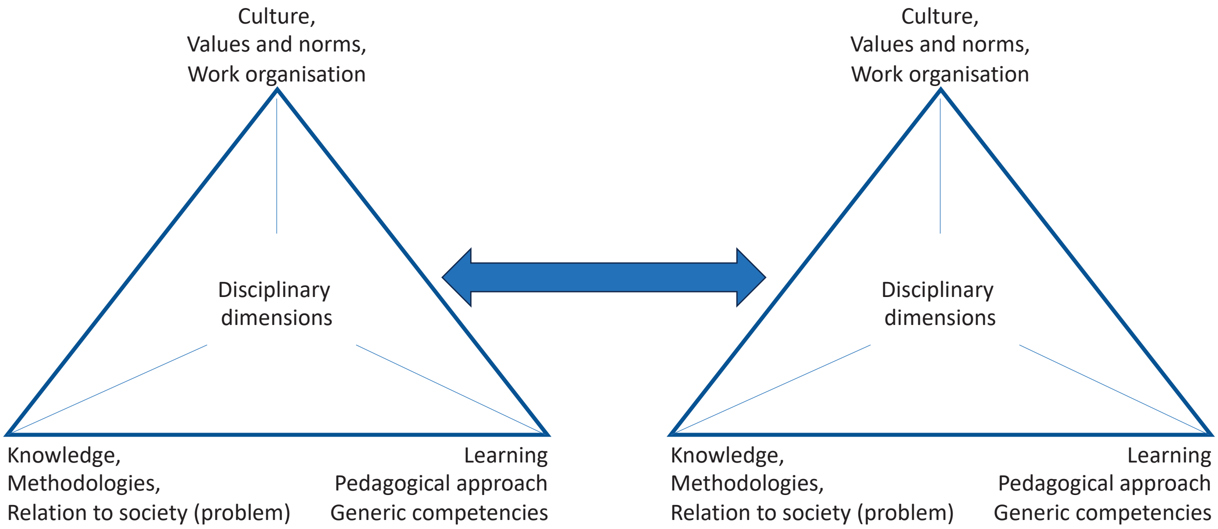

Figure 2. Dimensions of interdisciplinary collaboration.

This broader understanding of disciplines corresponds with the ecological paradigm of interdisciplinary learning, which involves the cognitive, pedagogical, and organizational perspective (Kali, 2024). Both in the ecological and in these perspectives, lists of fundamental questions are raised:

- Which disciplines do we bring together?
- What knowledge and epistemologies do they bring?
- What is the relation to society and the understanding of problems?
- What is the reflection on the culture, societal values, and work values?
- How do we understand learning from experiential to taught textbook knowledge?
- How are the projects organized? How much does the problem count in the projects?
- How is the work organized? How does the sharing, collaboration, structure, and coordination happen in the project?

These questions are just some of the facilitating questions academic staff should consider in the design process of interdisciplinary projects. The questions will also depend on the various interdisciplinary project types, as the collaboration pattern among the disciplines is very different in the column for single teams from the column for teams in networks, with several teams working together (Figure 1). What does it take to design different kinds of projects in an existing curriculum? In the following, we have chosen to examine the problem and collaborative team aspects to gain an understanding of the interdisciplinary project types.

3. Design Variables for Interdisciplinary Problems and Teams

3.1. Problem Dimensions Related to Different Project Types

In a problem-based learning context, the project is evidently bound to a problem, and different project types will go together with different problem types. A problem can be viewed pragmatically as an unfulfilled potential, an unsatisfactory situation, or a knowledge gap; these are areas of tension in the so-called problem triangle (Habbal et al., 2024). The problem triangle implies that the problem has a starting point, e.g., a potential for optimizing an energy system, but due to increasing insight into the situational context, students might question whether this type of energy system is in fact the most optimal to face current challenges. Whereas these three problem types in combination present a more basic view of the problem, more specific problem types can be specified.

In a PBL context, Savin-Baden defines different problem types, including problems designed to promote cognitive competency, problems designed to promote learning through activity, project-led problems, practical resolutions, design-based problems, problems combining knowledge with action, problems managing dilemmas, problems defined by teams in relation to practice, and a problem type characterized by seeing alternatives (Savin-Baden, 2014). To a similar level of detail, Jonassen has defined different problem types related to different levels of structuredness, having algorithmic problems as the most well-structured and dilemmas as the most ill-structured problem types. In both cases, attention is given to the dilemmas potentially embedded in the problem (Jonassen, 2000; Savin-Baden, 2014).

Other scholars specify the type of problem by different dimensions or scales. The problem difficulty can be analyzed by the level of complexity and structuredness (Hung, 2016). Complexity is related to the breadth, attainment level, intricacy, and interrelatedness of the problem space, whereas structuredness is related to the transparency, stability, and predictability of the problem space (Hung, 2016). Complexity is a recurrent theme in the characterization of problems related to the number of issues, functions, and variables involved in the problem, whereas structuredness is a question of problems being ill-structured or well-structured. Ill-structured problems embed unknown problem elements and information that leads to multiple solution paths. In other words, ill-structured and complex problems provide a divergent and ambiguous problem and solution space (Jonassen & Hung, 2015).

The Cynefin framework provides another perspective on the complexity of problems. Complexity in this context belongs to the unordered domain where emergent patterns can be perceived but not predicted, and the patterns only appear logical in retrospect (Kurtz & Snowden, 2003). Based on the Cynefin framework, complexity is related to emerging learning environments in engineering education, and it is stressed that, in terms of complex systems, where it is not clear whether there is a good solution or a problem or opportunity, even the best student projects offer only glimpses of such complexity (Hadgraft & Kolmos, 2020). Furthermore, whereas the simple and complicated are tied to technical knowledge and skills, complexity is tied to contexts, systems, sustainability, and values, which calls for more systemic curricula strategies (Hadgraft & Kolmos, 2020). This concept of complexity is thereby linked closely to the societal context.

Wanzerböck et al. have presented a two-dimensional model for the problem–solution space characterizing different levels of divergence and convergence (Wanzenböck et al., 2020). A high divergence expresses a high wickedness of the problem (Rittel & Webber, 1973). The model highlights the dialectic relationship between "solutions in search of problems" and "problems in search of solutions", which calls for an alignment of both views, and the disorientations in the case of divergent views on both dimensions is emphasized (Wanzenböck et al., 2020). The 'wickedness' or divergence of the problem space and solution space, respectively, and all together, represents different levels of complexity and ill-structuredness, but it also represents an important distinction as it determines what initiates the process of problem design. Are the solutions in search of problems, or is it the other way around? A study on design students' approach to the problem–solution space found that, especially for ill-structured problems, the problem and solution space is explored in parallel, with a constant iteration between the spaces (Martinec et al., 2020).

Holgaard et al. (2017) have pointed out the problem design process, where the problem, through problem identification, problem analysis, and problem formulation, is narrowed down to something tangible for and by the students. In this case, the problem analysis is the glue that brings together the problem–solution space in an iterative process, where the spaces can be divergent. The problem design approach can introduce a student-centered approach that emphasizes that students obtain experience-based problem design competencies (Holgaard et al., 2017). It should be considered that, when the complexity of the problem increases, the challenge for the students to prepare the problem design will most likely also increase. As a result, it is crucial to consider whether faculty or students are designing the problem. Furthermore, in an interdisciplinary context, it is also important to acknowledge that the problem design can be carried out as a co-construction process across disciplines, which most likely will lead to a more in-depth contextual understanding of the problem.

Applying the above theories, we can develop variation in the design of the problem in relation to the complexity, structuredness, problem–solution space, and the level of co-construction in the problem design and problem solving.

In discipline and inter-team projects, see Figure 1, disciplines are the point of departure for delimiting the problem and solution space. The initiating problem might be open, but the problem is narrowed down to something that can be handled from one discipline; in the context of engineering education, it is a technological solution space specified by disciplinary learning outcomes. Inter-teams are expanding the solution space or depth as more groups create the opportunity to provide more in-depth problem analysis and present a more comprehensive solution. The complexity might be high from a technical point of view, but complexity considering the societal context of the problem is limited to including aspects from other disciplines without co-constructing activities. The co-construction of problems and solutions is thereby delimited by the disciplinary boundaries.

In the domain and system projects, the problem space is delimited to a given domain or system, which is pictured beforehand. In the domain project, the solution space is within a specific area of knowledge, practice, or site, e.g., starting from a project theme, which is opening the problem space to specific disciplines with similar epistemologies. In the system project, the solution space is linked to a specific boundary object, for example, an artifact embedded in a technological system, which in a similar way opens the problem space, or rather the system, to different views within the same epistemological paradigm. It is thereby the solution space and the disciplines that are the decisive parameters, whereas the problem space provides the context of study. It is an iterative process between defining the problem and the solution within the given boundaries and securing an interdependence of disciplines selected. The different disciplines provide students with the opportunity to address a broader contextual understanding of the domain or system studied, and the knowledge, practices, and technological systems are co-constructed across similar disciplines.

In the mixed-micro project and the mission project, the problem space is the decisive parameter, and the breadth of the problem provides challenges for narrowing down the problem space as the problem field cannot be understood without an understanding of complex societal interdependencies. As the problem space is the decisive (yet wicked) parameter, it is not clear at the beginning which solution paths and disciplinary combinations are needed.

Likewise, it is a complex matter to break down the problem in supplementing parts, which at the same time are to be connected in a systemic whole. We have reached a high level of complexity. The project types address this challenge by an experts-in-teams approach (in mixed micro-projects) and teams of experts approach (in the mission projects).

Special concern should be given to the mission projects, which have the highest degree of comprehensiveness and complexity. Due to the openness, comprehensiveness, and complexity of both the solution and the problem space, the problem design becomes a complex exercise starting from an overall mission that must be transformed into complementary projects. As such, it can be argued that the problem–solution space might become as broad as to include or combine other project types, which shows the complexity and inclusiveness of the design of mission projects. The challenge is, however, to interrelate the projects derived from an overall mission.

In sum, the nature of the problem types defined is related to the following aspects of the problem:

- The comprehensiveness of the solution space increases when moving from single teams to multi-teams, as more teams can cover more depth and scope of the problem;
- The complexity of the problems increases from the disciplinary to the broad interdisciplinary as the problem space becomes increasingly open and related to the sociocultural context;
- More co-construction is needed with increasing interdisciplinarity, as a certain depth and variation in the understanding of the problem–solution space is needed for complex problems;
- The structuredness of the problem decreases towards the broad interdisciplinary projects as the problem–solution space becomes less predictable;
- The problem design challenge increases for the broad interdisciplinary projects as it is getting more difficult for students/faculty to design the problem due to the increasing uncertainties in the problem–solution space.

3.2. The Collaborative Team Aspect

PBL is defined by including collaboration in teams, which means that students are working on a common goal with coordinated actions, which is a common definition of teams (Atkinson, 2001; Klein, 2014; Kozlowski & Ilgen, 2006). The literature on teams is enormous, ranging from small group teaching to team collaboration in single teams and across teams. Where humans are put together for work purposes, there will be barriers and issues among the individual members, and the nature of the task or purpose for the team will altogether be a complex reality to study.

Katzenbach and Smith (2006) have studied teamwork in companies and identified similar issues as in the educational sphere. They develop a taxonomy for teamwork ranging from a group to high-performing teams where there is an added value for teams in terms of performing much better than a group of individuals (Katzenbach & Smith, 2006, 2008). One of the core variables in developing from a group of individuals to a high-performing team is shared commitment and ownership, which indicate that the individuals prioritize the common goal over the individual interest. Shared leadership, individual and mutual accountability, the ownership of formulated goals, collective work products, open-ended discussions, assessing work products, and discussing, deciding, and collaborating on work are some of the characteristics that they emphasize for high-performing teams (Katzenbach & Smith, 2008). The Katzenbach and Smith model is based on teams in companies, and it is important to keep in mind that engineering has a high level of team organization, as technology development relies on system development.

Teamwork skills have been studied for a long time, and as part of the transition from education to work, it is important to learn these skills, such as collaboration, communication, and conflict solving for team members, during formal education (Hall & Weaver, 2001). However, the conditions for team development and common commitment do have different conditions in education; for example, product development is part of a larger curriculum and does not meet the same criteria as in work life. One of the studies focuses on the design of teamwork and reports on courses where students have been practicing self-managed team projects. They conclude that this can happen in their context when faculty can act as role models, provide some kind of scaffolding, and students are encouraged to become decision-makers (McNair et al., 2011).

There is no doubt that collaboration among individuals will often create issues and, consequently, team success within disciplines in engineering has been studied (de Campos et al., 2012; Tonso, 2006). Interdependence and trust, the ability to overcome conflicts (personal and professional) and to minimize social loafing are some of the key variables for an effective team collaboration (Borrego et al., 2013). A study based on student reflection reports from disciplinary project teams indicates that trust, engagement, and confidence are among some of the core elements for individual students in the collaborative team processes (Spliid, 2011). Another study identifies cognitive trust and sharing as part of the core variables for establishing team success, indicating that it is not only the personal trust but indeed also the trust in sharing and learning scientific knowledge (Dimas et al., 2023). There are a few review books that provide overviews of the field in which they identify interpersonal aspects, structural aspects, and building shared knowledge in teams, which is a necessary component in team success (Newell & Bain, 2018). Cognitive trust is a condition for building up shared knowledge where students share language and are not afraid of challenging each other and asking questions of understanding.

Cognitive trust is challenging when we move to interdisciplinary teams. Students with different disciplinary backgrounds do not know each other's disciplinary languages, cultures, and learning. Compared to teamwork in disciplinary contexts, interdisciplinary teams belong to an open system and are heterogeneous by their members from different fields (Klein, 2014). The design of the teamwork is therefore important, both concerning problems and team constructions.

A study on self-efficacy for students working in multidisciplinary teams indicates that there is a variation in the student group from some students who increased their confidence whereas other students decreased their confidence (Schaffer et al., 2012). This indicates that it might definitely not be so easy to work in interdisciplinary teams, and consequently, students find the experience dissatisfying (Beddoes & Borrego, 2014). Territory disciplinary battles, combined with a lack of integrative skills, systems thinking, and disciplinary humility are among some of the issues that are reported (Klein, 2014). Also, conflicts are unavoidable and concern both the disciplines (understanding problems, methodologies, and work processes) and interpersonal issues (Klein, 2014).

The studies identify both issues and possibilities, and for sure, the design and facilitation of the interdisciplinary teamwork are important. The positive experiences are e.g., reported from experiments and practices such as expert-in-teams at NTNU, Norway, where students from different disciplinary backgrounds work together and where there is a facilitation of the learning of generic competences in an interdisciplinary context (Sortland, 2001;

Wallin et al., 2017). A recent study concludes that cross-disciplinary teamwork actually forms a better base for students to learn collaborative skills compared to students working in disciplinary teams (Cima et al., 2024). As for the Norwegian experiences, the results might depend on the design and the facilitation of the learning processes. Other positive results are to be found in studies on multidisciplinary team projects: when students are positive, team spirits play an important role, and multidisciplinarity gives students the opportunity to experience their own discipline in relation to other disciplines (Heikkinen & Isomöttönen, 2015; Routhe et al., 2023).

The size of the team is an important factor, whereas smaller teams have more chances for creating trust and confidence opposite the larger teams. Coordination issues will also be dependent on the team constellation, both in terms of disciplines and size (Klein, 2014). Interdisciplinary teams are not all the same, both in regards to the task undertaken and the stability of the teams: stable teams and ad hoc teams (Klein, 2014). Stable interdisciplinary teams may create a shared knowledge base and common understanding of research practices, whereas the ad hoc teams are established to carry out very specific tasks. The ad hoc teams might have the opportunity of a fresher approach, but, on the other side, they might not have the chance to overcome the knowledge and cultural boundaries and will be of more high risk. Ad hoc teams are much more flexible and might even become a trend in work organizations.

From Teams to Knots is a book on the developing trends within work organizations and the need for competences to participate and contribute to a much more flexible work process (Engeström, 2008). Also, boundary crossing is seen as an important generic competence in learning collaboration (Fortuin et al., 2024).

For effective single-team collaboration, there is a need for the team members to have mutual accountability, engagement, ownership, collective work products, and open-ended discussions, which can only take place if there is social and cognitive trust and shared mental modeling processes going on. On the negative side are the unsolved social and professional conflicts and the social loafing, which might increase if there is a lack of ownership. All these variables become more essential in interdisciplinary teams as the students are not sharing the disciplinary languages but must start by teaching each other.

Leadership is a factor in the studies of teams (Newell & Bain, 2018); however, the coordination and leadership dimension becomes significant in the studies of teams in network or multiteam systems. The work organization has to address the complexity in tasks and teams of teams, or teams in networks, and can be a response to an ever more unpredictable world (McChrystal et al., 2015). Multiteam systems (MTS) refer to a strategy where two or more teams work together, either directly or indirectly, to achieve specific group objectives (Shuffler et al., 2015).

MTS is a relatively new field, with the first literature emerging around 2000 and with a real takeoff around 2010 (Mathieu et al., 2001; Zaccaro et al., 2020). The tasks carried out will require more than a single team can handle and are often characterized by being complex and challenging. The literature is very much focused on organizations where different units and international companies are working together across language, culture, disciplinary, and educational boundaries (Luciano et al., 2018). Production today is global and might be innovated in one place, produced in another, and consumed in a third place, and it may involve academics and technicians.

In the composition of an MTS, many types of sub- or single teams can be applied, both in terms of stable and ad hoc teams, which create different conditions. Team success is characterized by the collaborative part (interpersonal, motivation, shared knowledge, and cognitive trust) and the task carried out (strategy, activities, and project management), where the added component for MTS is coordination, meaning both project management and leadership to coordinate the activities in the sub-teams (Turner et al., 2020). However, this is not an easy task, as this inter-team coordination might have tensions among the teams along with tensions among the individual team members (Wagner, 2023).

Summing this up in relation to our six project types, there are some general conditions for single teams, such as mutual responsibilities and interdependence, the social interpersonal dimension together with motivation, the ability to create shared knowledge, and cognitive trust are essential. Surely, this will get more and more complicated as we move from disciplinary teams to narrow and broad interdisciplinary teams, as the cognitive trust will be challenged.

When students do not understand each other's language, it might create a distance, including a social and emotional distance. In general, less cognitive or disciplinary sharing requires more communication to collaborate. Therefore, it is crucial in the design of interdisciplinary single-team projects to articulate the issues that might arise. This can be done in different ways; however, it is most efficient by letting the students reflect during and on their experiences from the collaborative processes. Facilitation by supervisors can be a solution or as it is done in "expert-in-teams" at NTNU by elder students. It might not be necessary to sit in the meetings calling for time-out, but it might be enough to run workshops and establish a baseline, which the students can use for their reflections.

Moving from single teams to MTS involves other dimensions as the coordination becomes important. Surely, also in this case, the coordination becomes more complicated as we move from disciplinary to narrow and broad disciplinary projects.

For *inter-team projects*, the cognitive trust among the teams and the coordination among the teams might be easier compared to the broader *system- and M-projects*. The system projects might create some issues in the understanding of the disciplinary languages, although the student project teams are working on the same device. For the broad interdisciplinary projects, it might be challenging as the students in their teams and across teams need to have a common understanding of the direction. In the vertical axis of the product type model, Figure 1, less cognitive or disciplinary sharing requires more communication to collaborate. Students might have their cognitive trust in the disciplinary teams, but they must construct this across the disciplinary teams. Also in these cases, students have the opportunity for learning coordination in terms of different forms of leadership, such as shared, rotating, or hierarchical leadership (Routhe et al., 2024). However, the students need to reflect on the forms of leadership they choose, and they need to learn to articulate their practices. For the MTS team construction, each single team will need to have cognitive trust, and in MTS there will very often be ad hoc teams to solve or link special issues.

At a general level, for both single and MTS, the generic competencies will be more needed as the students do not share a disciplinary background. The generic competencies are means to learn disciplines, but if students must work on broader interdisciplinary challenges, we need to turn the learning outcomes upside down, so the disciplines are the means for learning interdisciplinary collaboration.

4. Perspectives

In this article, we have tried to elaborate a framework for understanding a greater variation in problem-based projects. Since the 1960s and 1970s, when the first problem- and project-based practices were introduced, efforts have been made to develop the learning principles of that pedagogy. We are trying to define interdisciplinary projects with variation in the understanding of the problems and the collaboration embedded in the different practices.

There is a lot of research on interdisciplinary research and less on interdisciplinary collaboration in teams. To formulate a framework for interdisciplinary team collaboration in projects, we have stepped backwards by looking at what a discipline is. That gave some new insights as it reminded us that a discipline is not just the knowledge and epistemologies but indeed also other dimensions, such as culture and learning, which are both sometimes hard to make explicit. How students have learned project management, for example, which project phases to emphasize and how the collaborative culture is practiced, will always be contextually dependent on the previous and present practices. The social atmosphere might be very strict and to-the-point in one culture and much more indirect in other cultures. Students quickly learn the hidden codes—what to say and what not to say.

Understanding the disciplines from a community of practice point of view results in even more nuances, as a program at one university might have a totally different culture compared to similar programs at other universities, even if the discipline shares journals, conferences, etc. Therefore, it is difficult to outline general recommendations for interdisciplinary collaboration. The disciplinary dimensions (knowledge, culture, and learning) will always influence the practices.

When we review the literature on the more specific variables in interdisciplinary projects, these dimensions are somehow absent or not present. There are variables like empathy, risk-taking, and humility; however, these are more outlined as individual traits than cultural tendencies (Repko et al., 2019). The literature on problems and collaboration is often without specific cultural, disciplinary, or learning perspectives.

Figure 3 is a development of Figures 1 and 2 in the sense that we have drawn the project teams and illustrated the disciplines by the colors of participants. The constructions of these types of project teams are at a framing level, and this will give a language to speak about the variation. The disadvantage with defining boundaries between project types is that we create new limitations. In practice, system projects will consist of ad hoc teams as well as stable teams, and some will be disciplinary and others interdisciplinary. In that sense, practice will overtake the project-type framework.

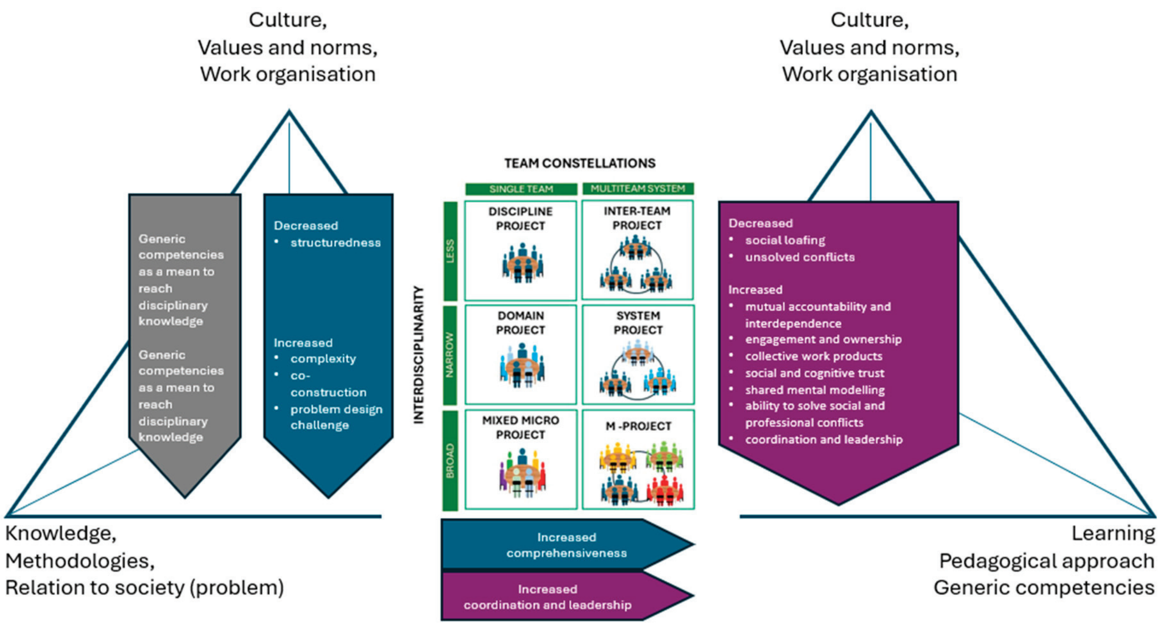

Figure 3. Combined disciplinary dimensions, project types, scales of problem, and collaboration outcomes.

We can learn from the literature on problems and collaboration. In a design phase, the problems will get less structured and more complex. There might be more co-construction and increased challenges, and the problem design will be increasingly challenged when moving from disciplinary to narrow and broad interdisciplinary aspects. Like the collaborative constructions, for teams to function well, we need a decrease in the social loafing and the unsolved conflicts. On the other hand, we need an increase in the mutual respect, engagement, and ownership for the collective product, with social and cognitive trust, shared modeling, and the ability to solve conflicts. Furthermore, we move from single and disciplinary teams to teams across disciplines, which involve increased coordination and leadership; see Figure 3.

As a general statement, we find that there is a clear tendency for the generic competencies to move from being a means for disciplinary learning to becoming a learning objective for the disciplines to reach.

We have drawn the framework for interdisciplinary collaboration as a fundamental factor behind the six project types and the considerations for the design of problems and collaboration to remind ourselves that the disciplines also involve cultures and learning approaches. This is not only about increased coordination and leadership; it is also about increased coordination and leadership across different disciplines, cultures, and understandings of learning, which is much more complicated.

No matter which project type we address, the teams will need to create social and cognitive trust, and as we approach the broader interdisciplinary perspectives, this will get more complicated to facilitate. Not even academic staff will always be aware of the specific learning approach in their own discipline. Often this awareness will occur in comparison to other disciplinary practices.

However, for the design of interdisciplinary team projects for students, it is important to consider the boundaries the students will have to cross. The theories on boundaries can help facilitate these processes by the phases of identification, coordination, reflection, and transformation (Akkerman & Bakker, 2011; Fortuin et al., 2024). Identification is the process of identifying problems and the peers' disciplinary backgrounds and personal quality. Akkerman and Bakker (2011) call this othering, which is a synonym of what we understand as variation and comparison.

Reflection on variation gives the opportunity to understand one's own practices and boundaries better, as there is a mirror for what can and cannot be recognized. Coordination in this discourse is understood as communication and translation, but it can also be understood from the organization perspective as management and leadership, although it is based much more on a semantic understanding. Reflection is to learn from experiences, which is an ongoing process. Transformation is to create new common understanding and shared mental modeling and, from a social perspective, the social and cognitive trust making an open dialogue possible.

These four phases are not to be regarded as sequential but as overlapping and parallel phases that are going on and as iterative learning processes. For any introduction process, it is important to let the students experience all four phases and try to organize some events or situations where the students are facilitated in a reflective process. What they need is also to create their own understanding of the interdisciplinary collaboration and to keep working on a deeper understanding of the common problem that leads their project process. There are many already known activities that can frame the learning and be an opener. What is important is that the learning and reflection are based on variation and comparison to create an environment that can facilitate an open, curious, social, and cognitive environment for new knowledge constructions.

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Article

Influence on Students' Learning in a Problem- and Project-Based Approach to Implement STEM Projects in Engineering Curriculum

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Abstract: In recent decades, a transformation in university-level engineering programs has been proposed, shifting towards active, student-centered teaching approaches such as problem- and project-based learning (P^2BL). At the same time, interdisciplinary STEM education has taken on a central role in engineering instruction by fostering connections between different disciplines and enhancing the use of scientific skills. In this article, we present the design, implementation, and evaluation of a new curriculum that integrates the P^2BL approach within an integrated STEM framework in the Process and Product Innovation Engineering degree at the Dual Engineering School—IMH Campus. We focus on one of the key teaching materials we have developed to structure an approach based on problem- and project-based learning: the long-term interdisciplinary STEM (iSTEM) project. This initiative has been implemented over the past three years in the first semester of the first year of the engineering degree program. We describe its design and execution, followed by an analysis of the evaluation methodology and results in relation to the defined learning objectives. Additionally, we present the evaluation tools used and the findings obtained, assessing both the iSTEM project's ability to engage students in learning the subject and its impact on their knowledge development. The findings obtained from the various assessment instruments indicate that the implementation of the P^2BL teaching methodology enables students to apply core engineering skills in problem-solving, while simultaneously fostering a deep understanding of the concepts, laws, and models from the different disciplines involved. Notably, the results also suggest that the development and application of engineering skills is a gradual process that requires time. Therefore, it is essential for students to continue engaging with the P^2BL approach throughout their undergraduate studies.

Keywords: problem-based learning; project-based learning; engineering degree; integrated STEM project; active teaching at university

1. Introduction

In recent decades, a change from a lecture-based teaching approach in undergraduate engineering courses to student-centered, problem- and project-based active teaching (P^2BL) approaches has been proposed (Hmelo-Silver, 2004). This strategy is our choice for an active mind-on teaching approach that focuses on critical thinking, reflection, and deep understanding (Dolmans et al., 1994). This teaching model aligns with the learning theory we adhere to, socio-constructivism (Leach & Scott, 2003), in which problems and projects are, as much as possible, placed in real engineering contexts, and students are repeatedly encouraged to build new knowledge upon prior knowledge while interacting in small groups with other students.

On the other hand, interdisciplinary STEM education is taking center stage in engineering education (Roehrig et al., 2012). At the same time, the development of STEM curricula has become increasingly relevant in both pre-university and university education (English & King, 2019). Numerous researchers have highlighted that connecting interdisciplinary bodies of knowledge enables students to synthesize information across multiple disciplines, fostering integrative competencies in engineering education that go beyond a single field of study. The interest of the P^2BL approach in a STEM scientific–technical context lies in finding ways to develop students' content knowledge and plan appropriate learning activities and instructional strategies. However, there is little research into the impact of this teaching approach on undergraduate engineering students' attitudinal understanding and use of scientific–technical practices, as well as their perceptions of learning using P^2BL in a STEM context.

This study will first examine the design and implementation of learning activities such as "Predict and Argue" and "Design and Do" within the context of the Dual Engineering School at IMH Campus. These activities aim to integrate STEM content into the P^2BL approach, fostering students' core competencies through problem-solving processes. Secondly, we will evaluate the implementation carried out in the first year of engineering over three academic years, presenting the results on students' conceptual, procedural, and attitudinal learning. A mixed-methods approach, combining qualitative and quantitative analysis, has been used to analyze the empirical data collected.

2. The P^2BL Model of the Dual Engineering School at IMH Campus

IMH Campus is made up of companies, associations, and public institutions from the Basque Country. It is an integral part of the Advanced and Digital Manufacturing Cluster (AFM) and a key player in the Basque Network of Science and Technology. The campus is composed of two main components: the Vocational Training Integrated Center of the Basque Government and the Elgoibar Dual Engineering School, which is affiliated with the University of the Basque Country (UPV/EHU). The campus is a specialized educational institution in Advanced and Digital Manufacturing and is actively engaged in lifelong learning and applied research in collaboration with industry. It is also a pioneer in implementing dual education in higher education in Spain, with over 25 years of experience in this model.

Graduates of the *Process and Product Innovation Engineering* bachelor's degree at Elgoibar Dual Engineering School—IMH Campus are highly regarded and enjoy excellent employability in the industry, largely due to the dual nature of their education. This educational model integrates academic learning with hands-on experience in industrial settings across different sectors. The curriculum is designed so that 75% of the credits are completed in the academic environment, while the other 25% is dedicated to project development within a company. Unlike traditional curricula, where the number of credits assigned to laboratory or company practices is relatively low, the dual model emphasizes the integration of theoretical knowledge with professional experience. In addition, in-person teaching is structured to strengthen skills that complement practical learning, allowing students to develop project design abilities within a business context, while fostering connections between the company and the school.

However, in recent years, some faculty members and the management of the center have identified certain areas for improvement in academic teaching. These include increased dropout rates, a higher percentage of failures in theoretical subjects, a lack of development of higher-order skills (such as metacognition and hypothetical thinking), and limited initiative or autonomy in problem-solving. To address these challenges, a working group was established during the 2022–2023 academic year. Its primary task was to investigate whether the perception of academic dissatisfaction was also shared by the managers and tutors of the partner companies involved in the degree's curriculum. In the follow-up meetings regarding the development of competencies within the companies, the managers and tutors expressed that the students' scientific knowledge and attitude were satisfactory. However, they emphasized the need to improve other competencies, such as teamwork, problem-solving skills, and the ability to acquire new knowledge, among others. Based on this feedback, the working group proceeded to update the degree curriculum and integrate an active learning approach into the credits delivered within the Elgoibar Dual Engineering School.

In relation to the curriculum update, the working group established the following general objectives (*Process and Product Innovation Engineering* degree; see https://www.ehu.eus/es/web/graduak/grado-ingenieria-innovacion-de-procesos-y-productos/verificacion-seguimiento-y-acreditacion, accessed on 2 April 2025). These objectives primarily focus on the following:

Conceptual and Procedural Competencies:

1. To gain a deep and meaningful understanding of engineering design;
2. To develop the ability to design and manufacture products using scientific and technical methods, enabling students to evaluate and make informed design decisions;
3. To foster teamwork skills.

Attitudes:

4. To increase students' interest in engineering and enhance their satisfaction with the learning process;
5. To raise awareness among students about the roles and responsibilities of engineers in society and help them recognize and address ethical issues.

Regarding the teaching approach to be implemented in the classes, the working group decided to adopt active learning techniques, which are widely supported by research in science and engineering education (Prince, 2004; Dancy & Henderson, 2007). Consequently, a problem-based and project-based learning (P^2BL) approach was chosen. Problem-based learning is a pedagogical strategy that presents complex tasks through questions or problems, encouraging students to design solutions, tackle challenges, make decisions, and conduct independent research. Moreover, by working on real-world products, it seeks to enhance student motivation (Dutch, 2001; Thomas, 2009). On the other hand, project-based learning focuses on guiding students through the processes of inquiry, knowledge construction, and problem-solving, culminating in the creation of a final product (Bell, 2010). The decision to shift the curriculum towards a problem- and project-based approach is grounded in evidence from educational research, which shows that both methods complement each other in shaping the skills of future engineers. The transition to this new curriculum framework is illustrated in Figure 1.

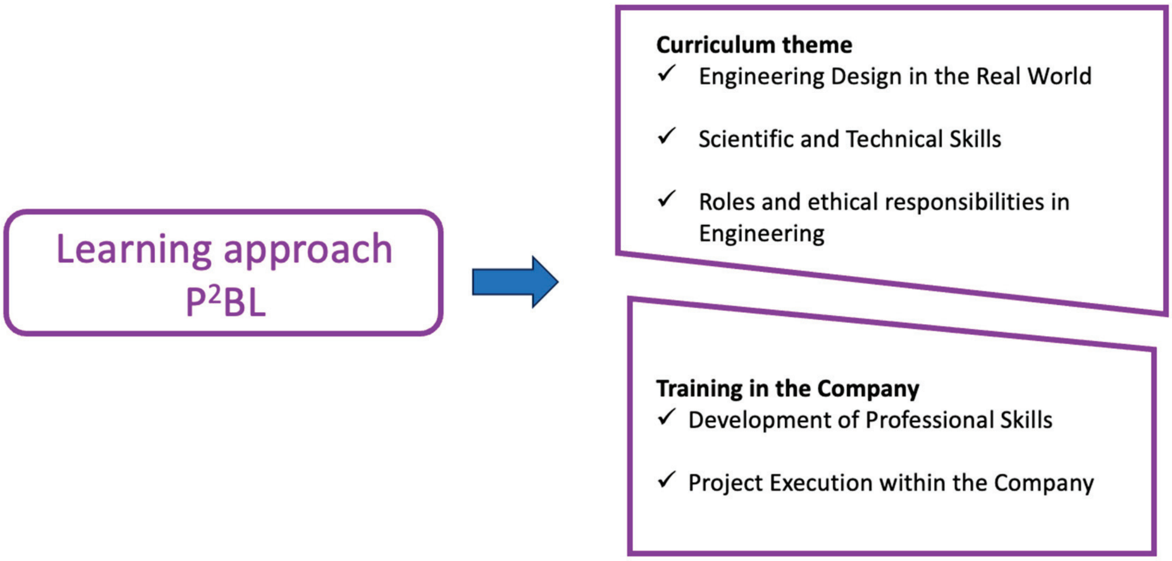


Figure 1. Framework for implementing an engineering-P^{2}BL dual curriculum.

3. Implementing the P^{2}BL Dual Curriculum Framework to Transform the Study Plan

The engineering degree curriculum is designed around the direct connection between theoretical studies, practical design, and problem-solving and project activities. The dual training in industry, combined with the academic curriculum, enables students to integrate key aspects of design and manufacturing. However, this integration presents a significant challenge in the first year of the program, particularly in teaching problem-solving and project-based learning.

The Elgoibar Dual Engineering School at IMH Campus has a long-established track record of incorporating projects into its curriculum. For decades, various initiatives have been implemented that were primarily focused on project-based problem-solving within company training (see https://www.imh.eus/en/engineering-school/dual-model-characteristics?set_language=en, accessed on 2 April 2025). However, our previous experience centered on outcome-driven projects and problems, whereas in this new phase, we aim to focus on the development of competencies and learning objectives. Projects and problems aimed at achieving specific results—such as improving a design or creating a prototype—are primarily designed to apply previously acquired knowledge and skills. In contrast, the projects and problems in the new curriculum are intended to foster the development of specific competencies and the acquisition of new knowledge throughout the process. Therefore, defining clear learning objectives is a critical first step in designing STEM projects and problems. When designing interdisciplinary STEM projects for the new curriculum, we face the challenge of accurately defining the competencies to be developed in each project.

Most students entering our engineering program come from a traditional educational system centered around knowledge transmission through "lectures" (a teacher-centered model) and have a limited understanding of engineering. When confronted with a different teaching model, conflicts can arise between students' established habits and expectations, often leading to frustration (Little, 1997). This presents a challenge in designing projects and problems that incorporate scaffolding activities to help students navigate the complexities of a P^{2}BL-based approach. One of the main challenges in designing and implementing the STEM projects in the new curriculum is equipping students with the necessary skills and helping them identify the knowledge they need to acquire to successfully complete the project. This is achieved by guiding students through an effective problem-solving/project approach and offering a mentoring program integrated into the academic schedule throughout the 14-week semester.

The new first year of the curriculum is organized into two 14-week semesters, each with its corresponding evaluation (see Figure 2). Each semester includes between one and three problems in each of the four to six disciplinary subjects, along with an interdisciplinary STEM project that spans the entire semester. Student groups consist of six members for the STEM project and three students for the problems and activities in the disciplinary classes. In the context of our problem- and project-based learning (P^2BL) curriculum, the learning process is primarily stimulated through small-group work. This approach provides students with the opportunity to develop collaborative skills that are essential in professional settings, such as those required in engineering teams. Furthermore, by being trained as independent learners, students engaged in PBL methodologies are expected to identify their own knowledge gaps and actively seek out the necessary resources to address them collectively (De Graaff & Kolmos, 2003; Jaques, 2000).

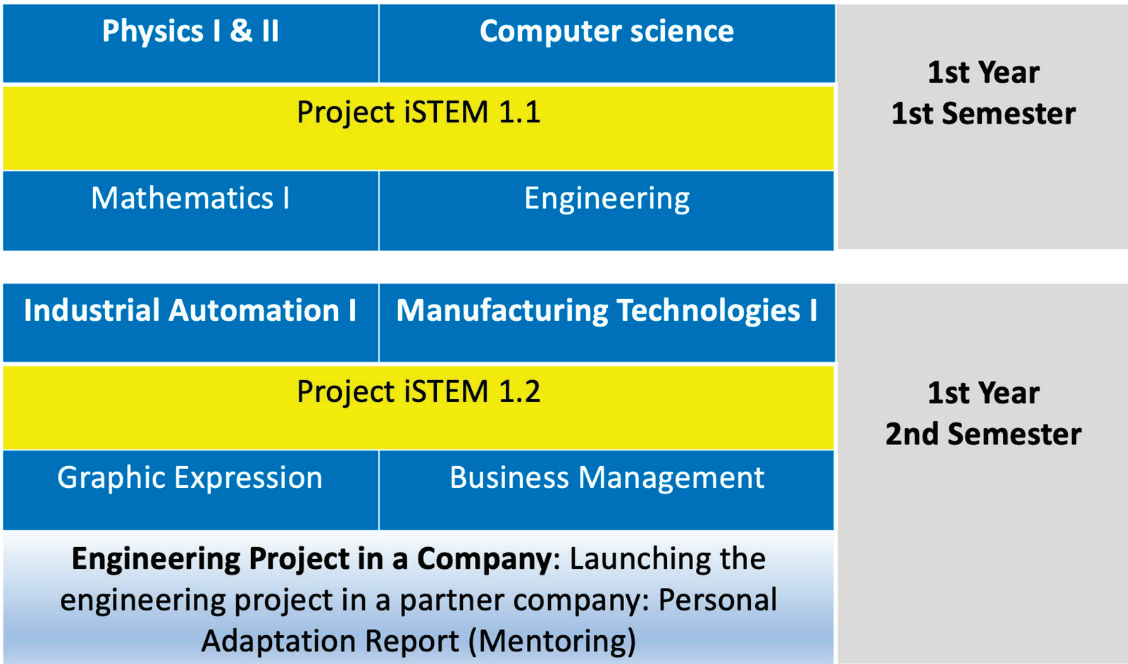


Figure 2. Interdisciplinary STEM projects integrated into the first-year curriculum of the engineering degree at IMH Campus.

Long-term interdisciplinary STEM projects (12 weeks) offer several advantages, such as reinforcing a comprehensive and deep understanding of the relevant disciplinary knowledge, motivating students to develop a more professional perspective of engineering, and helping them manage their time by focusing on a limited set of topics. Additionally, these projects foster collaboration among the professors involved.

The support for training students in problem-solving and projects serves as a guide for applying scientific–technical skills, generally following five steps. However, this is not a strict heuristic that requires all steps to be applied (Guisasola & Zuza, 2024):

(1) First, a context for the phenomenon or model to be analyzed in the project must be established. This context or problem should be accessible to students, but not obvious, and it should not necessarily have a single solution.
(2) After the presentation, students should be encouraged to express their initial ideas and hypotheses about the project through graphics, drawings, written arguments, etc. This marks the beginning of the knowledge acquisition process.

(3) During the process, prioritizing evidence is essential, whether through planning, evaluating, or developing a design that may be closed, structured, guided, or open.
(4) To make the project more realistic, it is beneficial to analyze real or hypothetical data, enabling students to represent, evaluate, and connect results. This allows them to confirm or reject their initial ideas using the analyzed data.
(5) Finally, students should resolve the project based on their learning. These conclusions must be communicated as students reflect on what they have learned, how they did it, and how their knowledge has been applied.

In this article, we will focus on the interdisciplinary STEM (iSTEM) project, which has been implemented for three years in the first semester of the first year of the engineering degree program. We will begin by outlining its design and implementation, and then present the evaluation approach and results in relation to the defined learning objectives.

Design and Implementation of an Interdisciplinary STEM Project Focused on Learning in the New Curriculum

We aim to establish a strong connection between the semester project and the concepts and challenges covered in the classroom. The project is introduced in two 4 h sessions at the beginning of the first semester. Throughout the semester, the link between the project and the course content is explicitly emphasized. At the end of the semester, two additional 6 h sessions are held to address students' questions about the project report. To support students in their work, a structured worksheet-style guide is provided (see Figure 3). Each worksheet (WS) includes tasks related to the project's key questions or problems that students must solve. Worksheets are an effective tool for fostering active learning through problem-solving and project-based approaches (Sujarittham et al., 2016). They help students focus on essential concepts and provide multiple representations to enhance comprehension. Worksheets are highly versatile and can be adapted to meet specific learning objectives. Students worked in groups of six, with each group being required to submit a completed worksheet.

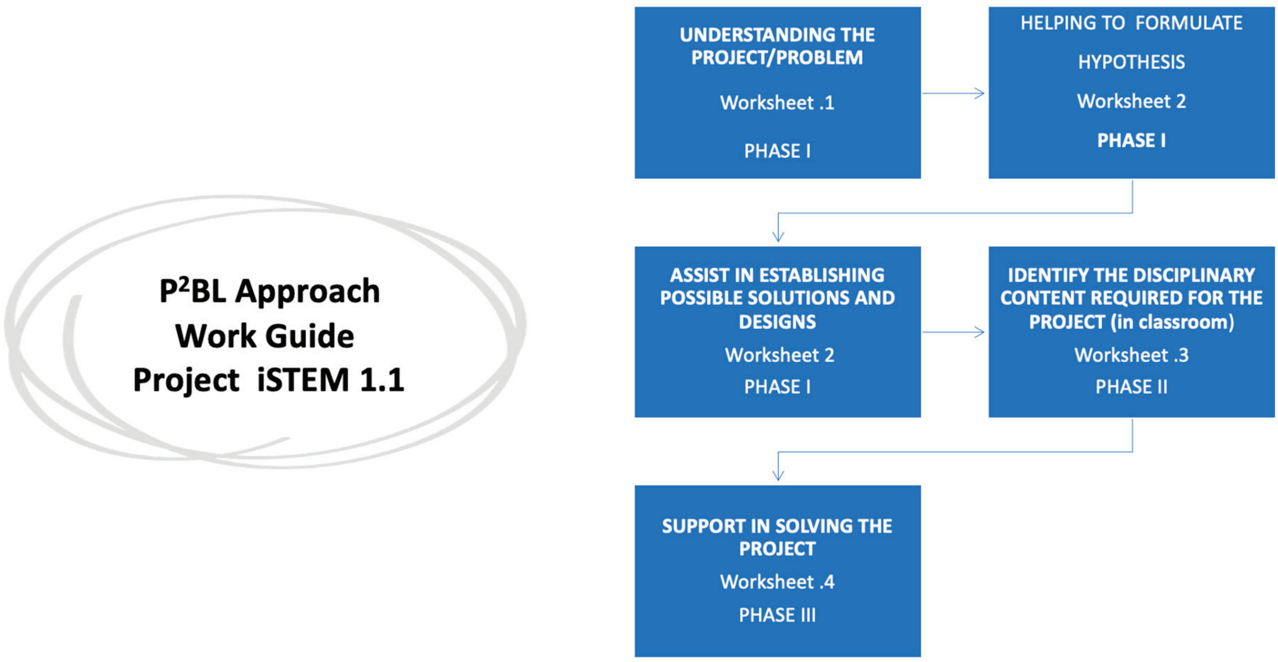


Figure 3. Interdisciplinary STEM (iSTEM) learning-oriented projects.

At the beginning of the first two sessions, the objectives and methodology for project-based problem-solving are introduced. Then, the problem statement is presented, and students work on Worksheet 1 (WS1).

For example, the project is introduced with the question: *"How can we achieve the most competitive machining process for a given part?"* A real-world scenario is provided, featuring a company that machines a part, identified as AFX29913 (IMH, Elgoibar, Spain), using three different machines: (i) Kondia-Seaska; (ii) Danobat TM-750; and (iii) Ibarmia ZVH-38 L1600.

Each machining process follows a different workflow to produce the same part, AFX29913. The machining process data for each machine, essential for developing the project, are provided. The company's primary goal is to determine which machine is the most competitive based on the following criteria: (1) lower energy costs; (2) machine efficiency; and (3) process speed.

After reviewing the project details, WS1 prompts students to answer the following questions to gain a deeper understanding of the project's objectives:

1. Describe the machining process under analysis. What is the initial part, and what is the final part? What process is followed to obtain the final part?
2. What variables are considered to evaluate the machining efficiency of the three machines? Explain the meaning of each variable.

In the second session, guided by the questions in WS2, students share their ideas on potential solutions for the project (see Figure 3). The focus is on planning the design and identifying the disciplinary content they need to learn, thereby initiating the knowledge acquisition process. Throughout the semester, students must track their learning across different subjects, both in class and through discipline-specific problem-solving activities. To support this process, WS3 serves as a guide, explicitly outlining the conceptual content from each discipline relevant to the project (phase II; see Figure 3).

In phase III (see Figure 3), students work with WS4, which helps them analyze data, evaluate results, confirm or reject initial hypotheses, and ultimately explain their approach to solving the project based on their learning and data-driven arguments. Additionally, WS4 guides students in preparing the project report, prompting them to reflect on and answer key questions such as the following:

Project Questions

- Define the project objectives.
- Outline the steps taken to solve it.
- What hypotheses were formulated for the resolution?

Definition of Process Variables

- Analyze the influence of each variable.

Evidence-Based Arguments for the Resolution Process

Project Summary with Recommendations and Conclusions

4. Evaluation of the Learning Impact Achieved During the Curriculum Change: Evaluation of the iSTEM Project 1.1

This section presents and analyzes the evaluation and subsequent refinement of the first version of the iSTEM 1.1 project, which was implemented in the 2022–2023 academic year, and whose second version was implemented in the 2023–2024 and 2024–2025 academic years. First, the preliminary evaluation is presented, with empirical evidence that guided the improvement of the initial version. Second, the results of the implementation of the refined iSTEM 1.1 project are discussed in relation to the learning achieved, the acquisition of scientific–technical skills, and the attitude toward project-based learning.

In our research, we conducted a retrospective analysis of the implementation of the iSTEM 1.1 project, using a multiple and convergent approach to highlight the various aspects of its evaluation (Nieveen, 2009; Guisasola et al., 2023). To achieve this, we proposed an analysis of results based on three dimensions (see Table 1):

(a) **Evaluation of the design's feasibility**, which includes the following:
  (a.1) Problems related to the clarity of activities that students must perform;
  (a.2) Problems related to the time required to complete the sequence;
  (a.3) Unexpected issues inherent in writing a new sequence with innovative content.

(b) **Quantitative and qualitative analysis of student learning**, which includes the following:
  (b.1) Conceptual understanding;
  (b.2) Acquisition of engineering procedures.

(c) **Evaluation of students' attitude and engagement with the project.**

Table 1. Assessment tools for the implementation of the iSTEM 1.1 project.

Instruments for detecting the viability of the design	Instruments for measuring the learning achieved through the implementation of the project	Redesign of the SEA
a. Teacher's diary b. Report of the observations made by the teaching staff during the implementation in the tutorials of the initial and final phases of the project	- Questionnaire on the understanding of concepts and laws included in the project (pre- and post-test) - Reports on the worksheets and final report - Attitude questionnaire	- Redefinition of writing topics, analogies, approach, etc. - Redesign of worksheets - Redesign of figures, graphs, etc. - Redesign of the project's prerequisites and its activities

For the analysis of the design's viability (first column of Table 1), we employed a qualitative research methodology with tools such as the teacher's diary and the teachers' observation reports (Carr & Kemmis, 1986). These tools are used as data sources to identify students' difficulties in understanding the objectives of the worksheets, as well as to deepen the teachers' understanding of the teaching methodology during the development of the projects. Our goal in this dimension is to ensure that the project's educational material is clear to the students and easy for the teachers to handle.

The assessment of the learning process relies on two main instruments (see the second column of Table 1): (a) a pre- and post-test questionnaire, administered individually to the students in an exam-like setting, aimed at measuring conceptual learning in each of the disciplines involved in the project; (b) a final report prepared by each student group, which presents, alongside their conceptual knowledge, the scientific and technical skills they used during the development and resolution of the project. For the analysis of the pre- and post-test questionnaires, we use descriptive statistics, such as the mean and standard deviation, for each variable studied. The students' final report is assessed using a rubric that considers the general engineering skills students should demonstrate to justify the project development and its outcomes.

To evaluate students' attitudes toward the project's learning process and their interest, a questionnaire with 20 statements on a Likert scale is used.

For the sake of brevity and to clearly illustrate how specific aspects of the evaluation influence the redesign, we first focus on the qualitative assessment and its impact on the reformulation of iSTEM 1.1, followed by the quantitative analysis of students' learning and attitudes. Both sections demonstrate how decisions were made to redesign elements of iSTEM 1.1.

5. Results of the First Version and Refinement of the iSTEM 1.1 Project

In the first implementation of the iSTEM project, during the first semester of the 2022–2023 academic year, the analysis of the information recorded by the teacher in the teacher's diary and the responses provided by students in the worksheets during the first implementation of the project showed evidence that students did not understand some of the objectives of the worksheet activities. For example, in Worksheet 3 (WS3), which student groups were supposed to fill out during phase 2, the students' responses did not distinguish between identifying the concept and determining where in the project they should apply it. For instance, one of the teachers wrote in their notebook how they presented WS3 in their classes:

> "Throughout the course, you will identify the necessary knowledge you mentioned in Worksheets 1 and 2. Now, you need to make these explicit in WS3. Once the necessary concept to develop the proposed challenge is defined, you must specify how it will be applied within the project."

However, the same teacher explained that:

> "Most students give the same response to questions 3 and 4; there is a misunderstanding of the questions, and they confuse the concept and its learning with the application of the concept in the project. They do not explain how the concept will be used and what problems it may solve."

These difficulties were shared by all teachers and persisted in the interpretation of WT3. This led to the reformulation of WS3, changing questions 3 and 4 in Worksheet 3 (see Table 2). The new questions focus on improving the wording to help enhance students' comprehension and provide better opportunities for reasoning.

Table 2. Rewriting of WS3.

WS3: "Once the necessary concepts to study in order to solve the project have been identified (Worksheets 1 and 2), in this worksheet, throughout the course, you must explicitly define each concept, as well as where and how you will apply it in the development of the project".	
Initial WS3	Revised WS3
1. Concept 2. Time of teaching in the course 3. At what point in the project statement is it used? 4. What is it applied for in the project?	1. Concept 2. Time of teaching in the course 3. How is the concept applied in the project and what problem does it solve?

The teachers' reports also highlighted discrepancies between the learning objectives defined for each subject and some of the questions in the pre- and post-test questionnaire used to assess learning. As an example, here we present a case from the Physics I course.

The responses to certain questions in the questionnaire revealed that students did not fully understand the objectives set. A particular case was Q1, whose learning objective (LO) was to assess the mechanical work done by constant or variable forces on a system using different strategies (analytical and graphical). Students did not interpret the question correctly and failed to explain the procedure used to calculate the work. In light of this difficulty, it was decided to reformulate Q1 and adjust the learning objectives to ensure better alignment between both (see Tables 3 and 4).

Table 3. Refinement of the learning objectives and Q1 in the Physics I course.

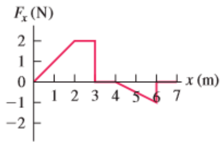
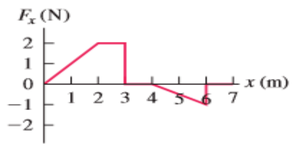
Learning Objectives and their Relationship with the Pre- and Post-Test Questionnaire Questions Initial iSTEM 1.1 Project	
Learning Objectives	Q1
LO2—Identifies the equation that represents the variable force in each graph and the variable position as a function of time. LO3—Plots the value of the force corresponding to each position in each section of the graph. LO4—Calculates the value of the work for each section of the graph, as well as the total work both analytically and through areas. LO6—Interprets the obtained results with scientific reasoning.	Q1. A 2.0 kg scale model car, controlled by remote, is pushed to a force Fx parallel to the x-axis as it moves along a straight track. The x-component of the force varies with the car's x-coordinate, as depicted in the figure. Calculate the work done by the force Fx as the car moves from: (a) x = 0 m a x = 3.0 m (b) x = 3.0 m a x = 4.0 m (c) x = 4.0 m a x = 7.0 m (d) x = 0 m a x = 7.0 m (e) x = 7.0 m a x = 2.0 m 

Table 4. Relationship between the teaching objectives and the questionnaire questions in the Applied Physics I course.

Learning Objectives and their Relationship with the Pre- and Post-Test Questionnaire Questions Initial iSTEM 1.1 Project	
Learning Objectives	Q1
LO2—Identifies the independent variables in the mechanical work equation. LO3·LO4—Calculates the value of the work for each section of the graph with variable and constant force by applying the appropriate analytical equations. LO5—Calculates the value of the work for each section of the graph represented graphically from the area defined by the force and position variables. LO6—Correctly calculates the total work value based on the work definition and provides sound reasoning for the results.	Q1. A 2.0 kg scale model car, controlled by remote, is pushed to a force Fx parallel to the x-axis as it moves along a straight track. The x-component of the force varies with the car's x-coordinate, as depicted in the figure. Calculate the work done by the force Fx as the car moves from: (a) x = 0 m to x = 2.0 m. Calculate analytically the work done by the force and justify your answer. (b) x = 2.0 m to x = 4.0 m. Calculate graphically the work done by the force and justify your answer. (c) x = 4.0 m to x = 7.0 m. Calculate graphically the work done by the force and justify your answer. (d) x = 0 m to x = 7.0 m. Calculate both analytically and graphically the work done by the force and justify your answer. (e) x = 7.0 m to x = 2.0 m. Calculate both analytically and graphically the work done by the force and justify your answer. 

In summary, based on the empirical data obtained from the journals and observation reports of the teachers during the first implementation of the iSTEM 1.1 design, the changes made include not only the reformulation of objectives and the questionnaire but also the revision of some activities in the worksheets to adapt them so that students could better understand their purpose and stimulate their interest in learning. The revised iSTEM 1.1 project was implemented with all first-semester students in the 2023–2024 and 2024–2025 academic years.

5.1. Results Regarding Students' Learning from the Implementation of the Revised Project During the 2023–2024 and 2024–2025 Courses

The conceptual learning of the students who participated in the project has been assessed through the results of the pre- and post-test questionnaire in each of the integrated disciplines. Data from all disciplines were collected during the 2023–2024 and 2024–2025 academic years, and statistical analysis has allowed for the determination of the impact of the iSTEM 1.1 project on student learning. Additionally, the learning and use of scientific and technical skills were evaluated through the analysis of the final report created by the student groups in the WS4 Worksheet. On the other hand, the students' interest and attitude towards the project, its objectives, and the working methods were measured using a Likert scale with a 1–10 interval. Below, we present some of the results in each of the described sections.

5.2. Results Regarding Students' Conceptual Understanding of the Concepts and Theories Included in the Project

Given the need for brevity in this article, we will focus on the results obtained in the Physics I course, as they are representative of the outcomes in the other subjects. Table 5 outlines the connection between the four questions of the Physics I questionnaire and the defined learning objectives.

Table 5. Relationship between the aim of the question and the learning objective in the Physics I topic.

Questions	Learning Objetives
Q1	Q1. See Table 4 Ask students to analyze and calculate the work done on a car model using constant or variable forces, applying both analytical (LO3 and LO4) and graphical (LO5) strategies. They must identify the variables that influence the process (LO2) and calculate the total work by summing the work characteristics of the different parts of the trajectory (LO6).
Q2	Q2. An object on a horizontal surface with friction moves at a constant speed, pushed by a person with a force of 4 N over a distance of 3 m. Is the total work done on the object positive, negative, or zero? Explain your answer. Ask students to analyze the work done by all forces on the object and justify their response (LO3 and LO4).
Q3	Q3. A force of 100 N is applied to system A, performing 50 J of work over a time interval of 25 s. A force of 50 N is applied to system B, performing 100 J of work over a period of 25 s. Which system has greater mechanical power? Justify your answer. Test the students' ability to identify the variables that define the mechanical power of a system and establish the relationships between them (LO7).
Q4	Q4. In several systems of units, conversion between different magnitudes is needed. Perform the following conversions: 1 dina $\rightarrow$ N 6 cm $\rightarrow$ hm 1 kW $\rightarrow$ kgm/s 8 kg $\rightarrow$ utm 4 mm $\rightarrow$ dam Test the students' ability to recognize and use appropriate units for the phenomenon being analyzed (LO1)

The pre- and post-test questionnaires were administered to students under exam conditions, and the results were included as part of the final grade for the subject unit. The scores from the pre-test and post-test were compared for all students in the 2023–2024 (N = 54) and 2024–2025 (N = 42) cohorts. The questions are analyzed according to a 1 to 4 scale on a rubric for achieving the learning objectives and are presented in Table 6, showing the mean and standard deviation of the scores obtained for each question. Some of the questions have been discussed in previous papers on student difficulties and improvements using a new engineering curriculum based on problem- and project-based learning (Gutiérrez-Berraondo et al., 2024). We summarize the relationship between the pre- and post-test questions in Table 6.

Table 6. Statistics of the scores obtained for each question and the level of significance (calculated using the Wilcoxon Signed-Rank test and Cohen's d, which is a measure of the effect size) of the comparisons between the pre-test and post-test in the 2023–2024 and 2024–2025 cohorts.

	2023–2024						**2024–2025**					
	Pre-Test		**Post-Test**		***p*-Value**	**Effect Size (r)**	**Pre-Test**		**Post-Test**		***p*-Value**	**Effect Size (r)**
	M	**SD**	**M**	**SD**			**M**	**SD**	**M**	**SD**		
Q1	1.14	0.69	2.62	1.04	$p < 0.05$	0.64	1.32	0.85	3.19	1.02	$p < 0.05$	0.71
Q1a	1.06	0.24	2.47	1.36	$p < 0.05$	0.58	1.84	1.21	3.43	0.96	$p < 0.05$	0.59
Q1b–c	1.06	0.24	2.24	1.19	$p < 0.05$	0.57	1.00	0.00	3.11	0.97	$p < 0.05$	0.84
Q1d	1.06	0.24	2.00	0.87	$p < 0.05$	0.59	1.03	0.16	3.43	0.90	$p < 0.05$	0.88
Q1e	1.38	0.60	1.76	0.69	$p < 0.05$	0.30	1.00	0.00	3.43	0.90	$p < 0.05$	0.89
Q2	1.21	0.47	2.03	0.92	$p < 0.05$	0.49	1.51	1.04	3.43	0.96	$p < 0.05$	0.69
Q3	2.59	1.44	1.91	1.07	$p = 0.056$	0.26	1.00	0.00	3.16	1.28	$p < 0.05$	0.77
Q4	1.12	0.20	2.47	0.75	$p < 0.05$	0.78	2.57	1.48	3.59	0.80	$p < 0.05$	0.43

In all the questions and their learning objectives (LO1–LO7), the mean scores of the post-test are significantly higher than those of the pre-test, indicating progress in the understanding of the assessed concepts. The standard deviation (SD) in the pre-test is generally greater, suggesting a higher level of dispersion in the initial knowledge of the students. In the post-test, the SD is lower in most cases, reflecting greater homogeneity in learning after the intervention. The Wilcoxon Signed-Rank test p-values are below 0.05, confirming that the differences between the pre-test and post-test are significant and not due to chance. This indicates that the intervention has had a considerable impact on learning, with the most pronounced effects in the results of questions Q1b, Q1c, Q1d, Q3, Q1e, and Q2. This suggests that students showed a significant improvement after the intervention in calculating work from algebraic representations and force–position graphs (LO3, LO5, and LO7). The objective LO7 (question Q3) has improved notably, with the majority of students successfully identifying the variables that measure power (LO7). This suggests that the revised iSTEM 1.1 project was effective in developing students' conceptual knowledge. However, the objective LO1 (use and conversion of units depending on the systems used), related to Q4, shows a smaller effect size difference compared to the other objectives. Attention must be given to this aspect in the teaching of the project.

When comparing the results of the two academic years, it can be observed that the trend between both iSTEM 1.1 cohorts shows greater improvement in the second intervention, with higher statistical significance and larger effects. This could indicate that the intervention is better understood by the faculty in terms of its implementation or that active teaching strategies are better mastered. Another factor that could influence this is that it is the third year of implementation within the new degree curriculum, and students have integrated the new way of working into their learning process. This last hypothesis is also supported by the results of the evaluation of the attitude towards learning, as shown in Section 5.4.

5.3. Results on Students' Application of Engineering Skills in the Project

The results of the use of engineering skills are obtained using a rubric with a score ranging from 1 (no use) to 4 (satisfactory use), depending on the level of application of the skills (see Table 7). The rubric is applied in the analysis of the final project report (WS4), where the groups of students report, argue, and calculate the results related to the development of the project. The results are shown in Table 7 and Figure 4 and correspond to academic years 2023–2024 (nine groups of six students) and 2024–2025 (seven groups of six students).

Table 7. Results of the analysis of the reports of the groups of students who carried out the project.

Scientific–Technical Skills	Number of Groups by Level of Achievement							
	2023–2024 (9 Groups)				2024–2025 (7 Groups)			
	Level				Level			
	L4	L3	L2	L1	L4	L3	L2	L1
S1. Describes the project and explicitly indicates its characteristics	2	4	3	-	2	4	1	-
S2. Properly states the initial development of the project and describes the hypotheses	1	-	-	8			6	1
S3. Correctly identifies the variables and how to measure them	5	4	-	-	3	3	1	-
S4. Lists the steps to carry out the project and makes them adequately explicit	3	3	3	-	-	4	2	1
S5. Explains the results obtained in relation to the hypotheses and takes into account their specific conditions and limitations	-	-	9	-	-	4	2	1
S6. Adequately uses the mathematical and computational representations related to the project	3	4	2	-	4	2	1	-
S7. The solution to the project presents explanations based on evidence, technological feasibility, cost, safety, and compliance with legal requirements	1	1	6	1	3	3	-	1
S8. Adequately explains the positive and negative aspects of the project solution	.	1	2	6	-	6	1	-

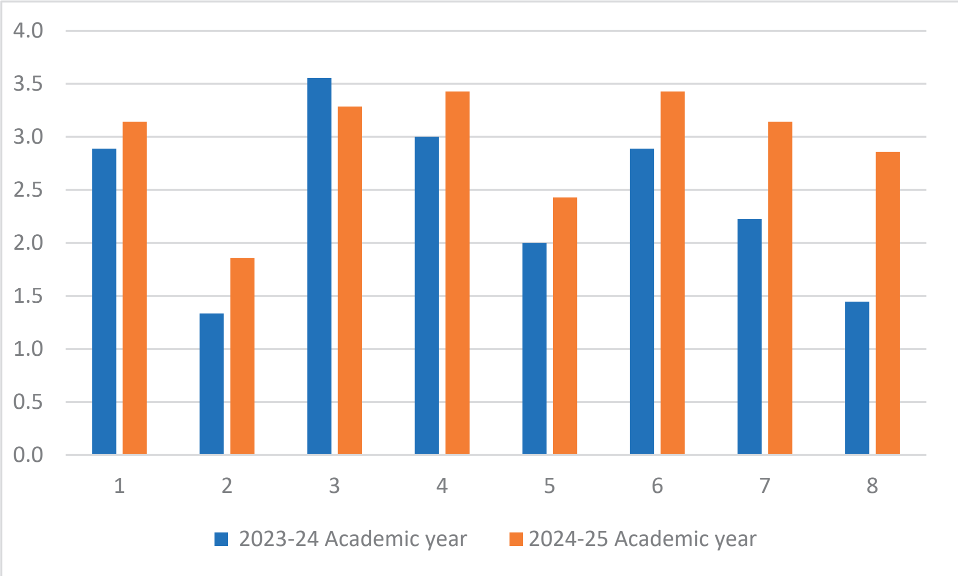


Figure 4. Average scores by level (ranging from 1 to 4 points) for each skill across academic years.

In the reports, most of the groups use skills 1, 3, 4, and 6 with scores of 3 or more to explain how they construct the steps to reach a solution, argue based on evidence, and consequently construct explanations. At skill level 7, there is a significant increase in performance from the 2023–2024 to the 2024–2025 academic year. In 2024–2025, all groups except one (six out of seven) achieved scores in levels L3 and L4, whereas in 2023–2024, only two groups reached these levels. However, an exception is observed in the ability to adequately state and describe hypotheses, which presents a lower performance compared to the rest (skill 2). This result is in agreement with the lower use of the analysis of results in relation to the hypotheses issued (skill 5). This situation could be related to the lack of previous training in scientific methodology by the students, suggesting that they are unaware of the concept of hypotheses and, therefore, have not developed this skill adequately. It is worth noting the improvement from the 23–24 course to the 24–25 course in the explanations of the solution obtained and its positive and negative aspects (skill 8). In this aspect, the professors analyzed the results of the 23–24 course and focused their explanations of the results of the project on explaining the need for good communication on both the projects and results in engineering.

In general, Table 7 shows an improvement in the use of the skills assessed from one academic year to the next, with most of them reaching levels above L2. However, the data for skills 2 and 5 reflect low utilization of the skills related to hypothesizing and using them for verification. These results are in agreement with other studies on the use of hypotheses in problem-solving (Ferguson-Hessler & De Jong, 1990). The results of S2 and S5 show a persistent difficulty in the acquisition of these skills by students. It is important to further analyze the causes of these difficulties for the design of future materials.

5.4. Students' Results Regarding Their Attitude Toward Project-Based Teaching

To evaluate the opinions and attitudes of the students about the contents worked on during the project, the way of working during the development of the project, and their satisfaction, a questionnaire was prepared with statements that are scored by the students between 0 and 10 according to their agreement (totally agree: 10 points) or disagreement (totally disagree: 0 points). Table 8 presents some results taking into account the median and standard deviation statistics that are appropriate for this type of analysis with a Likert scale (Cohen et al., 2007).

Table 8. Medians and standard deviations of students' scores and their attitudes towards some of the statements from the protocol in the 2024–2024 and 2024–2025 courses.

	2023–2024 Year Median (Standard Deviation)	2024–2025 Year Median (Standard Deviation)
THE CONTENTS THAT HAVE BEEN WORKED ON		
1. The amount of contents has been adequate.	7.0 (1.21)	7.3 (1.16)
2. The objectives pursued were clear (you knew what they were going to be used for).	7.0 (0.89)	6.4 (1.38)
3. When new concepts were introduced, they were related to the ones that had been introduced before.	7.0 (1.23)	7.0 (1.37)
THE WAY OF WORKING DURING THE PROJECT		
4. The teaching method was adequate to the contents covered.	7.0 (1.08)	7.0 (1.12)
5. The activities proposed in class were adequate so that they could be solved by the students.	7.0 (1.32)	6.9 (1.51)
6. There were common discussions that helped to clarify the solutions to the activities.	7.0 (1.54)	6.5 (1.67)
THE SATISFACTION WITH WHICH THE PROJECT HAS BEEN WORKED ON		
7. The classes of the project have managed to attract my attention.	6.0 (1.87)	6.6 (1.92)
8. There is support and willingness on the part of the teacher of the project and subject to help students overcome their difficulties.	7.0 (2.17)	7.5 (1.95)
9. In the class there has been a climate of cooperation among the students.	8.0 (3.26)	7.4 (3.17)

It was observed that the attitude of the students during the development of iSTEM 1.1 was positive, with scores between 6 and 8. The standard deviations in this context indicate a relatively low dispersion in comparison with the total range of the scale. The general trend from one academic year to the next has been to maintain these scores, except in items 2, 6, and 9, where a slight decrease was observed, but the dispersion above the median also increased as the standard deviation increased. In particular, item 2 reflects that the students' perception of the understanding of the project objectives did not improve with respect to the previous year. Although the difference is not significant, for the next course, it will be important to consider this aspect when presenting the project to the students. In item 9 on the climate of cooperation among students, although the evaluation is very positive, there is a higher dispersion than in the other items. In the explanations given by the students regarding their evaluations, in this item, it is observed that a significant group of students think that they have worked more than their group mates and that others have taken advantage of their work. This feeling in some students is significant and should be introduced in subsequent courses, fostering group dynamics that allow equity and equality in the contribution to the work of each student in the group.

6. Conclusions

We have outlined the teaching approach of the Dual Engineering curriculum at IMH Campus, which is based on a problem- and project-based learning (P^2BL) model that incorporates active learning strategies. The decision to structure the curriculum around problem- and project-based methodologies is supported by educational research, which demonstrates that both approaches complement each other in developing the competencies of future engineers. To illustrate this approach, we chose to describe one of the key teaching tools that bring it to life: long-term interdisciplinary STEM (iSTEM) projects. These projects offer several advantages, such as fostering a deeper and more comprehensive understanding of disciplinary knowledge, encouraging students to develop a more professional perspective on engineering, and helping them manage their time by focusing on a well-defined set of topics. Specifically, we detailed the design, implementation, and development of the iSTEM 1.1 project, which was undertaken by first-year students during their first semester.

The iSTEM project is designed to create teaching materials that establish strong connections between the project and the key concepts and challenges addressed in various disciplines throughout the semester. During its implementation, it became evident that engaging with the iSTEM project significantly benefited students, as reflected in their improved post-test scores. However, teachers also reported that some students faced difficulties in understanding and interpreting certain worksheet activities.

An important aspect of evaluating new approaches is the redesign of materials, which allows us to adjust the learning objectives we aim to teach. The analysis of the results from the first implementation of iSTEM led to a review that introduced substantial changes to the worksheets, both in terms of wording and teacher annotations related to their presentation to students. This resulted in the revised iSTEM project. Student achievement in conceptual understanding and the application of engineering procedures was higher with the revised project compared to its first-year implementation. Subsequently, the results with the revised iSTEM remained consistent in the second and third years of application.

An evaluation of the revised iSTEM project implementation revealed that most students successfully achieved the curriculum's learning objectives, both in conceptual understanding and in the application of scientific skills. Furthermore, no negative effects were observed when comparing student learning outcomes to those of the previous lecture-based curriculum. Additionally, students' attitudes toward the new iSTEM project methodology showed a marked improvement, with increased engagement and interest. This contrasts with the dissatisfaction expressed under the traditional curriculum, concerns that were a key factor in the shift toward the P^2BL model.

It should be recalled that the implementation of the iSTEM project was carried out in small engineering groups (between 40 and 50 students) on a privately managed campus. We do not have data on how it would work in larger groups in other universities. However, based on our teaching experience, we believe that our design may be useful for those teachers who are trained in active teaching strategies such as problem-solving and projects. We believe that our materials will help these teachers implement the active teaching approach that they recognize as more effective than the traditional one. On the contrary, we believe that our iSTEM design will not work in teaching contexts where teachers are primarily limited to transmitting knowledge and conducting an evaluation at the end of the semester. We feel that these teachers are not accustomed to developing the class by offering students opportunities to learn the concepts and laws while practicing scientific skills, which is a requirement of the P^2BL approach.

The value of these results is limited to one of the teaching materials that make up the new curriculum, the iSTEM projects. It does not tell us what the effect is of other changes in the curriculum, such as the introduction of active teaching techniques in the classes of each discipline. We have not shown whether these other changes, also with the P^2BL approach, produce similar or better changes more effectively and with the optimization of research efforts. This will be the focus of our next studies.

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Article

Solving STEM-Relevant Problems: A Study with Prospective Primary School Teachers

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Abstract: Solving a problem requires and promotes a diversity of competencies, which include conceptual knowledge, technical and methodological knowledge, and transversal competencies. Everyday STEM-relevant problems are contextualized, ill structured, and multidisciplinary in nature. By focusing on daily life issues, they promote students' engagement in the problem-solving process and enable them to perceive how science relates to their lives. This paper aims to characterize the processes followed by prospective primary school teachers when solving three STEM-relevant problems that have different features. The qualitative analysis of 77 participants' answers showed that complete problem-solving pathways were one among a variety of other paths identified. Most strategies adopted by the participants led them to ignore the contextual conditions of the problem and to reach solutions that did not attend to them. The affective relationship with the object may increase the problem solver's tendency to ignore the contextual conditions, but this issue deserves further research. The results shed some light on the features of the problems that teacher educators should select if they wish for their prospective teachers to learn and succeed in solving everyday STEM-relevant issues. This is required to promote their future students' engagement in problem-based learning processes.

Keywords: problem solving; STEM-related problems; everyday problems; prospective primary school teachers; science education; problem-based learning

1. Introduction

We are entering the second quarter of the century, and it continues to be important to argue for the promotion of skills recognized as necessary for 21st-century citizens. There is a need for schools to put 21st-century skills on the agenda. This means that they should educate children to become responsible, active, autonomous, and supportive people, who know and exercise their rights and duties, in dialog and with respect for others and with a democratic, pluralistic, critical, and creative spirit (OECD, 2009, 2023). These skills are required for citizens to engage in individual and collective processes that call for reflection and action regarding problems and dilemmas felt by each individual and society (OECD, 2018, 2023).

Nowadays, the most serious problems affecting society (e.g., climate change, the energy transition, water scarcity, and food provision and security) are partly due to the inappropriate ways in which man has used science and technology developments (Cheng et al., 2021). However, science and technology may offer solutions to these problems (J. Chen et al., 2023; Pickering et al., 2022) if research efforts and good will allow it. The issue is that some ordinary citizens and politicians avoid facing these problems directly. This is probably because, as some research suggests (Gautam et al., 2021; Moore et al., 2024; Kulin et al., 2021; Huber et al., 2022; Ricart et al., 2019), they are not fully aware of how threatening these problems are for life on Earth. A possible reason for this may lie in the inability of science education to develop the scientific literacy of 21st-century citizens and to equip them with skills that are relevant for every science-literate and responsible person.

More than a decade ago, Dayna Laur (2013) argued that students should engage with complex, action-oriented problems driven by open-ended, real-world questions that promote the development of 21st-century competencies (namely, critical thinking, collaboration, communication, and creativity). Later, the Science Education for Responsible Citizenship Report (European Commission, 2015) added that

> *"As the world faces these complex challenges, our ability to resolve these issues on our own or within our field of knowledge shrinks. Due to their scale and complexity, these major social and economic problems transcend borders and disciplines and necessitate new ways of thinking and methodological and organizational frameworks".* (p. 20)

The recognition of this need may underlie the growing interest in integrated STEM (science, technology, engineering, mathematics) education, which enables students to engage with complex real-world problems that intersect across multiple fields (Pleasants, 2020); this raises their interest in science, especially if the problem tasks are meaningful to them (Broman et al., 2022). Research (Kennedy & Odell, 2023; Tan et al., 2023) has shown that STEM approaches assume an interrelationship among science, technology, engineering, and mathematics. Everyday problems are ill-structured and encompass decision-making problems and design problems, among others (Walker & Leary, 2009). Decision-making problems require the solver to select from a set of alternatives and to assess the risks and benefits of their choice. Decision-making is an important skill in other more complex and ill-structured problems, such as design problems (Jonassen, 2012). The latter include planning and building a more or less technical product that incorporates knowledge that crosses disciplines (Walker & Leary, 2009).

Pleasants (2020) distinguishes between pure STEM and STEM-relevant problems, considering that the latter retain the contextual dimensions of complex issues (e.g., the social, cultural, political, and ethical dimensions), which the former relegate to the background and transform into context-specific boundary conditions. This difference may explain why STEM problems (based on scientific subject matter and its associated practices) often appear distant to learners (Mauffette et al., 2004) and why learners struggle when they try to make meaningful connections between science and their daily experiences (Tan et al., 2023). Although some students extract multiple pieces of information from the context in which each problem is embedded (Broman et al., 2018) and perceive the contextual information as relevant, others see it as unimportant and claim that it acts as a distractor (Broman et al., 2022) when they try to solve the problem.

Students' ability to extract information from a problem may differ from their level of reasoning and argumentation (Chi et al., 2023); in some cases, the former is greater than the latter. According to Tan et al. (2023), the extraction of information from a problem is influenced by specific words or examples provided in the task. Some students fail to integrate the information extracted and the knowledge that they activate to design a solution for the problem at hand. In addition, only a few students can comprehend the problem fully (Wider & Wider, 2023) due to a misunderstanding of the contextual information provided. Students might need appropriate scaffold prompts to use higher-order thinking and to develop answers that are more complex (Löffler et al., 2018; Tan et al., 2023; Vasconcelos & Pinto, 2023) and that align better with the problem's context and demands. Although most students can execute a part of the solving process correctly, only a few can obtain the entire solution correctly and reflect on the answers that they achieve (Wider & Wider, 2023).

Integrating STEM-based and problem-based approaches leads students to use sophisticated thinking strategies to process information (Contente & Galvão, 2022) and to improve their problem-solving skills (Ahmadi et al., 2023; Siswanto et al., 2024), with a specific emphasis on problem identification (Ahmadi et al., 2023) and scientific methodology skills development (Contente & Galvão, 2022). Students may also learn ways of speaking, doing, and being, as they solve integrated STEM problems in school (Tan et al., 2023). These transversal competencies are also worth developing in school education, as they are associated with communicating and relating to others and have a sphere of influence that has been increasingly found to cross country borders.

In real life, as in school, when encountered for the first time, a problem offers an obstacle to the problem solver, which the solver does not know how to overcome. However, he/she needs to overcome the obstacle to reach one or more solutions to the problem or to conclude that there is no solution to it (Jonassen, 2004; Neto, 1998; Pozo et al., 1995). Thus, a problem differs from an exercise, as the latter does not offer a meaningful obstacle to the solver, who knows how to solve it after learning the related content. Thus, the main goal of solving exercises is to train using previously acquired knowledge (Jonassen, 1997; Torregrosa, 1987).

Problems may be quantitative or qualitative/conceptual (Maries & Singh, 2023) and open or closed, but a problem statement usually does not include, at least explicitly, all data needed to solve the problem (Neto, 1998; Pozo et al., 1995; Torregrosa, 1987). When the problem solver learns how to solve a problem, it ceases to be a problem for him/her (Jonassen, 1997; Neto, 1998; Torregrosa, 1987), as the obstacle that is unique to the problem no longer exists.

Solving a problem requires and promotes a diversity of conceptual and procedural competencies, ranging from conceptual knowledge to technical and methodological knowledge, including transversal competencies like reasoning, creativity, planning, inquiry, analysis, synthesis (Contente & Galvão, 2022; Maries & Singh, 2023), and evaluation. Problems are more versatile than exercises. Problems may be used before, during, and after teaching the content that underlies them (Leite & Esteves, 2005), thus serving as learning, teaching, and assessment tools (Yerushalmi & Eylon, 2015). Problem-based learning is an example of the use of a problem as a starting point for learning (Boud & Feletti, 1997; Lambros, 2004). This means of using problems differentiates them from exercises, as the latter require previously learned knowledge, while the former may work as a tool to acquire new knowledge.

The literature shows that people may use diverse approaches (Hsu et al., 2024) and cognitive and affective tools (Hsu et al., 2024; Oh, 2024) to solve problems. This is because problem solving is a complex and nonlinear activity (Price et al., 2021; Wang et al., 2023) influenced by a multitude of factors (Wang et al., 2023). These include the appropriateness of the knowledge and skills that problem solvers activate (Price et al., 2021). To increase the probability of solving a problem successfully, a problem solver should follow a general strategy (Amanda et al., 2021; Çavaş et al., 2023; Lambros, 2004; Leite & Afonso, 2001) composed of four main steps. They are as follows:

(i) Performing a qualitative analysis of the problem to determine what is given in the problem statement, what the solver already knows about it, and what he/she needs to know and do to solve the problem. This requires the interpretation and extraction of information from the problem statement. This process is influenced by the problem solver's analytical capabilities, level of literacy, previous knowledge, and experiences, as well as his/her interpretation of the problem request.

(ii) Planning a strategy to move from what is given in the problem statement and known by the solver to what he/she needs to know and do to reach a solution (if there is one) to the problem. This includes planning, identifying specific tasks and relevant factors that may affect the situation described in the problem, locating relevant information sources, and selecting pertinent knowledge. Building an interdisciplinary team may also need to be considered.
(iii) Implementing the planned strategy and reviewing it if necessary, which requires the continuous monitoring of the development of the tasks, self-monitoring of the problem solver's actions, and the ability and courage to replace any part of the strategy that is not working, if applicable.
(iv) Evaluating the result against what is given in the problem statement and its perceived goal. This requires a critical examination of the result obtained to judge whether it is reasonable and consistent with the request of the problem.

These four steps are presented sequentially, but it should be stressed that they usually need to be implemented iteratively. They are umbrella steps that can encompass a diversity of strategies that may depend on the content of the problem (Hsu et al., 2024; Oh, 2024; Price et al., 2021).

Research has shown that some students fail to put into practice step (i), as they do not interpret the problem statement properly (Amanda et al., 2021; Maries & Singh, 2023; Silva et al., 2013) or are unable to understand the problem request (Ogunleye, 2009; Reddy & Panacharoensawad, 2017; Saka et al., 2024) or to extract information from it (Broman et al., 2018; Maries & Singh, 2023). These failures interfere with the next steps and may lead to unintended results. This interference is more important in contextualized problems than in academic ones (Salta & Tzougraki, 2010), as, in the former case, the solution needs to be situated in the context given in the problem statement. Research has also shown that many students fail in step (iv), as they do not finalize their reasoning or do not make critical and evaluative judgments of the results obtained (Maries & Singh, 2023; Silva et al., 2013). A consequence of this is that they may present a nonsensical result.

To help students to develop their problem-solving competencies, teachers should be familiar with their students' relevant initial knowledge and literacy levels and select problems that are authentic and relevant to the lives of their students, thus increasing the probability of their participation and motivation (Ayerbe-López & Perales-Palacios, 2023). Research on chemistry education (Broman et al., 2022) suggests that students may perceive science as relevant when they find it worthwhile, meaningful, and important to learn. In addition, teachers should help students to solve problems by providing appropriate scaffolding support (Maries & Singh, 2023). Moreover, teachers should be familiar with the problem-solving process and feel comfortable in solving problems and teaching problem solving. Initial teacher education should prepare teachers for this task. Teachers (Morgado, 2013) and teacher educators (Aidoo, 2023) believe that it is worth including problem-based learning in teacher education programs, but this is seldom implemented in preservice teacher education. Therefore, more research is needed on problem-based learning (Magaji et al., 2024) and the problem-solving processes followed by preservice teachers.

This paper aims to characterize the processes followed by prospective primary school teachers (PPSTs) to solve three everyday STEM-relevant problems, which differ in the information they provide, and the affective relationships that people establish with the key objects mentioned in the problem. The results will demonstrate how PPSTs approach different problems and the obstacles that should be overcome before they solve problems successfully. The results will also shed some light on the features of the problem statements that teachers should select if they wish for their students to learn how to solve

STEM-relevant problems. They will provide useful information for the improvement of prospective teachers' training on problem-solving-related topics.

2. Materials and Methods

2.1. Research Question and Design

In line with the research objective presented in the previous section, this research aims to answer the following question: How do PPSTs approach problem solving in STEM-related contexts?

Answering this question requires PPSTs to solve STEM-related problems. This would offer insights into how each participant approaches each problem based on his/her previous knowledge and experiences. Data were collected in a context that was as natural as possible (their usual classrooms) and no a priori categories were imposed on the data. Hence, our interpretation of the data allowed us to uncover and understand the diverse approaches that the group of participants used to solve the problems. Thus, this study fit into the qualitative paradigm (Sherman & Webb, 2005) and adopted a phenomenography design (Marton, 2005).

2.2. Participants

This study was conducted with undergraduate students attending a Basic Education program at a Portuguese university. Successful completion of this program is required to be admitted to a primary school teacher training Master's to teach 6- to 12-year-old children. Before enrolling in the undergraduate program, the students complete secondary school (12th grade) in a STEM or humanities area. In addition, they have to pass two compulsory national exams: Portuguese Language and Mathematics. During the undergraduate program, starting in the first year, they take Portuguese, Science, Mathematics, History, Geography, Arts, Physical Education, and Education courses. When the PPST were invited to participate in the study, they were enrolled in the third year of their undergraduate studies. To the best of our knowledge, they had undergone no previous formal training in solving problems similar to the ones used in this research.

The 77 students who attended classes on the day that the data collection took place were invited and accepted to participate in the study. This means that they agreed to answer the questionnaire described below. As mentioned above, this study was a qualitative one. However, working with a large number of participants, namely PPSTs, ensured that we achieved data saturation and obtained a good picture of the diversity of the strategies that may be used to solve such problems.

2.3. Technique and Instrument

This research focused on uncovering the processes followed by PPSTs when solving everyday STEM-relevant problems. To do so, it was necessary to have a set of purposefully chosen problems and to ask the participants to solve them individually and in writing. The problems dealt with situations that PPSTs might encounter in their personal or familiar daily lives and were contextualized within normal life. In addition, they required some scientific, mathematical, engineering, and technological knowledge, even though the diverse STEM components could have different weights in the diverse problems. They also had different features concerning data provision and the potential affective link between the individuals and the key object of the problem, as the latter may affect the problem-solving process. Then, it was decided to use three problems with the following general features:

- Problem 1—familiar and emotional object, common situation, with data;
- Problem 2—familiar and emotional object, common situation, no data;
- Problem 3—familiar but neutral place, new situation, no data.

Problem 1 (the hairdryer problem) was adapted from a previous study (Silva et al., 2013) and it was of a decision type (Walker & Leary, 2009). Problems 2 (the computer problem) and 3 (the institute's garden problem) were purposefully designed for this study. The former was of a decision type and the latter was of a design type (Walker & Leary, 2009). Two authors who were experienced in teaching and researching problem-based learning created the problems. Two other authors (one experienced in problem-based learning) commented on the problems for improvement. The improved problems were tested with a pilot group to check their adequacy among people similar to the participants and whether further improvements were needed. For this purpose, a sample questionnaire was applied to another group of 12 prospective teachers at the same university. They were asked to solve the problems, share their feelings on the problems, and comment on the problem statements and problem solving. The information collected and the analysis of the written answers suggested that there was no need for improvements.

The problem statements are given in Figures 1–3. They are written in English but were presented to the participants in their official language, which was Portuguese.

Your mother wants to buy a hairdryer because hers broke down. In a leaflet from a large shopping center, she has found three models (figure below), all at the same price. As she does not understand much about hairdryers, she needs help to choose the most suitable model to use daily.

Which of the hairdryers (A, B, or C) would you advise your mother to buy? Describe in detail the process you followed to make the choice, as your mother wants to understand exactly why she should choose one of these hairdryers.

Figure 1. The hairdryer problem (*antes* = before; *agora* = now).

In your family, there is a person who is very friendly with you, who has money but is very careful in how he manages and uses this money.

When you finish the course, this person wants to offer you a new laptop. The computer must be useful, not only for communicating but also for your work as a teacher.

As your family member does not know which computer to buy for you, you must prepare a well-founded proposal for the computer to be purchased by your relative.

Do not forget that you need to convince the person in question that this is the most suitable type of computer for them and that the cost is justified.

Describe in detail, giving reasons, the process that you would have to follow to prepare this proposal.

Figure 2. The computer problem.

The IE presidency has decided to renovate the interior garden, on the presidency side (next to the larger auditorium), with plants that make it attractive, provide pleasant aromas, and improve the environmental conditions. The presidency does not want the garden to require much maintenance and wants it to have an irrigation and a lighting system. A competition will be opened and competitors who wish to submit a proposal can visit the site and speak once with the president. Describe in detail, giving reasons, the process that you should follow to prepare a written proposal to be submitted to the competition.

Figure 3. The garden problem (IE = Institute of Education).

The hairdryer problem (Figure 1) focused on three hairdryers. They were on sale, had different power levels, and had the same sales price but different normal prices. For each hairdryer, the prices both before (*antes*) and during (*agora*) the sale were given, together with the hairdryer power (P). Based on previous research (Jee, 2021; Santani et al., 2015), being on sale was expected to interfere with the PPSTs' answers. Hairdryers are items that people use very often. The physical interaction with the hairdryer may induce positive relationships between the user and the product (Han et al., 2023), and this may have interfered with the answers. Each PPST was required to choose the best hairdryer to recommend to his/her mother for daily use. To do this successfully, he/she had to consider the data and contextual factors included in the problem statement and collect information on his/her mother's hair and hairstyle, which was not given in the problem.

The computer problem (Figure 2) was a science and technology-related problem that asked each participant in the study to prepare a well-founded proposal to provide advice to a relative willing to offer him/her a computer (laptop). A computer is an emotionally charged object (Afrashteh & Razzaghi, 2022), especially for young people. The proposal was required to satisfy a condition—that is, the computer had to be useful, not only for communicating but also for the PPST's work as a teacher after the completion of the initial teacher education program. No data were given, but the information indicated that the relative was a person with money who was highly concerned about financial management and expenditure. Hence, there had to be good justification for the cost of the computer. It was expected that the PPSTs would be sensitive to brands (Muller & Klerk, 2020) and provide a proposal based on the positive aspects of a certain brand (Namiranian, 2006), rather than on the contextual information provided.

The garden problem (Figure 3) focused on an open-air garden surrounded by the Institute of Education (IE) building. This place was familiar to the PPSTs, as they were used to attending classes in the IE building. The problem asked the PPSTs to prepare a proposal for the renovation of the garden. This is a complex task, as setting up a garden requires a multiplicity of competencies from the STEM area (Gulhan, 2023) and from other areas, like drawing, landscape architecture, economics, etc. Based on previous research (Corrochano et al., 2022; Eugenio-Gozalbo et al., 2020; Gulhan, 2023), it was expected that the PPSTs would experience some difficulty in using the variety of knowledge required to complete the task. The environmental features (e.g., sunny or shady), as well as the shape and the area of the place, were not given, but the respondents were told that they could visit the place and talk once to the president of the IE. Visiting the place enabled them to collect relevant environmental data.

2.4. Data Collection Procedures

Data were collected in 2023/2024 using a printed and anonymous questionnaire that included the three problems, as shown above, and two questions on some personal data (age and gender), which were not used. Two co-authors were responsible for face-to-face data collection during class time. They explained the aims and conditions of the research, ensured that the students understood that their participation was voluntary, and asked them to sign the informed consent statement. The University Ethics Council validated this statement and the project that constituted this research (CEICSH 146/2023). Afterward, they handed out the anonymous questionnaire to the PPSTs. Then, they asked the PPSTs to solve each problem and explain the solving process as best as possible. The PPSTs completed this task individually and without a time limit. The answering time ranged from 25 min to 60 min. Conversations between the PPSTs and access to printed or digital information were not allowed. The option to provide individual answers was due to our interest in obtaining information about the processes followed by each prospective teacher. The option for a written questionnaire (instead of a digital one) was given because the PPSTs may have needed to create diagrams, drawings, flowcharts, etc., which is easier to perform using a printed questionnaire.

2.5. Data Analysis

Two researchers, experienced in PBL teaching and research, qualitatively analyzed the answers to the three problems. They sought to identify the main characteristics of the processes followed by each PPST when solving each problem, without looking for *a priori* problem-solving strategies. The objective was to identify and understand the strategies used, rather than to compare them with a model or to count their frequencies. This necessitated using a thematic analysis to uncover the main strategy (or strategies) spontaneously used by the problem solver, which emerged from his/her answers to the problems. To carry out the qualitative and inductive data analyses, for each problem, they started by reading the answers separately. This ensured familiarity with the raw data and allowed some insight into the different strategies used by the participants in the study to solve each problem. Afterward, they read again the answers to each problem separately. This was intended to uncover the different strategies used by the PPSTs and to register illustrative examples of each strategy identified for each problem. After completing this second stage, they discussed the strategies used for each problem and the examples selected to illustrate them. This discussion aimed to reach a consensus on the different strategies spontaneously used by the participants in the study to solve each problem. All decisions on this matter were reached by consensus. It is worth stressing that each student used only one of the strategies listed. The next section will show, for each problem, the strategies and illustrative examples that they agreed on, after translation into English. These examples also show how the respondents solved the problems. One of the authors translated the illustrative answers from Portuguese to English (avoiding improvements to the wording) and another checked the translated answers to ensure that they complied with the original. One or two answers are used to illustrate each strategy, depending on the existence of variations in the implementation of the strategy and the illustrative power of the answers.

3. Results

The results of the qualitative data analysis will be presented problem by problem, with each problem given in a separate section. Some illustrative examples (after translation into English) support the inferences about the processes followed and the strategies used by the PPSTs to solve the problems.

3.1. The Hairdryer Problem

An analysis of how the PPSTs solved the hairdryer problem (see Figure 1 above) revealed seven overarching strategies. Five of them did not consider their mother's hair when making the choice, one strategy considered a typical mother's hair, and another strategy considered the respondent's mother's hair. Each PPST used one of the strategies. The seven different strategies were as follows:

(i) ignore the target and focus on accessories;
(ii) prioritize the inclusion of accessories;
(iii) prioritize the previous highest price;
(iv) prioritize the power;
(v) consider a combination of discounts and accessories;
(vi) consider one mother's hair;
(vii) consider his/her mother's hair.

One of the strategies (v) combined strategies (ii) and (iii) as the PPSTs considered both aspects to make their choices. These strategies will be presented below, and selected answers will be used to illustrate them.

(i) Ignore the target and focus on accessories

The problem stated that the respondents should give advice to their mothers on which hairdryer to buy (see Figure 1), but the PPSTs in this group based the decision on themselves, without any reference to their mothers' hair.

> *"The price of the three hairdryers is the same, so I would have to look at other aspects. I consider hairdryer B to have a reasonable and necessary power for everyday life, especially if there is a need to dry long hair. In addition, it offers a useful tip to diversify hairstyles. So, dryer B would be my choice."* (S37)

Instead of choosing a hairdryer for their mothers, the PPSTs in this group seemed to consider choosing a hairdryer for someone that they did not even know and thus preferred a versatile one that could be adapted to changes in style.

(ii) Prioritize the inclusion of accessories

The PPSTs in this group opted for hairdryer B because it had some accessories. They did not realize that the hairdryer was for their mothers, as they simply discussed "the mother". They did not consider how useful the accessories would be for their mothers; they seemed to believe that the more items the hairdryer had, the better it was for an unknown mother. As illustrated by the following answer, there was no reference to the mother's type of hair (e.g., thin or thick), hairstyle (e.g., straightened hair, wavy hair), or amount of hair (e.g., a lot or a little), which should have been considered.

> *"I would advise the mother to buy dryer B, because although it is not the most powerful hairdryer, it is the most complete one, as it contains one more object. Thus, as the three hairdryers are at the same price, it makes sense for the mother to buy B."* (S5)

Of course, the PPSTs whose mothers enjoyed, for example, drying their hair naturally could consider the inclusion of accessories; those whose mothers wore straightened hair should not have decided based on this aspect, as the diffusor would not have been useful to their mothers.

(iii) Prioritize the previous highest price

The PPSTs in this group opted for hairdryer B because it was the most expensive before the sale. As the sales price was the same for the three hairdryers, hairdryer B had the highest discount. For these PPSTs, the higher the hairdryer price, the higher the quality.

As illustrated by the answer below, their decisions depended on the difference between the previous prices and the sales price.

> *"The hairdryer that I would recommend purchasing, taking into account the available data, would be hairdryer B.*
>
> *The reasons for choosing it are:*
>
> *- Hairdryer B is the same price as the others;*
> *- Typically, in products sold to the public, a higher quality product is obtained for a higher base price."* (S44)

Thus, hairdryer B was chosen based on the price, ignoring its (intermediate) power and the features and style of the mother's hair.

(iv) Prioritize power

Hairdryers have different power levels, and the PPSTs in this group considered the hairdryer power as the key datum when making a decision, as opposed to its accessories or previous price, but they did this in two different ways. Some of them believed that the higher the power, the better the hairdryer, regardless of the features or style of their mother's hair. The two answers below illustrate these ideas:

> *"Although the discount on hairdryer B is greater and it comes with an accessory, I would advise my mother to choose hairdryer A, as it has greater power (2100 W) and would be more useful in her daily life than hairdryer B with its accessories."* (S13)

> *"I would choose hairdryer A. It has the highest power. Even though it wasn't the most expensive before, it would be a waste to choose, for example, hairdryer B, with all its accessories because my mother wouldn't use them."* (S6)

In both illustrative examples, the PPSTs mentioned the price before the sale and the accessories of hairdryer B, but they decided based on the power. However, they did not explain why greater power was important for their mothers or why the accessories were useless for them.

Other PPSTs believed that the lower the power, the better, because they felt that lower power would result in lower energy use and, therefore, the hair-drying process would be cheaper or more environmentally friendly, as illustrated below:

> *"I would advise my mother to buy hairdryer C. As they are all at the same price at the moment, it makes more sense to buy this hairdryer, due to its power being 1600 W, which means that, when you are using it, you won't use so much energy, and, even though it has low power compared to the other two hairdryers, it manages to fulfill its function."* (S27)

> *"Based on the fact that all hairdryers are now at the same price, I would advise purchasing hairdryer B. This is because we know that hairdryer C is the one that uses the least energy (1600 W) but this also makes it the hairdryer with the lowest power and therefore the hairdryer that, from the outset, will take longer to dry your hair, which may not be viable daily due to time constraints. Then, the options left are A and B, which differ in power by only 100 W; thinking more sustainably, hypothesis B ends up being the one with an intermediate quality–price rate. It is not the one that uses the largest amount of energy but it seems to have reasonable power and would be practical and functional in everyday life."* (S68)

These PPSTs established simplistic relationships between power and energy use, without considering the time needed to dry a given person's hair using each hairdryer. The first one ignored the time spent drying the hair; the second one mentioned it implicitly (the lowest power would take longer) but made a poorly explained decision between the hairdryers with the highest and intermediate power levels in favor of the latter, allegedly for sustainability reasons.

(v) Consider a combination of discounts and accessories

Other PPSTs combined two of the previous ideas to prepare the advice for their mothers and opted for the hairdryer with the largest discount and more accessories, i.e., hairdryer B. Hence, the notions of "the most expensive, the best" and "the more accessories, the better" underlaid their decisions.

> *"I would recommend hairdryer B, because, despite having only 100 W less than A (but more than C's 400 W), it comes with accessories that help with some hairstyles and can be quite useful, something that does not happen with the other two. Furthermore, it is the one with the biggest discount (in EUR) (almost EUR 10)."* (S49)

> *"I would advise my mother to buy hairdryer B because, in addition to having a complementary object, it has good power, and the price was previously EUR 34.8 and is currently EUR 25. Dryer B is the one that pays off the most on all levels."* (S35)

The members of this group did well in the sense that they combined two factors, but they did not (at least explicitly) consider their mothers' hair. It is possible that their mothers did not need the accessories but required a different power level.

(vi) Consider one mother's hair

In the problem, the hairdryer was for the student's mother. As mentioned in the Methodology section, different hairdryers may be more appropriate for one type of hair than another. Therefore, the choice of the hairdryer had to consider the PPST's mother's hair type and hairstyle. However, some of the PPSTs considered an unspecified mother, rather than their own (real) mother's hair, whose style they should have been familiar with (unless they had lost their mothers). The following answer illustrates this.

> *"The hairdryer choice would depend a lot on its purpose; that is, if the mother had curly hair, she would automatically recommend buying hairdryer B, as it is accompanied by a diffuser that is normally used to dry this type of hair. However, this hairdryer can also be used without this diffuser; that is, it becomes the most versatile hairdryer among the three. If my mother had little hair or short hair, I would tell her to buy hairdryer C, as you don't need a dryer with as much power to dry your hair daily; this way, the daily energy consumption would also be lower. Hairdryer A would be one of the last options to recommend, as it has a lot of power, which means more energy and, consequently, money spent. I believe that, if possible, if it meets the needs, the ideal would be hairdryer C. I think the environment would be grateful."* (S26)

This student appeared to be concerned about environmental sustainability (the reason for choosing the lowest power) but ignored the fact that lower power may require the hairdryer to work for longer.

Other PPSTs chose an (imaginary) mother too, but they planned to collect information from the mother about several issues beyond hairdryer use, as illustrated below:

> *"In this process, we have to take into account several factors:*
>
> *1—we have equal prices for the 3 hairdryers (A, B, and C);*
>
> *2—power, whether used or not, in the form of electricity;*
>
> *3—the existence of drying components (as in image B);*
>
> *4—the discount/best deal, e.g., price drop to EUR 25;*
>
> *5—the mother's hair type and other relevant information about her hair and skin;*
>
> *6—the apparent size of the hairdryer*

These are some factors that I would use as criteria to help the mother to make the choice. A first step would be to ask the mother directly for information: how many times she dries her hair per day/week; what type of hair she has (dry, straight, curly, dyed, etc.), how much space she has to store the hairdryer; what is her pre-purchase budget (regardless of the price being equal to EUR 25). With this information, I would draw a table to register information and carry out research on the efficiency and quality of the hairdryers, the type of hair, and the temperature it uses. The table would be:

Criteria A B C

[. . .]

In this table, I would also write information on the criteria that I mentioned initially and, after collecting information, would add up the scores. Afterward, there would be a discussion with the mother to see whether the selection based on the score would meet the initial specifications. If not, the choice could be made based on what seems to be the best deal: B has the biggest discount, average power compared to the other two, and extra components.". (S12)

These PPSTs tried to identify relevant factors and use data systematically collected on them (they even planned to organize the data in a table) to select the best hairdryer for an imaginary mother (as they never referred to "my mother" or showed an awareness of the mother's hairstyle, amount of hair, etc.). However, if they felt that this plan would not work, they would decide based on a criterion, namely the amount of discount, with the choice being hairdryer B, which had the largest discount.

(vii) Consider his/her mother's hair

A couple of PPSTs took their mothers' hair explicitly into account when deciding on the hairdryer to recommend. They considered either the hairstyle or the amount of hair, as illustrated below:

"I would advise my mother to buy dryer A.

Although hairdryer B has more functions, that is, it brings a curling tool, as my mother doesn't need it, as she has straight hair; also, if you look at the previous price, this one (B) was the most expensive, I don't recommend it because she won't use the curling tool.

Hairdryer A seems the most suitable for my mother as it has greater power than the others have, which is an advantage, as it dries the hair faster." (S25)

"I would recommend choosing hairdryer B. I would not consider hairdryer C since, compared to the other hairdryers, it has low power, and the prices are the same. Although hairdryer A has greater power than B, hairdryer B includes more hair-finishing tools than A. Therefore, hairdryer B would be more beneficial for my mother, and the difference in power between A and B would not make a difference to my mother because she has little hair, but the power of C would be too low. The accessories of hairdryer B are useful for drying straight or wavy/curly hair. I would not include the previous prices of the dryers in the evaluation process, since the markets often do not set the original prices but use others to make the promotion more eye-catching." (S55)

These groups of PPSTs were the only ones that explicitly chose a hairdryer for their mothers and considered their mothers' hair when deciding which hairdryer to recommend to her.

The quotations given above show that some PPSTs' solving processes (e.g., S49 and S68) drew heavily and explicitly on quantitative data (on the price and power) extracted from the problem statement. Others (e.g., S37 and S44) did not base their decisions on quantitative data, even though they considered them when solving the problem.

The qualitative analysis of the problem statement is a critical step in the problem-solving process. Reading some of the quotations from the PPSTs' answers given above (for instance, S13, S27, S44, and S55), one can see the omission of a qualitative analysis of the problem. Such an omission may have been due to the strategies encountered, which did not consider, for instance, the PPST's mother. Other quotations contain some evidence of an elementary qualitative analysis. The quotations from S68, which starts with a short framing sentence, and S12, which includes a few initial framing sentences, illustrate this group. The PPSTs extracted information about the power of the hairdryers from the problem. However, some of them lacked knowledge of the power concept, as illustrated, for instance, by S26, who stated, "*you don't need a dryer with as much power to dry your hair daily*".

Another key step in the problem-solving process is the evaluation of the solution regarding the problem's context and conditions. Some quotations, like the one from S12, mention the need to check "*if the selection [. . .] would meet the initial specifications*". However, many of the other quotations presented above, like the ones from S26 and S44, do not show evidence of this process. They do not indicate a return to the problem conditions to check whether the hairdryer chosen is suitable.

3.2. The Computer Problem

The analysis of the strategies that the PPSTs used to solve the computer problem (see Figure 2 above) revealed five overarching strategies that encompassed choice procedures that, in most cases, lacked detailed information and systematic needs analysis. Hence, five strategies were found in the respondents' answers:

(i) present the steps to follow;
(ii) choose by brand;
(iii) prioritize the features of the computer;
(iv) prioritize the features over the price;
(v) prioritize the teacher's needs.

When using most of these strategies, the PPSTs ignored what they would need from a computer in the future as teachers and based their proposals explicitly or implicitly on emotional aspects. Some of them described what they would do, step by step, and others were not so systematic; however, systematicity is not synonymous with unbiased choice, as it will be shown below. In addition, the information given on how their relative managed money was seldom considered.

(i) Present the steps to follow

The PPSTs in this group presented a sequence of steps. Each step focused on a parameter, without explicitly relating these parameters to their future needs as professional teachers. In addition, they either did not make clear what they would propose (did not finalize their reasoning) or planned a proposal but tried to impose their preferences. The following answers illustrate these ideas.

> "*Step 1—Check the memory I need to work on the computer.*
>
> *Step 2—View processing speed.*
>
> *Step 3—Take into account price quality.*
>
> *Step 4—See the diversity of brands.*
>
> *Step 5—If it is a computer to take around, it should be light, to not make me feel tired.*
>
> *Step 6—If it is possible to combine the useful with the pleasant, the aesthetic aspect also matters [and should be considered].*" (S4)

> *"Firstly, I would try to understand to what extent the person offering me the computer would have, a priori, settled on a budget or price range. If so, I would start investigating prices and computer models within that range.*
>
> *Secondly, I would choose the most suitable model or models based on price/quality.*
>
> *Finally, I would introduce them to my friend [relative], so that we could decide on the best option to choose together. If the person needed a more detailed explanation, this would be the time to do so and make my opinion clear."* (S45)

In these answers, it is unclear how the parameters considered would work as factors enabling the PPSTs to make a choice and provide a rationale for it. The first answer does not explain how the issues mentioned should influence the final proposal. For instance, it does not indicate whether the processing speed should be high, medium, or low. The second one is similar but it ultimately imposes the author's opinion, probably to satisfy his/her preference, despite the attention that the respondent seems willing to give to his/her relative.

(ii) Choose by brand

The respondents in this group appeared to have chosen in advance, in favor of a brand (brand X) that they fully trusted (the brand name was omitted to prevent advertising), and did not feel the need to look for information about other brands. Therefore, they failed to prepare a good rationale for their proposal. The following answers illustrate these ideas.

> *"Since I don't know much about computers, I would use an argument based on aesthetics and also the reputation it has, to convince this relative to offer me a 'brand X' computer."* (S7)

> *"The most suitable computer for my profession is the 'brand X', as it is the most rapid on the market and has large memory, most applications only work properly on its software, it has an excellent battery, and it comes in several colors. Furthermore, it is still tactile and easy to carry due to its small size and thickness."* (S23)

In any case, these PPSTs ignored the fact that they were asked to prepare a good rationale for the proposal to present to their relative/friend who was concerned about financial expenditure. Moreover, they did not consider that other people might be unaware of the relative advantages of brand X and that they may need to provide convincing information about brand X and other brands.

Other PPSTs in this group described the features that they believed that a teacher's computer should have, but, in the end, they simply imposed their preferences for a "brand X" computer.

> *"When purchasing a computer, particularly for a teacher, the computer must be light, as the teacher walks a lot in the school, and it must have plenty of storage to have space to store many test files, assessments, etc.*
>
> *It must be able to run programs such as spreadsheets and PowerPoint, among others.*
>
> *In my opinion, these are some important points that a teacher's computer should have.*
>
> *Then, a search must be carried out to immediately exclude those that do not have those characteristics.*
>
> *Having said that, the most suitable computer is the 'brand X', as it has the qualities and I am used to the 'brand X's' devices."* (S64)

Knowledge of the brand and, in this case, experience with it eliminated the need to perform a comparison of the brands and models. There were other participants who started by presenting the brand (brand X) that they wished to try and put forth arguments to justify their choice.

"To convince the person that my choice is the right one and duly considered, I would make a list of pros and cons to prove that the computer in question was the best choice. Therefore, I would say that the selected computer is a 'model y' of 'brand X' computer with the M1 processor (2023) for the value of EUR 1050 and I would present the following list.

'Brand X', 'Model Y'

Pros | Cons

[. . .. .]

After presenting the list [5 pros, 1 cons], I would analyze each point in more detail, saying:

- 'Brand X' or an element of it has/does

- 'Brand X' offers a EUR 100 discount for students and teachers [. . .] goes from EUR 1150 to EUR 1050." (S17)

The respondents in this group presented information (e.g., price, processor) about the computer that they desired (brand X) and an analysis of its advantages and disadvantages (with more advantages than disadvantages), instead of performing such an analysis for some different brands and models to select the one that best fit their needs.

(iii) Prioritize the features of the computer

The PPSTs in this group concentrated on the general features of the computer, without explicitly considering what they would need as teachers. The following answer illustrates this.

"I need a good computer. It does not need to be top of the range or have a specific brand. The most important aspect is that it has good memory, a good processor (above 5-core), and a good video card. This is because, more than beauty, the computer should not crash and should perform tasks properly. Furthermore, excessive weight and a very small size can compromise quality." (S50)

The members of this group of PPSTs wished for a good computer, with no suitable justification and without considering whether their future tasks would require a good computer.

(iv) Prioritize the features over the price

The PPSTs in this group mentioned some computer variables that they believed were important in a computer, without stating how or why they mattered to a teacher. Afterward, they considered the price as a tiebreaker criterion.

"Considering the nature of the gift and the person offering it, it should never reach an exorbitant amount.

However, it will have to have certain characteristics:

- Memory capacity
- Presentation ability
- Ability to create teaching resources
- Ability to access information quickly
- Product durability
- Ease of mobility

When finding a computer that meets the listed characteristics, the price should be chosen to be as low as possible, respecting whoever offered it." (S44)

Although considering the price as a tiebreaker criterion in the case of similar features is wise, the answers should have been more explicit about how and why the features mentioned were relevant for a teacher.

(v) Prioritize the teacher's needs

The PPSTs in this group used teachers' needs as the rationale for their computer choices, although they did not fully explain how it worked, as shown below.

> *"For me, a computer, or the most important thing in a computer, is its storage capacity and memory, as we have many tools, documents, and programs, which are very "heavy", and if the computer does not have a large memory capacity, it will cause problems... it becomes slow and even blocks, sometimes it no longer even supports some programs that we need to install. Another strong point of the computer is the graphics card, to support visual arts programs, for example, to explain subjects through these programs to students with good image resolution so that they are clear and perceptible. And lastly, it must be light, as we always carry a lot of material, including books, and it is more convenient to be small and light, yet with great autonomy to last for a long time without a need to carry the charger."* (S25)

In this answer, the function of the computer graphics card and the storage capacity are reasonably explained but other features are not.

Other PPSTs recognized that they were not experts in computers and therefore they would need to obtain information on computers. Hence, they decided that they would ask for help to determine the model to suggest to their relative. The following answer illustrates this procedure.

> *"To begin with, and as I wouldn't understand much about the subject, I would go to a store where they sell computers, and ask a technician what would be the ideal computer to buy based on my needs. Given the information collected, I would then decide which computer to choose and understand how it differs from the others. After analyzing all the details, I would look for the same computer in different stores, to understand if the prices differ from one store to the other and if this would be the ideal computer. Finally, after choosing the computer and the buying location, I would present the proposal to my relative."* (S28)

The PPSTs in this group recognized the need to collect information on different brands and to compare it in order to prepare a proposal to present to their relative. After deciding on the required features, they would look for the computer of their choice at the lowest price. For these PPSTs, the selection should be based on relevant features, and the price served as a tiebreaker.

It is worth noting that some PPSTs did not consider that they did not possess sufficient knowledge to choose the computer, while others did. To make an informed decision and prepare a proposal, the latter claimed that they would make brand-based decisions (S7) or ask for a third person's help (S28) instead of looking for information.

Some transcriptions showed that the PPSTs mentioned quantitative variables and data (e.g., S4, S17, and S45), while others (e.g., S7, S23, S50, and S64) referred to qualitative comparisons, without mentioning or arguing for the need for quantitative data.

Some transcriptions from the students' answers showed that the PPSTs used information taken from the problem statement, without globally analyzing the context that it described. For instance, S4, S17, and S23 put forward ideas about computer features without explicitly relating them to their future needs as teachers; S25 and S50 did not consider that the computer would be on offer, which should have fulfilled some conditions. S44 and S64 extracted information from the problem context but did not explicitly use it to decide. Their transcripts—for example, those of S17, S25, and S50—do not provide evidence of the completion of the problem, as there is no mention of the proposal or evidence of an awareness of its absence. This suggests that the PPSTs did not perform a qualitative analysis of the problem statement and did not critically analyze the solution.

The latter would have allowed the PPSTs to perceive that the proposal was missing and the problem-solving process was incomplete.

3.3. The Garden Problem

An analysis of the strategies used to solve the garden problem (see Figure 3 above) revealed four overarching strategies. Some strategies did not answer the problem, as they showed a sequence of recommendations or steps to follow in renewing the IE garden. However, others moved beyond this, as they planned data collection or considered how to use the data collected. The four strategies identified are as follows:

(i) make recommendations instead of a proposal;
(ii) list the steps to follow;
(iii) collect additional information;
(iv) collect and use additional information.

As with the previous problems, these ideas will be further developed and illustrated with selected answers.

(i) Make recommendations instead of a proposal

The PPSTs in this group created a list of recommendations for the IE to follow, instead of describing how he/she would prepare a proposal that complied with the terms of reference mentioned in the problem statement. The following answer illustrates this.

> *In my opinion, the education institute should opt for plants that do not exactly have a season, that is, that are only beautiful in summer or winter. I think they should choose to create several beds with cactus plants, as a cactus does not require maintenance or a lot of water. They should put more tables so that everyone can enjoy the garden. Cacti should be of different colors surrounded by black or white little stones, thus creating a welcoming atmosphere.* (S21)

This PPST is an example of one who did not perceive that he/she should present a concrete proposal for the garden, instead of creating recommendations to propose to the IE.

(ii) List the steps to follow

The PPSTs in this group created a list of steps to follow to answer the problem, although the list was incoherent or incomplete. The following answer illustrates a case in which the sequence of steps lacked underlying logic.

> *"Start by thinking about what plants you could place, following the criteria that the presidency of the Institute of Education wants.*
>
> *Afterward, visit the place to see what it is like and so on, and speak to the president to clarify any doubts that might emerge or so.*
>
> *After visiting the place and having a conversation with the president of the Institute of Education, agree on all the initial ideas.*
>
> *And finally, submit the written proposal to the competition."* (S61)

Selecting plants before visiting the place is illogical. Similarly, visiting the place "to see what it is like" fails to take full advantage of the visit or to consider the importance of data (e.g., dimensions) in preparing a good proposal.

Other answers in this group omitted relevant steps/procedures needed to prepare the proposal, as illustrated below.

> *"Initially, I would have to go to the site to understand the current state of the garden. From there, I would think, based on the demands/requests made, I would research and study the best way to respond to the request, with the lowest possible budget and in the*

most beautiful way. From there, I would make a budget and present it to the IE presidency with a physical model that I would prepare too." (S2)

It is unclear whether information collected onsite (on the current state of the garden) would be used to build the physical model to propose for the garden and submit to the contest.

(iii) Collect additional information

This group included answers that listed steps to follow and information to collect from the president (as suggested in the problem statement), but they did not describe how the information collected would be used. The following answer illustrates this idea.

"- Plan possible questions to ask the presidency before visiting the site.

- During the visit, carefully observe the facilities and assess the needs of the space taking into account the requirements mentioned.

- Find out which materials are suitable and what the different prices are.

- Establish a budget based on the differences in proposed solutions found, explaining the advantages not only in cost but also in the quality and durability of the product, as well as the possibility of requiring less or more maintenance.

- State which proposals you consider most appropriate given the information provided.

- Show availability to clarify doubts." (S65)

The answers in this group considered posing questions and performing observations, but it was unclear how the data collected would be used to create the proposal. An analysis of some of them suggested that the information collected would simply be put together and submitted for the contest. This idea is illustrated by the following answer.

"To prepare the written proposal to submit to the competition, it is important to visit the space where the intervention will take place and evaluate the level of attractiveness and attendance by students at the Institute of Education.

If possible, I could talk to students who use this space and ask what they would change/add to make the space more enjoyable to use.

After this space assessment process, the cost assessment process follows regarding the installation of an irrigation and lighting system, together with the assessment of the cost of the plants to be placed and any extras/materials suggested by the students (e.g.,: garden benches, set of tables and chair).

After this intensive process of evaluating costs on the various surfaces/decoration items and the budgets given by professionals installing irrigation and lighting systems, it is important to gather all this information in a document and communicate the results obtained, as well as the proposal to be made most advantageous to the presidency of the Institute of Education." (S4)

This answer states that "*it is important to gather all this information in a document and communicate the results obtained*", but the results should be used to prepare the garden project and not simply handed to the president of the institute.

(iv) Collect and use additional information

The answers in this group described the collection of information and the use of such information, albeit not always in an explicit way. Some PPSTs planned to collect information from the president only, but others considered other individuals, like students or community members. The following answers illustrate these situations.

"1st—Visit the space, take measurements, see sun exposure, analyze the type of soil, and the use it will have after renovation.

2nd—Taking into account the results obtained in the 1st step, select the species most suitable for the space and that meets the intended renovation requirements; drawing up a space plan taking into account sun exposure and the function to be performed (e.g., whether it will be a leisure and/or rest space).

3rd—In the garden plan, place the selected species and forecast the evolution of the space [. . .], include the rule points and how it will work [. . .], and include the lighting system [. . .].

4th—Prepare a report including the research work, the final space plan, and the approximate budget of the proposal." (S43)

"1. Visit the place in the morning.

2. Interview some members of the community that use the place.

3. Visit the place in the afternoon.

During these visits and having my notes, I would make a preliminary proposal based on the ambiance, luminosity, thermal comfort, and users' opinions on what would please them more or less, what they expect, etc.

Once this is in place, I would meet with the presidency, to align the proposals and "smooth out the edges", seeing what can be done to please most of the interested parties. Finally, I would submit the proposal to the competition, after, of course, having studied the costs and trying to rationalize resources. (S50)

According to these answers, only a single person would propose a garden. However, other PPSTs recognized that this would be a challenging and demanding task and planned to use a multidisciplinary team, as shown below.

"Firstly, it involves the formation of a multidisciplinary team in the areas of landscaping, botany/gardening/irrigation systems/person connected to the Institute (but not linked to the presidency) [to assist in preparing the proposal].

In the first phase, the team's initial ideas and possible problems were discussed [–> preparation for the visit to the place and conversation with a member of the presidency].

Following the visit and collection of information, the team would again assess problems and solutions. The possibility of involving the educational community through a survey would be considered.

As a result, the proposal that was already being prepared would be reviewed; there may be more moments of inquiry or conversation with members of the presidency, if possible; which would lead to the final proposal.". (S12)

To comply with the call's terms of reference, a multidisciplinary team would be required, which would perform a variety of specialized tasks (e.g., creating a plan for the garden, selecting plants, and choosing lighting and watering systems), as argued by S12. However, reading the transcripts above, it can be found that some PPSTs planned to complete all tasks themselves, as illustrated by S2. Others used a non-personal writing mode, which did not indicate whether they were conscious of the task's demands. In any case, it was unclear whether they were aware of the diversity of knowledge and abilities required and whether or not they possessed them.

Some transcriptions (e.g., S21 and S61) indicate that the PPSTs did not mention or feel the need for quantitative variables and data. Others mentioned quantitative items, like the area of the garden (S12), the budget (S43), and the costs (S50), but did not develop them.

An analysis of the transcripts presented above indicates that S4 started by mentioning the proposal, while the others do not. There is some evidence that the PPSTs read the problem statement, as they mentioned some items included in it. However, they did not explicitly indicate their knowledge of the problem and what they needed to know or do to solve it. Some PPSTs showed planning abilities (e.g., S12, S43), as they mentioned what they would need to do. Some transcripts showed that the PPSTs failed to address the objective as they did not mention the proposal (e.g., S21), while others understood that they had to prepare a physical model (S2). Other transcripts indicated that the PPSTs mentioned the proposal's submission but showed no evidence of the proposal's revision considering the data given in the problem statement or collected (e.g., S61). These findings reveal that a critical analysis of the problem's solution against the problem's demands was not performed.

4. Discussion

This research aimed to characterize the processes followed by PPSTs when solving three STEM-relevant problems, which had different features. A qualitative analysis of the PPSTs' answers was performed to identify the overarching strategies underlying their problem-solving processes. The large number of answers analyzed suggests that saturation was reached. This means that the diverse range of approaches adopted by similar participants to solve these problems was probably identified.

An analysis of the overarching strategies followed by the participants when solving the three problems shows that the PPSTs used a variety of approaches when solving each problem, as expected based on previous studies (e.g., Hsu et al., 2024; Oh, 2024). In contrast to what is required when solving a complex and interdisciplinary problem (Price et al., 2021; Wang et al., 2023), the PPSTs' approaches were, in general, linear, and the PPSTs did not return to the problem statement, even to perform a critical analysis of the results. Price et al. (2021) argue that appropriate knowledge and skills influence the problem-solving process. Some PPSTs' answers indicated a lack of relevant knowledge, which they seldom acknowledged. Most of the strategies identified depended on product attributes (W.-L. Chen & Chiang, 2010), hedonic factors (Jee, 2021; Santani et al., 2015), i.e., smart shopping perceptions, and brand factors (Muller & Klerk, 2020), although those factors influenced the PPSTs in different ways.

Problems 1 and 2 were related to purchasing objects. According to W.-L. Chen and Chiang (2010), "Consumers' purchasing behavior is affected not only by cultural, social, personal and psychological factors but also, most importantly, by the consideration of product attributes" (p. 396). In the case of the hairdryer problem, most of the strategies focused on the product attributes and price, i.e., on the hairdryer's power (strategy iv), accessories (i and ii), or accessories combined with a discount (v). These strategies were influenced by the product features, as could be expected based on W.-L. Chen and Chiang (2010), and they did not consider the target user of the hairdryer (the problem solver's mother). Strategy (iii) appeared to be driven by hedonic benefits (Jee, 2021), a behavior associated with sales that leads to choosing the item with the largest discount, due to the self-perception of being a smart shopper (e.g., Jee, 2021; Santani et al., 2015). Quantitative information on the power and price explicitly underlaid three strategies (iii, iv, and v) and seemed to influence the others, namely strategy (i). This may have been because the students were used to solving algorithmic (Salta & Tzougraki, 2010) instead of decision-making problems, which require making choices and assessing the risks and benefits of alternatives (Walker & Leary, 2009; Jonassen, 2012). A hairdryer is a product that is often used in people's daily lives. Therefore, some people may exhibit strong physical interactions with hairdryers. As Han et al. (2023) argue, this physical interaction may induce a positive relationship between the user and the product, which may override other key elements. These positive relationships and the PPSTs' difficulty in integrating the information extracted in the problem-solving strategy (Broman et al., 2018; Maries &

Singh, 2023; Tan et al., 2023) may explain why all but one (vii) of the strategies ignored the fact that the hairdryer was for the problem solver's mother. Instead, they focused on choosing a product as if it were for themselves or for a non-identified mother (as seen in strategy vi). Despite these difficulties, all strategies led to a final result, although there was little evidence of a critical analysis of the latter, which several authors (Çavaş et al., 2023; Lambros, 2004; Leite & Afonso, 2001) consider an important step.

A computer is a technological product that students (including PPSTs) use daily. Computer users develop attachments to them, mostly related to their utilitarian aspects (Afrashteh & Razzaghi, 2022). This attachment is often assessed based on emotionally perceived performance. According to Han et al. (2023), attachment may cause an emotional bond that may override other features or contextual factors. Emotional bonds may underlie strategy (iii), which focused on the computer's features without considering its future purpose. Young people are sensitive to brands associated with good performance and consider "status indicators" (Namiranian, 2006). Hence, a brand's name influences their choices (Muller & Klerk, 2020) and works as a choice simplifier and a guarantee that a product can be relied upon (Namiranian, 2006). One of the overarching strategies (ii) was based on faith in a given brand (name omitted), which resulted in the perception of good performance and fulfilled a desire for status, as the brand in question was more expensive than the others. The brand-driven choice, alone or together with the difficulty in interpreting the problem (Maries & Singh, 2023; Silva et al., 2013) and extracting information from the problem (Broman et al., 2018; Maries & Singh, 2023), prevented some problem solvers from considering two of the contextual conditions of the problem. These were the fact that the computer had to be useful for their work in the future (as teachers) and the fact that the person who was offering them the computer was concerned about spending money. This required the solver to compare the information provided by different brands. Some years ago, Namiranian (2006) concluded that young people wish for brands to provide information that enables them to compare the alternatives available easily and simply. Some participants described a set of steps to follow (as in strategy i), which may include a brand comparison (as in strategy ii), but they did not explain how this should be performed. In some cases, this procedure seemed to be an excuse to impose the solver's preferences, probably based on an affective bond with a given brand or model. They failed to make critical and evaluative judgments of the results obtained, which are relevant procedures in problem solving (Maries & Singh, 2023; Silva et al., 2013). Strategy (iv) prioritized the features over the price and used the price as a tiebreaker; this would be reasonable in light of the contextual information given. However, the importance of the prioritized features was not fully explained. Omitting a good analysis and explanation of the relevant features would result in a weak proposal. Only strategy (v) presented a reasonable explanation. It drew on information from different brands and used the price as a tiebreaker. In this strategy, the brand did not override the price or the computer's features.

Settling and keeping a garden is a demanding task that requires and promotes the development of relevant knowledge, skills, and attitudes under the scope of STEM disciplines and other knowledge areas (Gulhan, 2023). This is why garden-based education has been described as having educational value for several school levels (Eugenio-Gozalbo et al., 2020; Kong & Chen, 2023), including for preservice teacher education (Corrochano et al., 2022). It should be stressed that a garden is an "object" that can be approached at different levels of complexity, thus serving a diversity of purposes. The problem used in this work complied with the conditions acknowledged by Ayerbe-López and Perales-Palacios (2023) for a problem, as it had a high level of complexity and required knowledge of a diversity of disciplines, including the STEM disciplines, drawing, landscape architecture, economics, and others. Strategy (i) indicates that the problem solvers did not understand the goal of the problem, as was seen in previous research (Ogunleye, 2009; Reddy & Panacharoensawad, 2017; Saka et al., 2024). In addition, strategies (i) and (ii) do not demonstrate the ability of the respondents to identify the knowledge required, which is one of the demands of the problem-solving process (Çavaş et al., 2023; Lambros, 2004). While the users of strategy (ii) put forward some steps to follow, they did not present concrete descriptions of the tasks that they would include or the information that they would look for. As in other research studies (Maries & Singh, 2023; Silva et al., 2013), the participants did not finalize their reasoning and failed to consider the design of a project for the garden. Although strategy (iii) considered collecting additional information, it was unclear what this information would be used for. The participants perceived the target as the contest, rather than the design of the proposal. This indicates that the PPSTs did not understand the problem, as was found by other authors (Ogunleye, 2009; Reddy & Panacharoensawad, 2017; Saka et al., 2024), and they did not perceive it as a design problem that required the incorporation of knowledge across several disciplines to develop a product (Walker & Leary, 2009), namely the garden project. Strategy (iv) was better aligned with the goal of the problem, as it considered a logical path to follow, acknowledged the need for a variety of knowledge, as pointed out by Gulhan (2023), and considered the usefulness of a multidisciplinary team.

From the above, it seems that external factors, rather than the problem itself, influenced most of the strategies used by the participants to solve the three problems. As expected, data influenced the problem-solving process when provided (as in the hairdryer problem), but the participants did not show a strong ability to identify data in the other problems. The influence of external factors led to solutions that did not satisfy the problem's goal, lacked scientific support, and depended on brands and attachment. In addition, two key steps of the general problem-solving strategy described in Section 1 were not present in the problem-solving processes of the PPSTs, as shown in the previous section. As in other studies (Amanda et al., 2021), these steps were the first (qualitative analysis of the problem) and the last (critical analysis of the solution) ones. They were identified (Pozo et al., 1995; Torregrosa, 1987) as problematic because of the types of problems that students are usually asked to solve in school. The structure of school problems may lead to success without a careful analysis of the problem statement (Salta & Tzougraki, 2010). Success in similar conditions is not possible with ill-structured and contextualized problems, which research (Amanda et al., 2021; Maries & Singh, 2023; Silva et al., 2013) shows are challenging for problem solvers to interpret. The absence of a critical analysis of the solution was reported in the literature (Maries & Singh, 2023; Silva et al., 2013) as a reason for incomplete problem-solving. Again, school problems are straightforward and usually have a (single) solution (Maries & Singh, 2023; Pozo et al., 1995). These features lead to success even without analyzing the problem statement or the result obtained, but they should be rejected for the benefit of students of all school levels.

5. Conclusions

This paper describes qualitative research aiming to characterize the processes followed by prospective primary school teachers when solving three STEM-related problems. The research was based on data collected by a questionnaire at one higher education institution and focused on three STEM-relevant problems. The participants used a variety of strategies to solve each problem, most of which did not lead to a complete answer. The influence of external factors (e.g., hedonic factors, attachment, and brands) and the omission of some key steps of the problem-solving process (i.e., a qualitative analysis of the problem statement and a critical analysis of the results) were observed in most strategies used by the problem solvers. This means that, when teacher educators train prospective teachers to solve problems, they should use ill-structured STEM-relevant problems, which require their students, either prospective teachers or other students, to use and develop cross-discipline knowledge and to plan, implement, and assess a problem-solving strategy. In addition, teacher educators should focus on the key general steps of the problem-solving process, as advocated for by several authors (e.g., Amanda et al., 2021; Çavaş et al., 2023; Lambros, 2004), paying specific attention to the analysis of the problem and the critical analysis of the results. They should also consider the internal and external factors (Jonassen, 2000) that may affect the problem-solving process, including the context of the problem (Salta & Tzougraki, 2010), emotional issues (Afrashteh & Razzaghi, 2022; Jonassen, 2012), brands (Muller & Klerk, 2020), and hedonic factors (Jee, 2021). Unfortunately, science education pays little attention to these factors.

As with other research studies, our work has some limitations. We developed our interpretations of the transcripts without consulting the participants. Interviewing some participants about their answers would have increased the reliability of the data analysis. Moreover, using pairs of problems with similar features would enable the analysis of the consistency of the participants' answers across problem contexts. Conducting quantitative survey-like studies would allow researchers to identify which strategies prevail. Such studies should include participants from different institutions so that their results are generalizable. It would also be worth determining whether students of other cultural contexts and school levels use the overarching strategies identified. This would provide a better basis for the development of educational strategies that address the tendency to allow external factors to override the data and the contextual information provided in the problem statement.

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Article

Perceptions of Pre-Service Teachers in a Pedagogical Residency Program Teaching Physics Using a PBL Approach

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Abstract

Background: Unlike medical training, science teacher training in Brazil does not include PBL as a curricular methodology. However, there is a Pedagogical Residency Program (PRP) that allows teaching experiences that are different from those provided in the undergraduate course. Thus, in this research, we propose a formative intervention in PBL for scholarship holders in the Pedagogical Residency Program (hereinafter Residents), aiming to answer the following question: "What are the perceptions of pre-service teachers about the planning, implementation, and evaluation of a PBL intervention in physics teaching?". Methods: Five Residents taught an elective course specially designed for the application of PBL to teach secondary school physics. The training of the Residents in PBL occurred almost simultaneously with the offering of the elective subject. To reveal their perceptions, we collected Residents' teaching plans, problem scenarios, and reflective analyses. Results: The results demonstrate that the Residents encountered several difficulties in developing and implementing the PBL methodology when teaching physics. Regarding development, the difficulties lie in coherently aligning the learning objectives with the highly complex active methodology of PBL. In addition, another clear difficulty is developing a problem situation appropriate to the knowledge that one wishes to develop. During the intervention, the Residents realized how difficult it is to implement PBL to allow students to develop skills and knowledge in a reflective way. Conclusions: The results indicate that PRP is necessary to develop methodologies such as PBL, as it allows supervision and reflection on practice. However, we also observed that the results point to the urgent need to introduce PBL in the initial training of science teachers; this process can be established in three stages: strategically studying lesson planning for the implementation of PBL, developing problem situations that align with the knowledge that one wishes to develop, and developing metacognitive regulation and argumentation skills to conduct interventions based on PBL.

Keywords: PBL teacher training; pre-service teachers; teaching physics; problem situation

1. Introduction

Problem-Based Learning (PBL) is one of the teaching approaches that falls under Inquiry-Based Learning, where students take an active stance when solving a problem in order to acquire new knowledge and various skills (Alt & Raichel, 2020; Morey et al., 2021; Shahbodin et al., 2023; Uluçınar, 2023). In this approach, the problem to be solved does not have a simple or closed answer, prompting students to interpret information, develop hypotheses, and make decisions in order to integrate scientific knowledge and present a possible solution (Lenkauskaite & Mazeikiene, 2012; Alt & Raichel, 2020). Another relevant aspect of the PBL approach is the role of the teacher or tutor, that is, a more experienced person who helps the group to identify the demands that the problem brings, search for necessary information, analyze the findings, design possible solutions, and evaluate the process (Aidoo, 2023; Sattarova et al., 2023).

Thus, PBL is carried out in small groups of students, accompanied by a tutor, to solve complex problems that draw on elements of the students' real context (B. P. Silva et al., 2024) or on an imaginary, creative, or fictional context that motivates them to participate and engage in problem-solving (Lenkauskaite & Mazeikiene, 2012; Akben, 2019; Cavadas et al., 2022). Therefore, according to Akben (2019), "it can be suggested that the problem situation to be developed is the most important step in the implementation of the approach" (p. 232).

Because of this emphasis on real problems, some medical training courses structure their entire curriculum around PBL. Johansson et al. (2020) point out that PBL contributes to individuals' real learning, cultural environment, social interaction, agency, and communication, which are important skills for health professionals. Although the medical field provides numerous real problems for PBL, Phelan et al. (2022) point out the need for the problem to be designed in a way that respects the students' cognitive abilities, especially in the initial years of the course.

Science is also considered an area that is conducive to PBL, especially when problems are socio-scientific (SSI) or relate to Science, Technology, Engineering, and Mathematics (STEM) (Akben, 2019; Rubini et al., 2019; Hernández-Ramos et al., 2021). These multidisciplinary approaches are essential in preparing students to respond to complex economic, social, and environmental challenges, such as those presented by COVID-19 and climate change (Kuvac & Koc, 2018; Smith et al., 2022). Uluçınar (2023), in a meta-analysis that sought to identify the effect of PBL on academic performance in science education, found that the PBL approach has a strong effect on academic performance, regardless of the country where the study was conducted, the area of study, or the educational level. Several studies also indicate that the PBL approach helps promote scientific literacy (Rubini et al., 2019), self-regulation of learning (Alt & Raichel, 2020; Baptista, 2025), argumentation, engagement, and motivation (Hernández-Ramos et al., 2021), collaborative learning (Saputro et al., 2020), and critical thinking (Kuvac & Koc, 2018; Saputro et al., 2020).

All of these skills are important for building a society that can better address the challenges posed by the 21st century, such as Artificial Intelligence, climate change, unbridled consumption, social inequalities, food production, and distribution and environmental imbalances. Schools are the ideal setting for the implementation of PBL, as they offer a multiplicity of learning opportunities to young people. However, basic education teachers are not prepared to implement this approach. Research conducted by Akben (2019), Kuvac and Koc (2018), and Saputro et al. (2020) studied participants who received specific training to implement PBL. The metasynthesis developed by Dunst et al. (2019) analyzed 14 different types of teacher preparation in initial training. They observed that students' active involvement in instructional practices improves their acquisition of skills, knowledge, and attitudes towards the learning process, indicating that PBL, compared to other methods, is an effective approach in teacher training. PBL falls under the "Course-Based Learning Methods" category, contributing significantly to academic performance and the development of skills, knowledge, and attitudes.

Despite the visible contributions of teacher training anchored in Problem-Based Learning (PBL), its application in initial science teacher training generally only occurs in research studies, in which teachers receive specific training in PBL (Kuvac & Koc, 2018; Akben, 2019; Saputro et al., 2020). Kuvac and Koc (2018) conducted a 10-week study with 51 pre-service science teachers. The experimental group studied the PBL model, and the control group studied the face-to-face model. The authors sought to understand the effect of PBL on attitudes toward the environment, the theme of the 10-week course. Thus, they used a personal information form and an environmental attitudes inventory. The PBL format proved to be more effective than the traditional format in developing environmental attitudes in pre-service teachers.

Cavadas et al. (2022) studied the integration of science and mathematics knowledge in pre-service teachers' training using PBL. The authors developed an activity for pre-service science and mathematics teachers, structured around a research problem divided into two integrated problems. Using specific integration indicators, the authors were able to identify the level of integration between science and mathematics in pre-service teachers for each phase of the PBL activity. After solving the problem, the authors considered that all participants achieved integration with meaningful connections between the ideas of science and mathematics.

Novikasari (2020) used PBL to integrate mathematical content knowledge (MCK) with mathematical pedagogical content knowledge (MPCK) in pre-service teachers. The results showed significant differences between MCK and MPCK in classes that participated in PBL activities compared to conventional classes. These differences highlight the need for future teachers, in the PBL model, to take control of learning activities and be active in the search for solutions.

In order to identify possible contributions of PBL to the development of self-efficacy and critical thinking, Saputro et al. (2020) developed a quasi-experimental study with 44 pre-service teachers, with a control group (n = 22) and an experimental group (n = 22). Both groups studied the same topics (related to science) in three weekly meetings for six weeks, but the experimental group worked on three problem situations in the PBL approach. Both groups completed, before and after the intervention, the Self-Efficacy Scale (SES) and the Critical Thinking Questionnaire (CTQ). The results indicate that the PBL approach is more effective in increasing critical thinking skills and self-efficacy. In addition to being efficient in developing scientific and pedagogical knowledge, self-efficacy, and critical thinking skills, PBL should be taught to pre-service teachers so that future teachers can apply it in their classrooms. The challenges involve the perceptions of teachers in receiving training on PBL, the adequate development of problems that allow its applicability in basic education, and the application of PBL itself.

In terms of formulating appropriate problems, experts state that the problem needs to be close to reality, relevant to students, challenging, and structured within the cognitive possibilities of those solving it (Lenkauskaite & Mazeikiene, 2012; Akben, 2019; B. P. Silva et al., 2024); it also depends on collaboration to improve learning (Smith et al., 2022). However, Lenkauskaite and Mazeikiene (2012) point out that PBL requires students to invest significant effort and motivation to solve problems, and students are more likely to be motivated and engaged if the problem is of personal interest to them (B. P. Silva et al., 2024). To meet these demands, the problem can also be fictional (Akçay, 2009). Thus, the development of problems is one of the elements that future teachers should approach with sufficient attention and care.

Ekici (2016) observed, based on a PBL training course for pre-service science teachers, that participants can develop good problems—relating everyday life to scientific events—that are consistent with learning objectives. However, when applying PBL in the basic education science classroom, participants revealed some difficulties, such as classroom management, overcrowded classes, inability to ensure the participation of all students, and the inability of students to transfer knowledge to everyday issues. These issues mean that pre-service teachers, despite considering the PBL method appropriate, find it difficult to implement it in basic education.

Regarding problem-solving in a PBL approach, A. C. Silva and De Chiaro (2018) analyzed two different teachers, one with expertise in argumentation and the other without. The results show that expertise in argumentation allows teachers to perform pragmatic, argumentative, and epistemic discursive actions that result in a greater occurrence of argumentative elements, such as point of view, justification, and counterargument, leading to critical and reflective learning. Marthaliakirana et al. (2022) also observe the promotion of critical and reflective thinking when metacognitive prompts are provided by teachers. Some prompts used by the teacher involved the use of mind maps, flowcharts to plan the solution process, monitoring, peer evaluation, and self-evaluation.

We can thus observe that there are a number of advantages to the PBL approach for improving learning and acquiring important skills for the 21st century. However, there are many challenges that are mainly related to the need for adequate teacher training to implement PBL in basic education. However, despite the fact that physics teacher training in Brazil addresses several methodological strategies that promote active learning, PBL is not taught in undergraduate courses, neither in terms of developing and implementing a teaching plan nor experiencing it as a participant while studying to be a teacher (B. P. Silva et al., 2024).

With this in mind, we implemented a training process for scholarship holders of the Pedagogical Residency Program (PRP) in undergraduate courses in physics, who we will call Residents from now on. The PRP allows Residents to work in Basic Education Schools, in subjects in their area of training, supervised by a preceptor (a teacher at the Basic Education School) and accompanied by a coordinator (a professor from the undergraduate course in Physics at a Higher Education Institution). The PRP is a unique opportunity for pre-service teachers to experience the day-to-day life of a school in a more immersive and purposeful way. This is because they spend much more time in schools and under teacher supervision than in the mandatory supervised internships in their curriculum. Thus, the PRP also serves as a formative process, in which new teaching methodologies can be experienced by these students, who become the subject of research to improve pre-service teacher training.

In this scenario, some questions arose: What are the perceptions of pre-service teachers about the planning, application, and evaluation of a PBL intervention in physics teaching? What could the application of PBL in a Pedagogical Residency Program indicate about the training needed to effectively implement this methodology? Based on these questions, three objectives were outlined for this research: (a) to identify the Residents' conceptions about learning objectives, methodologies, and learning assessment; (b) examine the Residents' conceptions about problem situations; and (c) analyze the Residents' perceptions/learning about the "attitudes" necessary to conduct a PBL program.

The PBL training prepared and supported these Residents in teaching an elective subject alongside their preceptor teacher for a semester in a Basic Education School. During this process, we sought to understand their perceptions about the planning, implementation, and evaluation of PBL.

2. Materials and Methods

Among the public policies for teacher training in Brazil is the Pedagogical Residency Program (PRP) proposed by the Coordination for the Improvement of Higher Education Personnel, CAPES, in 2018, which aims to promote institutional pedagogical residency projects implemented by Higher Education Institutions (HEIs), contributing to the improvement of pre-service basic education teacher training. Thus, the PRP allows Residents (teacher in training) to work in a Basic Education School (BES) and teach subjects in his/her area of training, supervised by a preceptor teacher at the Basic Education School and accompanied by a coordinator at the HEI.

This immersion allows the Resident to experience the day-to-day life of a school and the administrative and pedagogical demands faced by teachers. Residents receive a scholarship for 18 months and must dedicate approximately 20 h per week to the program. The preceptor teacher also receives a scholarship and supervises up to 5 Residents per semester. The limit of 5 Residents per school is imposed by the general rules of the PRP and aims to ensure the quality of the monitoring and supervision provided by the preceptor teacher. At the HEI, a professor, who also receives a scholarship, coordinates both the activities of the preceptor teacher and the Residents. All participants were involved in the planning, monitoring, and evaluation of the activities developed during the academic semester at the BES.

The Residents were selected through an open selection process announced in a Public Notice for all undergraduate Physics students at the HEI. To enroll, it was necessary to have completed at least 50% of the course, including subjects such as Didactics, Learning Assessment, Supervised Internships, and Physics Teaching Methodologies, and be available to dedicate 20 h per week to the Residency. Interviews and academic transcripts were used to evaluate them in the selection process. The 5 chosen Residents, 3 women and 2 men, are between 20 and 24 years old and live in the school's neighboring cities. Two of them even attended high school at the same BES where the research was conducted.

After the Residents were selected, a meeting (Google Meet) was held to present and clarify the details of the research, and to inform them that participation was optional and that they could withdraw at any stage. All five Residents agreed to participate in the research, and the online meeting sessions between the HEI coordinator, preceptor teacher, and Residents were conducted via the Google Meet platform, all of which were recorded in video and audio. In addition, the Residents were accompanied in all their activities at the field school by the preceptor teacher, with observation and recording in a field diary serving as elements for constructing the results and analysis.

Table 1 presents the methodological flow developed during the research, divided into phases, highlighting the description of the activity and those involved, the data collection instruments, and the proposed objectives. The objectives of the research were (a) to identify the Residents' conceptions about learning objectives, methodologies, and learning assessment; (b) identify the Residents' conceptions about problem situations; and (c) analyze the Residents' perceptions/learning about the "attitudes" necessary to conduct a PBL program. More details are described in the text below.

Before the start of the semester at school, we surveyed the Residents' initial conceptions about the construction of teaching plans, through Questionnaire 1 (Q1) (Google Form) with the following questions: 1. Have you ever developed a teaching plan? What elements and/or characteristics do you consider essential in a teaching plan? 2. What do you consider important for the development of learning objectives when planning a lesson and/or an intervention? 3. What should influence the choice of a teaching methodology? 4. What should influence the choice of learning assessment strategies/instruments?

In this scenario, the HEI's professor and the BES's preceptor teacher proposed an elective subject entitled "Turning on the Lights: From Darkness to Space Travel" to be offered during the semester at the BES. In this way, the Residents would act in this subject as tutors. The school is located in a city in the interior of the state of Pernambuco in Brazil and is a public state school. The elective course involved 12 weekly meetings of 100 min each and aimed to work on concepts related to light, from the historical issues surrounding the phenomenon to issues related to fictitious space travel.

Table 1. Methodological flow.

Phase	Activity Description	Data Collection Instruments	Research Objectives
Diagnosis and planning	Explore Residents' conceptions about developing teaching plans.	Questionnaire 1 (Google Form)	(a)
	Definition of the contents to be covered in the elective subject and by each Resident (all involved).	Recorded Meeting (Google Meet)	(a)
	Residents prepare teaching plans for the first 6 meetings of the elective subject.	Teaching Plans (Google Classroom)	(a)
	Residents present their teaching plans for review and adjustments before the start of meetings at the BES (all involved).	Recorded Meeting (Google Meet)	(a)
PBL training course and the first 6 meetings at the BES	The preceptor teacher supervises the Residents in the first 6 meetings at the school.	Observation and Field Diary	(a)
	Presentation of the problem situation and its characteristics to the Residents.	Recorded Meeting (Google Meet)	(b)
	Residents' reflection on the PS characteristics and the role of the teacher in this methodological approach.	Questionnaire 2 (Google Form)	(b)
	Each Resident developed a PS based on the general context with light as a theme.	Google Classroom	(b)
	Peer review of the prepared PS.	Questionnaire 3 (Google Classroom)	(b)
	Discussion of issues related to planning and conducting the PBL approach with peers and supervised by the preceptor teacher.	Observation and Field Diary	(b)
	Finalized the elaboration of the problem situations and discussed the formative assessment in the PBL approach.	Recorded Meeting (Google Meet)	(b)
Implementation and evaluation of the PBL proposal at the BES	The preceptor teacher supervises the Residents at the 4 PBL meetings at the school.	Observation and Field Diary	(c)
	Reflections and analysis of the intervention after the first 2 meetings, applying the PBL approach.	Questionnaire 4 (Google Classroom)	(c)
	Residents' perceptions of the tutoring process in a PBL approach.	Questionnaire 5 (Google Classroom)	(c)

The first 6 meetings at the school were used to study the basic concepts related to the phenomenon of light. The classes taught in these meetings were designed and conducted by the Residents, so the teaching plans they developed and Q1 were instruments for analyzing the Residents' conceptions about teaching planning. In the sixth meeting, the five Residents worked together, sharing class time and collectively developing teaching materials and a lesson plan. Thus, we collected documentary data and empirical observations over the six weeks, which allowed us to reflect on the research participants' competencies and skills, as well as their conceptions of learning objectives, teaching methodologies, and learning assessment.

The Residents worked hard to prepare for these first 6 meetings, developing teaching materials and low-cost experiments, which promoted student engagement, a fact reported by them in follow-up meetings held with the preceptor teacher and the coordinator. The following 4 meetings were used to implement a PBL proposal, where the Residents acted as tutors for groups of 5 students each. The final two meetings were used to evaluate the entire course.

Concurrently with the meetings at the BES, the Residents participated in a PBL training course taught by the BES's preceptor teacher and the HEI's professor. For these meetings, we used Google Meet, since some of the Residents do not live in the same city, thus avoiding unnecessary travel costs and time. A Google Classroom was also created, from which the questionnaires and texts were made available, and enabled the collection of teaching plans and other materials. The training took place before the Residents began implementing PBL in the BES. Thus, we used the following problem situation for the training of the Residents:

> *You are a high school teacher and you notice that your students are very interested in science, especially when you offer an elective subject on the topic of "Light", and the students are very participative and accept various challenges. Motivated by this situation, but at the same time concerned about maintaining and taking advantage of this active disposition of your class, you seek help from the studies you carried out during your undergraduate studies on teaching methodologies in order to develop something that allows your students to be even more protagonists of their learning. Then, you rediscover the possibilities presented by the Problem-Based Learning (PBL) methodology. PBL has the potential to work with real situations, motivate and involve students in an investigative process and enable the development of attitudinal, procedural and conceptual learning. On the other hand, you do not remember having seen or read about the implementation of PBL in high school, especially for teaching topics related to Physics. However, PBL seems to be a good option to address the topic of Light, within the social context of your students, motivating and further developing their interest in science. Therefore, how can you develop a problem situation and apply it in the PBL methodology to address the topic of LIGHT with your high school students, knowing that you have 4 weeks/meetings, with 2 h/class per meeting?*

The context of the problem situation was based on Residents' reports on whether students participated and were interested in classes on the topic studied (light). Ribeiro et al. (2020) point out that contextualizing the theme of the problem situation to the participant's reality brings them closer to the proposed question. For the authors, this is the first of four characteristics of an effective problem. The second characteristic is that the problem situation should prompt critical reflection on the subject addressed. In our case, critical reflection appears in the excerpt: *Motivated by this situation, but at the same time concerned with maintaining and taking advantage of this active disposition of your class, you seek help in the studies carried out during your undergraduate degree on teaching methodologies in order to develop something that allows your students to be even more protagonists of learning*. The third characteristic is to motivate the participant to seek solutions, as we put it in the excerpt: *Then, you rediscover the possibilities presented by the Problem-Based Learning (PBL) methodology. PBL has the potential to work with real situations, motivate and involve students in an investigative process, and enable the development of attitudinal, procedural, and conceptual learning*. Finally, the final section of the problem situation favors the proposition of hypotheses, research, investigations, questions, and discussions, leading to decision-making, which is the fourth and final characteristic that an effective problem must present, according to Ribeiro et al. (2020).

After the meeting where we presented the problem situation (PS) and its characteristics (Ribeiro et al., 2020), the Residents answered Questionnaire 2 (Q2). Q2 was prepared using Google Form and made available on Google Classroom. The Q2 aimed to make them reflect on the characteristics of the problem situation and the role of the teacher when using a methodological approach that uses a PS. The questions that make up Q2 are as follows: 1. Have you ever had contact with Problem Situations during your undergraduate course? If so, what were they like? 2. What are the main characteristics of a Problem Situation based on what we discussed in the last meeting? 3. How do you differentiate the characteristics of a Problem Situation before/after our meeting? 4. What is the role of the Teacher when working with a Problem Situation? 5. How does contextualization influence the Problem Situation? 6. To what extent should the teacher know a possible solution to the proposed Problem Situation?

After answering Q2, the Residents had one week to present their first proposal for a problem situation, remembering that each of them should bring a proposal, since they would be tutoring different groups. Nonetheless, we observed that the Residents had difficulty contextualizing their proposals, even though they demonstrated an understanding of the importance of context for the PS. They constructed questions without context or with a very high level of difficulty. R3, for example, proposed: "Since there are two main theories that seek to explain how light behaves, you propose to study them to identify and expose the poorly explained points of both theories, so that from there you and your team can present your own conclusions, bringing a new model to explain the behavior of light". We observed that R3 created a problem that is not contextualized with the students' reality, has no solution, and does not present knowledge to guide the construction of a possible solution, completely contradicting the importance of contextualization in problem situations, the role of the teacher as a mediator, and knowing possible solutions to the problem. The trainers (the preceptor teacher and PRP coordinator) proposed a contextualization focused on "space travel" that united all the Residents, and from this proposal, they were able to construct their problem situations.

So, it was necessary to construct a context to provide a basis for the production of the problem situations. Given the theme of the elective subject, the context was as follows:

> *You are a crew member of the largest starship of the United Federation of Earth, and you are one of those responsible for searching for other planets that can sustain life, and consequently populate them. Arriving at one of the new possible planets that are candidates for colonization, you realize that some events work differently from how they did on Earth, including phenomena in the atmosphere, fauna and flora, and even in the crew members themselves. Knowing that you need to survive in this place, you need to learn how things work here. The star is a red supergiant star, which has a luminous intensity that is very different from the Sun (the star in Earth's solar system), much greater in fact, in the same way that it may not produce much light with a certain wavelength, thus leaving some colors very rare to see. The atmosphere has elements that make it work as a polarizing filter, filtering the light that is emitted by the star. Therefore, not all of the light from this star reaches the surface of the planet. With this fact in mind, we already know that several things can happen in very different ways.*

Note that the contextualization is not close to the students' daily lives; however, it is related to the theme of the elective discipline "from darkness to space travel", so a fictional scenario was more appropriate to provoke student engagement, as pointed out by Akben (2019) and B. P. Silva et al. (2024). Based on this contextualization, each Resident constructed a problem aiming to integrate knowledge in an interdisciplinary way with the theme of light as the central axis. With themes focused on the growth of flora (R1), the color of the sky (R2), human vision (R3), the production of vitamin D (R4), and bird locomotion (R5). Below, the problem situations developed by the Residents, based on the general context proposed, are presented:

R1 Seeing the need to grow one's own food, it is noted that when plants sprout, they present certain characteristics that are very different from those on Earth. Knowing that light is of great importance for the development of plants, how do you explain the characteristics they presented, and how could food cultivation work on this new planet?

R2 To your surprise, the sky is red. Knowing that one of the factors responsible for the sky's color is its star. How would you explain this effect? What properties end up generating this phenomenon?

R3 Upon arriving on the new planet, humans notice that they are having a different perception of colors, so that they cannot see certain colors, as if there was something blocking the passage of certain colors to their eyes. Knowing this, they assemble a team to analyze the planet's atmosphere and light and seek to understand this phenomenon. What possible causes do you think contribute to this happening?

R4 After weeks on the new planet, most of the crew members presented symptoms such as joint pain, fatigue and muscle weakness. After tests, it was confirmed that it was a vitamin D deficiency. Considering that the crew members' diet is extremely strict, that is, factors related to diet are ruled out, what factors and characteristics of this new planet could directly interfere with the deficiency of this vitamin? Investigate, discuss and raise hypotheses as to how this could occur.

R5 With the animals that were transported on the ship along with the crew, upon arriving on this new planet, in a new environment, it is clear that some of them, especially the birds, feel much more lost and have some difficulty moving around and feeling space. All of this is related to their vision. Considering that some animals, especially birds, see differently than humans, in relation to lights, what could be the possible cause for them to have this vision deficit? And what would be a solution to this problem?

Then, the problem situation was presented and discussed under the supervision of the preceptor teacher and analyzed by peers, using Questionnaire 3 (Q3) as a guide for this analysis. Q3 had the following questions: 1. What questions can you ask about the PS? 2. What concepts of optics or light can be related to this PS? 3. What knowledge related to other sciences can help answer/understand this PS? 4. In a brief search on the Internet, what did you find that could help answer this PS? After providing individual answers to these questions, we shared and discussed them to simulate possible questions from the students. The Q3 questionnaire was administered to Residents after a meeting held at the school, where each Resident had the opportunity to present the problem situation they had developed to their colleagues. This presentation was coordinated by the supervising teacher, who chose how the peer evaluation of the problem situation would take place, that is, which Resident would analyze the problem situation developed by their colleague. Thus, R1 analyzed the SP developed by R5, R2 analyzed the SP developed by R4, R3 analyzed the SP of R1, R4 analyzed the SP of R3, and R5 analyzed the SP of R2.

Issues related to planning and conducting the PBL approach were also discussed at this meeting. The following week, we finalized the elaboration of the problem situations and discussed the formative assessment in the PBL approach. In addition to the formative meetings, readings were also made available to the Residents, such as Ribeiro et al. (2020) and Camargo (2019). The following meetings were for monitoring the implementation of PBL at the school. After 2 weeks of the 4 meetings of applying PBL at the school, the

Residents answered Questionnaire 4 (Q4) so that they could present their reflections and analyze the intervention at this point. Q4 has the following questions: 1. Comment on the students' expectations and reactions when the Problem Situation was presented to them; 2. Comment on the difficulties encountered in conducting the PS without "giving away the gold", that is, helping them think about it, but without providing answers; 3. What knowledge/concepts of Physics were listed by the students as possible "responsible" for the problem presented in the PS? 4. How do you think it is possible to evaluate students' learning in the process of solving the PS? 5. After applying PS in these first two weeks, would you make any changes to your PS? Which ones?

A final questionnaire (Q5) was given to the Residents in order to understand how they perceived the tutoring process. To guide the Residents' reflections, we asked: 1. What were the impressions left by the students when working in groups? Were you able to observe behaviors that revealed attitudinal knowledge? Comment. 2. PBL fosters scientific thinking, however, was there a change in the way students thought/dialogued/shared knowledge when they tried to build a solution to the problem situation? Comment in great detail. 3. List the main difficulties encountered when working with problem situations. 4. What possible improvements could be made to make the problem situation more effective? 5. When participating as a tutor, it is possible to perceive the heterogeneity of the group. How were divergent opinions developed?

As can be seen, all data collection instruments are qualitative. The questionnaire responses were very detailed, indicating that the Residents reflected on each question. Additionally, we used the preceptor's field diary, the Residents' teaching plans, and Google Meet recordings. Thus, the analysis was based on reading the responses and identifying common themes that allowed us to understand how these Residents understand teaching planning, especially the relationships they are able to develop between learning objectives, methodologies, and formative assessment. To analyze the problem situation, we observed whether the Residents were able to achieve the four characteristics proposed by Ribeiro et al. (2020), the processes of elaboration of the PS (Q2), and how they analyze the problem situation created by their colleagues (Q3). The analysis of the implementation process, which involved the application of questionnaires Q4 and Q5, also involved the elaboration of themes that could help us understand how the Residents felt about conducting PBL and how they perceived changes or reactions from the students who participated in the application of PBL.

This research is part of the research developed by one of the authors and was submitted for analysis by the Research Ethics Committee through the *Plataforma Brasil* for the National Health Council, having been approved under number CAAE 80019824.0.0000.5208.

3. Results

To achieve our first research objective, that is, to identify Residents' conceptions about learning objectives, methodologies, and learning assessment, the responses to Q1 and the plans prepared for the first six meetings in the elective discipline were used. Next, we will discuss the processes of elaboration and analysis of problem situations (PSs) carried out by the Residents, in order to respond to our second research objective: to identify the Residents' conceptions about problem situations. For this purpose, we will use the responses to Q2, observations, and the preceptor's field diary of the discussion and analysis among peers of the PS (Q3). The analysis of the implementation of PBL has two directions: one focused on how the Residents felt conducting the PBL approach (Q4) and how they observed changes or reactions of the students depending on the type of approach (Q5). The observations and field diary of the preceptor teacher, who accompanied the four PBL implementation meetings by the Residents, are also used to complement this analysis and respond to our third research objective: to analyze the Residents' perceptions/learning about the "attitudes" necessary to conduct a PBL program.

3.1. Conceptions on Teaching Planning

For the purpose of presenting the results, the Residents were named R1, R2, R3, R4, and R5, with R3 and R5 being men and the other Residents being women. In order to survey the Residents' initial conceptions about the construction of teaching plans, we used the Q1 questionnaire, the answers to which are presented in Table 2. Table 3 presents the relationships between learning objectives, methodologies, and assessment that Residents expressed on the teaching plans prepared for the first five meetings in the elective course. These were taught individually by each Resident: the first class was taught by R1, the second by R5, the third by R3, the fourth by R4, the fifth by R2, and they worked together in the sixth class. The observations and field diary of the preceptor teacher helped analyze how Residents can (or not) put into practice the teaching plans they developed.

Table 2. Residents' responses to Q1.

Questions	Resident	Response
1. Have you ever developed a teaching plan? What elements and/or characteristics do you consider essential in a teaching plan?	R1	*Yes, teaching methodologies, activities, class structure, time management, well-defined objectives, etc.*
	R2	*During my two internships, I was able to develop some lesson plans, some of which I put into practice in my teaching. Initially, the most important point is planning, organizing schedules, the methodology that will be applied, how the subject will be approached, what the main theme will be, how you will conduct the class and assessment methods.*
	R3	*Yes, in the Didactics discipline I prepared a lesson plan, I believe it is essential, a good way to evaluate the students' learning process, because in my opinion, just an evaluation does not guarantee that they are learning, good planning and organization are necessary.*
	R4	*I have never prepared one, however, in the Didactics discipline I had the experience of analyzing a lesson plan. I believe that it is the necessary tool to provide an overview of the teaching-learning process to both the teacher and the students. Thus, based on the learning objectives proposed by the teacher, it will be possible to outline in the lesson plan the methodological processes and resources that will be the basis for achieving these objectives. In addition, I believe it is essential to explain how the evaluation processes will be carried out.*
	R5	*No, I never developed any teaching plan.*

Table 2. *Cont.*

Questions	Resident	Response
2. What do you consider important for the development of learning objectives when planning a lesson and/or an intervention?	R1	*Where you want to go, how to get there, why you want to get there and the importance of this goal*
	R2	*Observation, research, collection of testimonies from the school structure and satisfaction analysis. In other words, everything that will show the successes and mistakes that have already occurred in the institution, so that a more accurate and safer path can be planned.*
	R3	*I believe that what is most important is to have the objective of learning where the student is not limited to behaviorist teaching models, where the focus of "learning" is to get a good grade or pass the entrance exam. I think it is necessary that the main objective is the development of reasoning, questioning and curiosity, where knowledge is the true reward of teaching, and passing the test is a consequence.*
	R4	*I believe that as a basis, the teacher should take into account what is proposed by the curriculum, such as the guidelines of the BNCC and the school program content. In addition, the teacher should have prior knowledge and take into account the difficulties and skills that the students have, which may vary between classes in the same year. This way, the teacher will be democratic and fair when creating a plan that suits each class. For example, in classes with a predominance of extroverted students, the teacher can consider whether group work will be the best option to promote learning or not.*
	R5	*Well, I think the main thing is that students achieve the objectives. Therefore, I believe that when developing learning objectives when planning a lesson and/or intervention, it is important to keep in mind the possible difficulties and the best ways to approach your methodology in order to achieve the intended objectives.*
3. What should influence the choice of a teaching methodology?	R1	*In my opinion, the development and acceptance of the class.*
	R2	*The level of the students in the classroom, how they behave depending on the methodology applied, and how I can achieve better concentration from the majority of the class.*
	R3	*The specificities of each class, and also of each student.*

Table 2. *Cont.*

Questions	Resident	Response
	R4	*The content to be covered and the characteristics of the individuals in each class directly influence the chosen methodology. In physics teaching, some content is more amenable to conducting experiments, for example. Thus, the teacher may opt for this form of teaching-learning process, which does not prevent other methodologies from being combined. The teacher may also ask students for suggestions on which methodologies they feel most comfortable with or would like to use. By mutual agreement, the teacher and the students may choose the best methodologies for given content and situations. From this perspective, the teacher may consider these factors, in addition to indirect factors such as workload, management demands, the school's physical structure, and available resources.*
	R5	*Different study methodologies work in different ways to achieve the desired goal. Therefore, it is important to check whether the chosen methodology is the most effective for the intended purpose. It is important to observe whether this methodology can make the student memorize, question, and finally learn the content.*
4. What should influence the choice of learning assessment strategies/instruments?	R1	*Development and acceptance of the class.*
	R2	*Know the possibilities, application and limitations of the instruments and students. Knowing your class and how it deals with different dynamics is essential, analyzing which points you get the best results and following that path.*
	R3	*Once again, the specificities of each class or student. It is necessary to analyze the difficulties encountered by each class, or individually by each student, and we can adapt to the pace and difficulties of each one.*
	R4	*Firstly, the teacher's view of what assessment is will directly influence this process. When the teacher understands that assessment is linked to an investigation process that goes from the classroom, considering individual and social factors, to moments after exams, including feedback and guidance, for example, the assessment process will have a broader and fairer meaning. Therefore, whatever assessment instruments the teacher chooses, it is important that they are based on meaningful learning.*

Table 2. *Cont.*

Questions	Resident	Response
	R5	*Speaking of learning assessment, I believe in three forms of assessment: The first would be a more classic assessment, checking whether the student has learned specific elements, perhaps as a written assessment; The second would be something more long-term, checking how much the student has improved over time in learning a certain content; And finally, the third would be to let the student self-evaluate, being honest with themselves about what they managed and/or failed to learn.*

Table 3. Relationships between Learning Objectives, Methodologies, and Assessment expressed on the teaching plans.

Resident	Objectives	Methodologies	Assessment
R1	*List and discuss the importance of Light, how we see it and what sensations it can provide to human beings.*	*Individual activity on how the eye works based on drawings and explanatory writing individually, lecture, peer review*	*We will have a Formative Assessment, which will be constructed based on the efforts and performance/participation of students regarding the content worked on and proposed exercises*
R2	*know and understand the behavior of light* *introduce the concept of the polarizer and how it works*	*Dialogued lecture* *Demonstrations of the use of the polarizer Presentation of the summary of what was discussed during the lecture*	*The assessment will be done through questions*
R3	*Understand and discuss the origin of light;* *Understand the wave and particle theories of light and their main differences* *Introduce the different explanatory aspects of light and related phenomena* *Apply prior knowledge to the interpretation of everyday situations involving light and its different properties*	*Identify students' prior knowledge through questions. Dialogued lecture*	*The assessment will be done through questions*
R4	*Continue with reflections on Newton's corpuscular theory and Huygens' wave theory* *Understand the differences between the two theories* *Learn about the phenomenon of wave interference* *Analyze experiments with slits and reflect on their results* *Understand the types, classifications, propagation media and characteristics of waves in general* *Theoretically understand light behaving like a wave*	*Review and present new topics* *Demonstrate and contextualize with everyday examples* *Ask questions with the aim of creating in students the feeling of needing to solve a problem*	*Contextualize the content with everyday situations* *Questions and challenges during the explanation* *Conversation about the questions*
R5	*Introduce students to the concepts of colors related to visible light*	*Dialogued lecture*	*Research relating the finding to what was given in class and explaining where this relationship comes from and how they thought about that specifically*

Through the answers to Q1 (Table 2), it is clear that R5 had never prepared or analyzed a teaching plan before, explaining why his teaching plan was the poorest in terms of learning objectives and teaching methodology; however, it is observed that the evaluation proposal is closer to a formative assessment, as we can see by Table 3. However, this did not prevent him from making an important point about learning objectives at Q1, that they should be designed in such a way that they are achievable by students and that the methodology used should enable this achievement:

I believe that when developing learning objectives when planning a lesson and/or intervention, it is important to keep in mind the possible difficulties and the best ways to approach your methodology in order to achieve the intended objectives. (R5)

Observation of R5's performance revealed commitment to executing the plan, which presented appropriate content for the proposal, despite having difficulty recapitulating knowledge covered in the previous class as a starting point. Furthermore, R5 failed to manage time appropriately, and his assessment proposal was not implemented in the class. Therefore, without the assessment, it is difficult to determine whether his concern with the relationship between objectives and methodology was realized.

Only R1 expressed concern about managing time appropriately during the class, explaining this as an essential element to be considered in the teaching plan (Q1—Table 2). In the individualized class, the preceptor observed that R1 managed time (setting aside sufficient periods for students to take notes, express questions, discuss, and solve problems) and managed students more effectively. This performance can be attributed to the fact that R1 has more classroom experience than the other Residents, an aspect raised by the preceptor during the Residents' monitoring. R1 presented the development and acceptance of the class as the only element in defining the methodology and assessment strategies (Q1—Table 2). However, R1 taught the first class and did not have time to get to know the class. This indicates that the methodology and assessment were likely linked to her previous experience and the content to be taught.

We observed that only R2 has a different view on learning objectives, as expressed in Table 2:

Observation, research, collection of testimonies from the school structure and satisfaction analysis. In other words, everything that will show the successes and mistakes that have already occurred in the institution, so that a more accurate and safer path can be planned. (R2)

R2 also expresses a concern with class knowledge and behavior as elements for defining methodology and assessment (Q1—Table 2). However, unlike R1, she teaches the last class and has time to get to know the class better. The teaching plan (Table 3) presented appropriate content, objectives, and methodology. However, it did not clearly explain how the assessment would occur, simply stating: *The assessment will be done through questions. (R2)*. Observation of R2's teaching plan implementation, conducted by the preceptor teacher, reveals that, like R5, R2 had difficulty recapitulating the knowledge covered in previous classes as a starting point. Furthermore, R2 failed to adequately consider the assessment process, asking students questions during the class without observing any form of recording or feedback.

R3, like R1 and R2, also reports that the class profile influences the learning assessment instrument or model (Q1—Table 2). Although the teaching plan (Table 3), proposed by R3, highlights a concern with identifying students' prior knowledge, like R2 and R5, R3 had difficulty revisiting knowledge covered in previous classes (preceptor's observation). The preceptor also points out that R3 had significant difficulty creating a dialogic environment as proposed in his plan and only implemented a written assessment with 10 questions on the topic. Thus, there is a disconnect between practice and what R3 presents as important for developing learning objectives (Q1—Table 2):

> *I believe that what is most important is to have a learning objective where the student is not limited to behaviorist teaching models, where the focus of "learning" is on getting a good grade or passing the entrance exam. I think it is necessary that the main objective is the development of reasoning, questioning and curiosity, where knowledge is the true reward of teaching, and passing the test is a consequence. (R3)*

The teaching plan proposed by R4 was the most comprehensive. His learning objectives already highlight the importance of reviewing previously covered content: *Continue with reflections on Newton's corpuscular theory and Huygens' wave theory (R4).* It is worth noting that his class takes place a week after R3's, which introduces this content. In total, R4 presents six objectives that are aligned with the methodological and assessment proposals. His proposals are aligned with his reflections when answering Q1 (Table 2), particularly regarding learning assessment:

> *Firstly, the teacher's view of what assessment is will directly influence this process. When the teacher understands that assessment is linked to an investigation process that extends from the classroom, considering individual and social factors, to moments after exams, including feedback and guidance, for example, the assessment process will have a broader and fairer meaning. (R4)*

The preceptor points out that R4 was able to consolidate his entire teaching proposal during the class.

After classes, in a meeting with the Residents, when asked about the implementation of their teaching plans, they revealed difficulty in conducting a dialogue presentation and were unanimous in their fear of teaching Physics content to high school students.

3.2. Preparation and Analysis of Problem Situations

In order to understand how Residents reflected on what a problem situation (PS) is, and achieve our second research objective (to identify the Residents' conceptions about problem situation), after the meeting in which we presented and discussed the characteristics of a problem situation, we applied Q2. The Residents' responses to Q2, as shown in Table 4, indicated that R4 and R5 had no previous contact with PSs, R1 and R2 had already heard of PSs, and R3 had experienced an activity that involved PSs in a subject in their undergraduate course.

Table 4. Residents' responses to Q2.

Questions	Resident	Response
1. Have you ever had contact with Problem Situations during your undergraduate course? If so, what were they like?	R1	*Yes, I don't remember specifically which ones, but they all involved mechanics!*
	R2	*I haven't had any direct contact, but I've studied a little about problem situations and it was enriching.*
	R3	*An experience in a Physics Teaching Methodology 2 subject where we had to start from a problem situation to develop a contextualization for a class*
	R4	*No*
	R5	*No, I believe I have never had contact with problem situations, although I have heard about them during my undergraduate studies.*

Table 4. *Cont.*

Questions	Resident	Response
2. What are the main characteristics of a Problem Situation based on what we discussed in the last meeting?	R1	*The main characteristics are: theoretical support (which we have already started), contextualization of the problem, reflection and motivation for research. That the SP has an answer, if possible, it is interconnected with the student's daily life, etc.*
	R2	*change/cause, combination, comparison and equality.*
	R3	*Contextualize in relation to the student's reality, develop critical reflection and motivate them to seek solutions to the situation presented.*
	R4	*These are situations that lead students to reflect on a solution that is not immediate or automatic; such problems go beyond formulas. Thus, the student will have active learning, where the solution or possible solutions will be constructed throughout a previously structured process.*
	R5	*According to what was discussed and presented at our meeting, I believe that the main characteristics are: working with real situations, motivating and involving students in an investigative process and enabling the development of attitudinal, procedural and conceptual learning.*
3. How do you differentiate the characteristics of a Problem Situation before/after our meeting?	R1	*Well, as I already had some contact with this methodology, I already knew some things, but I thought a lot about the importance of involving the student's reality in a different way.*
	R2	*Before the meeting I had an idea about the characteristics of a problem situation very similar to what was discussed in the meeting, however, I had never imagined what it would be like in practice, as we did during the meeting.*
	R3	*In contextualization, seeking to bring the student's reality closer to our problem situation, then in reflection we will reflect on the problem, its characteristics and possible solutions, and from there begin to work to find possible solutions.*
	R4	*The situations must be motivating for students, in the sense that they can actually become interested in the possible solution. They must also be designed in such a way as to encourage the student to take an active and leading role in the face of the problem.*
	R5	*Before, I believed that problem situations were just about solving problems/questions in class. Today I see that it would be about working in a different way, making students learn from different perspectives, conceptually, practically, cognitively, and in terms of attitudes.*

Table 4. *Cont.*

Questions	Resident	Response
4. What is the role of the Teacher when working with a Problem Situation?	R1	*The main role of the teacher, in resolving a problem situation, is to mediate in a light way, readings, conversations, provoking questions in a way that leads students to reflect, seeking to understand how students would solve this problem!*
	R2	*He must be a mediator, facilitator and articulator of knowledge and not just the one who holds the information.*
	R3	*I believe that when developing a problem situation, the teacher places his student as an active part of the teaching-learning process, therefore, he must mediate discussions and encourage students' curiosity and critical thinking.*
	R4	*Provide an alternative to technical education that does little to encourage students to think about their practices, thus generating new, meaningful ways to construct learning.*
	R5	*I believe that the teacher should act as a mediator, helping students so that they can work and resolve the problem situation.*
5. How does contextualization influence the Problem Situation?	R1	*The contextualization of the problem situation brings students closer to their reality, motivating them to find ways to resolve a situation that is often considered obvious to them, breaks down deviations in thinking that may be generated and deviate from the resolution of the proposed issue, and associate's knowledge.*
	R2	*So that students feel like producers of knowledge, put them in this situation, allowing them to internalize it through their experiences, establishing conditions for problematization.*
	R3	*We must contextualize thinking about including the students' reality, so that it comes closer to something they experience or have experienced, as this makes it more stimulating.*
	R4	*Contextualization is directly linked to the student's motivation, because for them to be able to actually commit to a resolution or reflection, it is important that there is prior interest.*
	R5	*Contextualization helps to better understand the circumstances of the problem situation, understand the proposed cause of the problem, and can help in the search for a resolution to this problem.*

Table 4. *Cont.*

Questions	Resident	Response
6. To what extent should the teacher know a possible solution to the proposed Problem Situation?	R1	*When creating an effective problem situation, the teacher must reflect and have in his hands the answers that lead to the final result, and the final result.*
	R2	*The teacher must welcome differences and consider them in the teaching-learning process, recognizing that each student learns in a different way, has their own context and needs to be recognized as an individual.*
	R3	*The teacher must know the problem situation and possible solutions very well, because if the students are unable to develop, the teacher must guide them, showing them the path to follow.*
	R4	*The teacher must know the entire context, so that he or she can clarify any doubts that may arise during the students' reflection process. However, the teacher does not need to know the answer, or even if it is possible to arrive at it.*
	R5	*Well, considering that the teacher must act as a mediator and helper for the students during the resolution of a problem situation, he does not need to know everything about a possible solution, but I believe it is important that he knows the path to a possible solution, and that with that, he can direct the students to follow that path and solve that problem situation.*

In general, the Residents externalized (in Q2) some of the most important characteristics for a problem situation, approaching what was stated by Ribeiro et al. (2020):

> *These are situations that lead students to reflect on a solution that is not immediate or automatic; such problems go beyond formulas. Thus, the student will have active learning, where the solution or possible solutions will be constructed throughout a previously structured process. (R4)*

> *According to what was discussed and presented at our meeting, I believe that the main characteristics are: working with real situations, motivating and involving students in an investigative process and enabling the development of attitudinal, procedural and conceptual learning. (R5)*

Furthermore, we realized that the meeting where we presented the PS and its main characteristics helped the Residents to distance the PS used in methodologies, such as PBL, from the issues commonly used in science teaching, such as exams, examples solved on the board during classes, and even in experimental activities:

> *Before the meeting I had an idea about the characteristics of a problem situation very similar to what was discussed in the meeting, however, I had never imagined what it would be like in practice, as we did during the meeting. (R2)*

> *Before, I believed that problem situations were just about solving problems/questions in class. Today I see that it would be about working in a different way, making students learn from different perspectives, conceptually, practically, cognitively, and in terms of attitudes. (R5)*

The Residents also reported the main characteristics that the teacher or tutor should present when conducting the resolution of a problem situation, from the perspective of being the mediator of knowledge and placing the student as the protagonist, helping them develop important skills such as creativity and critical thinking.

When talking about how contextualization influences PSs, we observed that Residents 1, 3, and 4 attribute importance to its connection with student motivation. For them, it is essential to bring aspects of students' lives so that we can attract them and keep them interested in finding a solution to the PS:

> *We must contextualize thinking about including the students' reality, so that it comes closer to something they experience or have experienced, as this makes it more stimulating. (R3)*

> *Contextualization is directly linked to the student's motivation, because for them to be able to actually commit to a resolution or reflection, it is important that there is prior interest. (R4)*

R2 related the contextualization of the problem situation to the feeling of producing knowledge, which involves aspects of conducting PBL. For R5, this contextualization has a fundamental connection with the construction of a PS, so that it helps to understand the problem that one seeks to solve.

When asked about the need for the teacher to have knowledge of a possible solution for the proposed activity, R2 described some of the important characteristics for a teacher as a mediator, but did not talk about whether or not he knows the answer to the SP. On the other hand, R1 was emphatic in saying that the teacher must know the answer, which contradicts the main aspect of the PBL approach: the focus is not on the final result, but in on the process; that is, the learning that occurs on the way to solving the SP is more important than arriving at a final answer. The others considered that, to some extent, knowing the possible paths to a solution would be important to implement the PBL approach.

In general, the Residents had a good understanding of the problem situation and the role of the teacher in conducting a PBL approach. However, when we asked them to design a problem situation to implement in the elective course, we observed that they were unable to develop it, and we needed to create a general context for everyone (presented in item 2). Based on this general context, each Resident created a problematization that integrated knowledge of the physics of light with other areas, which were presented in Section 2. These PSs were discussed with the HEI's coordinator and preceptor teacher in online meetings. Furthermore, as described in Section 2, there was a meeting at the BES for peer analysis and discussion of all Residents' problem situations, monitored by the preceptor teacher. This meeting also discussed the expected attitudes in conducting PBL. Thus, all Residents came to class with clear indications of possible solutions and questions that could be asked by students. So, in theory, they were ready to apply PBL.

3.3. Reflections on Intervention: Tutors and PBL

The Q4 questionnaire, presented in Table 5, was answered by the Residents during the implementation of the PBL proposal, which lasted 4 weeks. The main idea was to help the Residents reflect on this initial moment of the intervention and, up until that moment, the main challenges they faced. The responses to Q4 and the preceptor's observations help achieve our third research objective: to analyze the Residents' perceptions/learning about the "attitudes" necessary to conduct a PBL program.

Table 5. Residents' responses to Q4.

Questions	Resident	Response
1. Comment on the students' expectations and reactions when the Problem Situation was presented to them.	R1	*At first, the students were extremely excited about solving the situation and this new problem.*
	R2	*When contextualizing the students about the problem situation, they presented behavior that I expected, many questions, a lot of imagination, and more than meeting my expectations, I had many positive surprises with the paths that the students were following since their first contact with PS.*
	R3	*At first, they were scared, but as the activity progressed and their doubts were clarified, the activity began to arouse curiosity and interest in the students.*
	R4	*The students were curious and motivated to solve the problem, since contextualization (involving space travel) is not usually addressed in the classroom, especially from a PBL approach.*
	R5	*I felt that both the expectations and the students' reactions were quite mixed. We did not "prepare" the students for the challenge that PBL would be. On the one hand, I felt that when PBL was announced, some of the students seemed to have a lot of doubts about what it meant, while others ended up not caring so much. On the other hand, when the Problem Situation was presented, everyone showed a lot of interest, they seemed quite enthusiastic about solving that problem, about "overcoming that challenge", so to speak.*
2. Comment on the difficulties encountered in conducting the PS without "giving away the gold", that is, helping them think about it, but without providing answers.	R1	*The biggest difficulty was mediating the students so that they could think again in the "correct" way, since they had many ideas and initially were unable to organize them.*
	R2	*I confess that it was difficult not to answer the questions asked by the students, because I am used to always answering the doubts of those who ask me questions, directing them indirectly was very difficult. One of the most difficult things was seeing that many of the paths they were following were not in line with what we wanted to find, and it was particularly challenging for me to find a way to show alternative paths.*
	R3	*Personally, I think one of the most complicated parts is guiding the conversation and research without giving the answers or making the answers very obvious. We have to be constantly policing ourselves so as not to respond without realizing it.*
	R4	*The students, or at least some of them, showed interest in finding solutions, including the hypotheses generated, although sometimes they deviated from what was proposed, they were creative and had a good scientific basis. However, the large number of students thinking of different hypotheses ended up creating an environment in which it was necessary to intervene. In this case, it was difficult to mediate and at the same time not provide answers.*

Table 5. *Cont.*

Questions	Resident	Response
	R5	*Initially, it was very difficult to give students directions without giving too many answers and ruining the idea of PBL. However, as time went by, as they shared their ideas and asked questions, I found that they progressed very well without having to rely on my help so much. But initially, it was very complex. I thought a lot and went over several words in my head, fearing that I would end up giving more information than I should have.*
3. What knowledge/concepts of Physics were listed by the students as possible "responsible" for the problem presented in the PS?	R1	*Excess light, Polarizer.*
	R2	*Some students were questioning the frequency and length of light, others were questioning what the planet's orbit, distance, polarization, among others.*
	R3	*The first ideas were related to the star, temperature and whether the light in the house would be different. After some discussions, concepts such as atmosphere, visible spectrum, reflection and refraction, ozone layer and ultraviolet rays began to appear.*
	R4	*Students always commented on wavelength and frequency, as well as mentioning light intensity.*
	R5	*The students had a basic idea of what could be responsible for the problem. They put the excess light emitted by the Red Supergiant Star as the cause of the problem faced by the birds. Since birds see in a very different way from humans, they can see not only the colors of common visible light that humans also see, but they can also see certain colors of the light spectrum that would be invisible to us humans.*
4. How do you think it is possible to evaluate students' learning in the process of solving the PS?	R1	*Through debates, preparation of questionnaires, etc.*
	R2	--
	R3	*I believe that the assessment should be procedural, by observing the discussions, ideas and conclusions presented by the students, in order to observe whether our initial objectives were achieved. For example, in my problem situation I have some objectives such as: discussing concepts of atmosphere, refraction and reflection of light, visible spectrum, and polarizing lenses. If they are able to have a good understanding of these concepts, applying them in problem situations and understanding where these concepts are present in their daily lives, the objective has been achieved because I believe that they have learned something.*
	R4	*Assessment, by its nature, is an ongoing process, and in relation to PBL, which is also a construction process, I think it is necessary to assess what was developed throughout the classes, listing possible paths and steps that were followed. From this perspective, I believe that an objective assessment instrument, such as a report or a form, would be viable and consistent with the proposal.*

Table 5. *Cont.*

Questions	Resident	Response
	R5	*Well, I believe it is important to see how everyone in the group participated and how they contributed. It would be interesting to see if there was any disagreement in the group about some of the ideas they had and how this was resolved. It would also be essential to see which concepts from physics and science they used to find the main reason for the problem and also how they found to solve this problem. I think that by observing all these points, we can indeed arrive at a great way of evaluating.*
5. After applying PS in these first two weeks, would you make any changes to your PS? Which ones?	R1	*Yes, it would involve some more information about the planet and talk more about the physics behind some materials.*
	R2	*I would actually do it, since it is my first contact, I believe it is going very well, but looking back, with the recent knowledge I have learned with this methodology, I believe that the PS presentation structure would be something that could be improved a lot. There would be no way I could reach this conclusion without first going through the application of what we created. I understand that experience leads to improvement, and in my opinion, we could have done something better in the PS presentation.*
	R3	*Yes. I wouldn't include images of the planet and the red atmosphere because they were very focused on the red issue, because they understood that the crew members saw everything red, and didn't see the other colors. It took a while for them to understand that the images were just to provide a little immersion so that they could imagine the scenario they were being presented with.*
	R4	*Not in the problem situation, but in the contextualization. I believe that making the idea of polarizers explicit, as was done, only got in the way of facilitating the problem situation. Since it is an extremely important concept in some situations.*
	R5	*Yes. I underestimated the students too much. If I could, I would remove some of the information present in the PS, because I believe it may have helped them reach certain answers very quickly. Not that they didn't have a lot of difficulty, because they did, and quite a lot, but I believe they could have thought a little more about certain aspects before arriving at what was considered the main thing for the PS. Or, I could do the opposite, and add even more information, so that the students would be more careful when filtering what they think would be the essential thing for that PS. I would also establish certain rules about how they should act, such as, for example, each member of the group establishing a theory about the problem, or else, making certain roles of each member clearer, so that some of the students, at certain moments, could have greater participation, instead of waiting for a "leader" to guide them.*

The presentation of the PBL proposal left the elective students concerned: *that when PBL was announced, some of the students seemed to have a lot of doubts about what it meant (R5)*. But when the problem situation was presented, they became motivated:

> *At first, the students were extremely excited about solving the situation and this new problem. (R1)*

> *The students were curious and motivated to solve the problem, since contextualization (involving space travel) is not usually addressed in the classroom, especially from a PBL approach. (R4)*

> *... when the Problem Situation was presented, everyone showed a lot of interest ... (R5)*

All Residents described difficulties in mediating the PBL process in order to promote the construction of knowledge by students:

> *The biggest difficulty was mediating the students so that they could think again in the "correct" way ... (R1)*

> *I confess that it was difficult not to answer the questions asked by the students, ... One of the most difficult things was seeing that many of the paths they were following were not in line with what we wanted to find, and it was particularly challenging for me to find a way to show alternative paths. (R2)*

> *Personally, I think one of the most complicated parts is guiding the conversation and research without giving the answers or making the answers very obvious. (R3)*

> *it was difficult to mediate and at the same time not provide answers (R4)*

> *Initially, it was very difficult to give students directions without giving too many answers and ruining the idea of PBL. (R5)*

These reflections align with the preceptor's observation. For him, both students and Residents struggled with time. Students understood the PS as a question with a single correct answer and that the Residents and the teacher were there to point out when they were wrong. Residents demonstrated an understanding of their role as tutors and a concern for observing it. However, the argumentative process of producing meaning and seeking solutions conflicted with what the Residents indicated as their traditional teaching style in basic physics courses. In other words, the Residents had difficulty teaching because, for them, even when there were problems to be solved, there was an expected solution, and the argument was built around it. Thus, although they developed a solution path and discussed it before contacting the students, guiding the students' argumentative propositions, indicating how they should search for/elaborate on their doubts (research on the internet, in books, or with experts), or suggesting physics concepts that reinforced or discredited ideas, were challenging for the Residents.

The Residents were also able to express their thoughts on the best way to assess student learning. In general, they felt it was important to observe each student's participation and contribution to solving the problem:

> *I think it is necessary to assess what was developed throughout the classes, listing possible paths and steps that were followed. (R4)*

> *Well, I believe it is important to see how everyone in the group participated and how they contributed. It would be interesting to see if there was any disagreement in the group about some of the ideas they had and how this was resolved. It would also be essential to see which concepts from physics and science they used to find the main reason for the problem and also how they found to solve this problem. (R5)*

They also expressed concern about whether the learning objectives were met:

I believe that the assessment should be procedural, by observing the discussions, ideas and conclusions presented by the students, in order to observe whether our initial objectives were achieved. For example, in my problem situation I have some objectives such as: discussing concepts of atmosphere, refraction and reflection of light, visible spectrum, and polarizing lenses. If they are able to have a good understanding of these concepts, applying them in problem situations and understanding where these concepts are present in their daily lives, the objective has been achieved because I believe that they have learned something. (R3)

In the follow-up meetings with the preceptor professor, the HEI's coordinator, and all the Residents, it was decided that each group of students would prepare a report to send to Terra, accepting the proposal made by R4: *I believe that an objective assessment instrument, such as a report or a form, would be viable and consistent with the proposal*.

When asked if they would make any changes to the problem situation after its implementation, all the Residents said yes. The reflections they made are relevant and demonstrate how experiencing PBL is important to better understand this approach, as R2 pointed out:

I would actually do it, since it is my first contact, I believe it is going very well, but looking back, with the recent knowledge I have learned with this methodology, I believe that the PS presentation structure would be something that could be improved a lot. There would be no way I could reach this conclusion without first going through the application of what we created. I understand that experience leads to improvement, and in my opinion, we could have done something better in the PS presentation

For R1, R3, and R4, adding or reducing information would be more interesting:

Yes, it would involve some more information about the planet (R1)

Yes. I wouldn't include images of the planet and the red atmosphere because they were very focused on the red issue (R3)

Not in the problem situation, but in the contextualization. I believe that making the idea of polarizers explicit, as was done, only got in the way of facilitating the problem situation. (R4)

On the other hand, R5 made three important reflections. The first is that he underestimated the students. The second was realizing that PBL can make the learning process more complex, not only by removing relevant information but also by adding information that is not necessarily relevant:

If I could, I would remove some of the information present in the PS, because I believe it may have helped them reach certain answers very quickly . . . Or, I could do the opposite, and add even more information, so that the students would be more careful when filtering what they think would be the essential thing for that PS.

The third concerns how PBL could have been implemented to ensure everyone participated:

I would also establish certain rules about how they should act, such as, for example, each member of the group establishing a theory about the problem, or else, making certain roles of each member clearer, so that some of the students, at certain moments, could have greater participation, instead of waiting for a "leader" to guide them.

3.4. Reflections on the Intervention: Students and PBL

To analyze the Residents' perceptions/learning about the "attitudes" necessary to conduct a PBL program, after the 4-week intervention with PBL, Q5 was applied, and the Residents’ responses are presented in Table 6. We wanted the Residents to reflect on how the students reacted to the group work and the learning they achieved. We were also interested in knowing what it was like to guide them through the process, and what improvements could be made after this first intervention with PBL.

Table 6. Residents’ responses to Q5.

Questions	Resident	Response
1. What were the impressions left by the students when working in groups? Were you able to observe behaviors that revealed attitudinal knowledge? Comment.	R1	*At first, everyone was very excited and dedicated, since all they needed was some basic research or asking someone they knew to plant something. As they resolved the problem, the students sought to understand how things work around them so that they could later relate them to the more abstract aspects of the first step.*
	R2	*Students demonstrated exceptional progress in working together, demonstrating exemplary attitudinal behaviors. The strategy of assigning responsibility for organizing the class, rather than allowing free choices, not only boosted participation by all, but also demonstrated a deep commitment to inclusion, amplifying the voices of those who initially felt more reserved.*
	R3	*At first, most students were motivated and very interested in the problem presented, but as the classes progressed and the difficulty of the problem presented caused some to lose some interest. With the application of PBL, it became clear how difficult it was to awaken and maintain students’ interest in the subjects. Some started out participating at the beginning and then had a drop-off, while others participated little or were involved from the beginning.*
	R4	*The students demonstrated that they knew how to work well in groups, although the groups were formed randomly, they always interacted with each other in order to seek new insights into problem situations.*
	R5	*Yes, they managed to work as a team, despite not knowing each other very well, since the groups were selected by the residents. They knew how to value each other’s opinions, respecting them. However, sometimes they valued each other’s opinions so much that they didn’t even try to debate or discuss an idea or theory. But despite this, the group worked very well together, they knew how to divide the roles well among themselves, so that everyone participated in some way. Of course, nothing is perfect. There is always one or another member of the group who does nothing at certain times, but even those who participated less acted together and helped the group in some way.*
2. PBL fosters scientific thinking, however, was there a change in the way students thought/dialogued/shared knowledge when they tried to build a solution to the problem situation? Comment in great detail.	R1	*Yes, at each moment they thought of something different and had a different idea, such as: making special seeds, cabins with waterproof materials, etc. Each one tried in their own way to come up with what they thought would be the correct answer according to their research. It is worth noting that, even though each one had an idea, they managed to intertwine the ideas and arrive at just one answer, encompassing the ideas of almost all the students.*

Table 6. *Cont.*

Questions	Resident	Response
	R2	*Upon receiving the PS, the students approached them in a comprehensive manner, exploring all possible paths to find solutions that were not limited to the scientific aspect alone. They demonstrated remarkable attitudinal behaviors by considering not only the technical resolution, but also evaluating the social, ethical and practical impact of the proposed solutions. The students demonstrated a remarkable expansion of knowledge, adopting a highly creative and insightful approach. They enriched their analyses by connecting the problem situations with examples from everyday life, highlighting how the concepts learned were tangibly applied to real situations, which impressed me greatly.*
	R3	*The PBL is able to teach students how the scientific method works in a more gentle and playful way. During the classes, students were able to understand and go through the same process as a researcher, developing hypotheses and seeking ways to prove them true or false. They were able to experience some of the enthusiasm and frustrations present in the daily life of a researcher. When we started the activities, we noticed that the students did not understand the dynamics of the activity very well, because they were used to a type of problem that would give the answer quickly. At first, that was what they tried to do, putting forward many hypotheses without much depth or basis. As the activities progressed and with the joint mediation of the supervising professor and the other residents, they were able to understand that they should seek a theory that was based on the laws of physics that we know, and that this would require research and study. Thus, after a few classes, the students were gaining a greater understanding of the related subjects and had more well-founded hypotheses.*
	R4	*In my opinion, the fact that this was the first contact for many students with situations involving a research perspective in science, together with the short amount of time for debate among them (since they did not have time set aside to discuss the problem situation outside of class), ended up generating little depth on the topic, making it difficult for me to analyze. However, it is possible that they constructed new perceptions about thinking, reflecting and collecting scientific information necessary to arrive (or not) at an answer.*
	R5	*No, no change was noticed in the way students thought/dialogued/shared knowledge regarding problem-solving. Thinking about it, I realized that the students were not very interested in dialoguing and sharing knowledge. Usually, one of the members was the one who gave the most answers and started the dialogs; he always took the lead in the conversations. As for the other members, it seemed to me that they were just agreeing with everything, but no longer interested, after a certain point, in thinking about what the problem situation needed. Therefore, I believe I can say that there was a certain change, but I do not think it was necessarily positive.*

Table 6. *Cont.*

Questions	Resident	Response
	R1	*Motivate students to think more than twice, direct without giving the answer, etc.*
	R2	*My first experience with PBL initially seemed quite complex. Creating a problem-solving situation that involved the topics we were studying in class represented one of the biggest challenges. It took a long process of discussion and collaboration to reach a consensus and build a solid problem-solving situation. However, once we found a suitable context to apply the problem-solving situation, everything started to flow quite positively. One of the difficulties I faced in this process was resisting the temptation to give my students direct answers, opting instead to play the role of mediator. This required an adjustment in my traditional teaching approach, but it allowed the students to develop their problem-solving skills in a more independent and autonomous way.*
	R3	*One of the biggest difficulties I encountered was in the preparation of the PS, because it must be done in a way that is stimulating and fits the level of knowledge of the class. It cannot be too difficult, and it cannot be too easy either, finding a balance. The second difficulty to highlight was maintaining the interest of the students. So, this is an important point for the teacher to analyze before introducing the PBL into the classroom. To observe whether this methodology would be appropriate for the class in order to have participation and a good use of learning and the time used for the activity.*
3. List the main difficulties encountered when working with problem situations.	R4	*Students always look for obvious and immediate solutions; The difficulty in understanding that even the most well-elaborated and apparently plausible hypotheses need a scientific basis and reference; Students were not rigorous when searching for explanations on Google, often being content with superficial explanations of scientific concepts; They made little use of tools such as Google Scholar*
	R5	*Formulating the problem situation. Even though this methodology had been explained more than once by the supervising professors, it was very difficult to understand how we should formulate the PS. Even after formulating it, it became very clear that none of them were "ideal" and therefore, many changes and reformulations were necessary to adjust them. Underestimating and overestimating the students. A very big difficulty was thinking about the students during this process. At certain times, there was very little information to be given to the students. Soon, this was changed, however, it ended up being executed in an unbalanced way. This balance was missing, since either the students were underestimated or overestimated. Directing the students. It was very clear from the beginning that the residents could help and direct the students towards a possible solution. However, this should be done in a more "superficial" and subjective way, without giving too many details and much less directly explaining how the problem worked. In the end, this turned out to be very successful, as the groups were able to come up with solutions and theories on their own, independent of the original ideas of the residents who formulated the problem situations. However, I must say that this was very difficult to do.*

Table 6. *Cont.*

Questions	Resident	Response
4. What possible improvements could be made to make the problem situation more effective?	R1	*Improvements to the base text and planet data, and redirection to more reliable base texts.*
	R2	*As this is our first experience with PBL, we recognize that there is room for improvement. However, given our initial inexperience, we are pleased with the remarkable and positive progress we have made. One aspect that we wish we had approached differently is the richness of detail. The inclusion of images, visuals, and audio elements would have provided a more enriching and in-depth experience for students, something we plan to carefully consider in future implementations.*
	R3	*I believe that being presented with a greater level of detail*
	R4	*More time allocated to the activity, which can be distributed over more weeks. More planning by the entire pedagogical residency team in terms of thinking about strategies to assess progress, in addition to just observation. In this way, more accurate data on the process can be obtained. Before proposing, give more emphasis to the importance of problem situations to try to minimize the difficulties listed in the answer to the previous question (which would be possible with more time allocated to the activity).*
	R5	*Define some points better, such as what you are working on in that PS, what goals you want them to achieve, what knowledge your students already need to know, and what they should learn from that. I believe that if it were something a little more closed, without necessarily months of class content, but something more like one or two specific weeks, it could have worked better. I say the same thing about the period that this entire active methodology lasted, which was 4 weeks. I believe that if it had been summarized in 3, it would have been better, because it would have prevented the students from becoming more discouraged.*
5. When participating as a tutor, it is possible to perceive the heterogeneity of the group. How were divergent opinions developed?	R1	*Yes, great. As each person sought an answer, each person defended their point of view based on the knowledge they had obtained through research, but they all had the same thing in common: making lightning-proof greenhouses, which helped them reach a common denominator in their answer.*
	R2	*Giving students greater autonomy in their search for answers has challenged me considerably. I admit that my previous approach, which involved providing all the knowledge I had on certain topics, had limited me in certain aspects, including my ability to act as a mediator. However, the surprising results I observed as students increasingly took ownership of the content and brought perspectives that I had not even considered, has enriched my experience and made me evolve and mature significantly in my conception of tutoring.*
	R3	*I didn't observe much divergence of opinions in the group I worked with, they had their own ideas, but they agreed on most of them. When a divergent point arose, they talked, explained their points of view and agreed on common points.*
	R4	*Members who had different perspectives were invited to defend their ideas, and of course, they would later have to seek scientific explanations that would validate their ideas. Thus, an idea could continue to be valid or discarded.*

Table 6. *Cont.*

Questions	Resident	Response
	R5	*I didn't feel that there was any real heterogeneity in the group, and I didn't witness any kind of divergent opinion. I noticed that each member of the group was focused on a specific piece of information, on a specific piece of knowledge at a time, which ended up giving rise to a great plurality of ideas. However, as I mentioned earlier, there were certain cases in which the students simply kept quiet, didn't want to participate and didn't get together to debate or generate any kind of discussion or disagreement regarding this. They simply decided to accept the answer of the first person who spoke as the truth and went back to researching it, and no longer cared about presenting a different line of thought from their colleague. There are several reasons for this, perhaps because they were embarrassed to speak, perhaps because they didn't want to expand on the subject any further, perhaps because they were lazy, since from the second week onwards, most of the students became discouraged.*

All Residents reported that the groups were able to organize themselves, divide tasks, work as a group, negotiate divergent opinions, and were able to develop a solution to the problems presented.

> *Students demonstrated exceptional progress in working together, demonstrating exemplary attitudinal behaviors … also demonstrated a deep commitment to inclusion, amplifying the voices of those who initially felt more reserved. (R2)*

> *When a divergent point arose, they talked, explained their points of view and agreed on common points. (R3)*

> *The students demonstrated that they knew how to work well in groups, although the groups were formed randomly, they always interacted with each other in order to seek new insights into problem situations. (R4)*

> *Yes, they managed to work as a team, despite not knowing each other very well, since the groups were selected by the Residents. They knew how to value each other's opinions, respecting them … the group worked very well together, they knew how to divide the roles well among themselves, so that everyone participated in some way. (R5)*

They also reported that the students shared knowledge (*they managed to intertwine the ideas and arrive at just one answer, encompassing the ideas of almost all the students R1*), were able to relate what they were learning to everyday life situations (*They enriched their analyses by connecting the problem situations with examples from everyday life R2*), and experienced the challenges of scientific research (*The PBL is able to teach students how the scientific method works in a more gentle and playful way R3* and *was the first contact for many students with situations involving a research perspective in science R4*). Only R5 reported that the students lost interest and ended up accepting what a single colleague presented:

> *Usually, one of the members was the one who gave the most answers and started the dialogs; he always took the lead in the conversations. As for the other members, it seemed to me that they were just agreeing with everything, but no longer interested, after a certain point, in thinking about what the problem situation needed. (R5)*

For the preceptor, all Residents had difficulty developing arguments related to the problem. The students also demonstrated little or no familiarity with solving open-ended problems, and several expressed dissatisfaction with the need to conduct research after class to support the hypotheses proposed for the problem situation.

For R1 and R4, the biggest challenge was getting students to think more elaborately:

> *Motivate students to think more than twice (R1)*

> *Students always look for obvious and immediate solutions; The difficulty in understanding that even the most well-elaborated and apparently plausible hypotheses need a scientific basis and reference. (R4)*

R3 and R5 again presented developing the problem situation as a major challenge:

> *One of the biggest difficulties I encountered was in the preparation of the PS, because it must be done in a way that is stimulating and fits the level of knowledge of the class. (R3)*

> *Formulating the problem situation. Even though this methodology had been ex-plained more than once by the supervising professors, it was very difficult to understand how we should formulate the PS. Even after formulating it, it became very clear that none of them were "ideal" and therefore, many changes and re-formulations were necessary to adjust them. (R5)*

For R2, conducting PBL was a great challenge, and the exercise of mediating the construction of knowledge, instead of the traditional teaching model, helped students develop problem-solving skills:

> *Creating a problem-solving situation that involved the topics we were studying in class represented one of the biggest challenges. It took a long process of discussion and collaboration to reach a consensus and build a solid problem-solving situation . . . One of the difficulties I faced in this process was resisting the temptation to give my students direct answers, opting instead to play the role of mediator. This required an adjustment in my traditional teaching approach, but it allowed the students to develop their problem-solving skills in a more independent and autonomous way. (R2)*

When reflecting on improvements in the PS after completing the intervention, R4's contribution stands out for considering the broader context of PBL, including the organization of the Residents' collective work and focusing on evaluation procedures:

> *More time allocated to the activity, which can be distributed over more weeks. More planning by the entire pedagogical residency team in terms of thinking about strategies to assess progress, in addition to just observation. In this way, more accurate data on the process can be obtained. Before proposing, give more emphasis to the importance of problem situations to try to minimize the difficulties listed in the answer to the previous question (which would be possible with more time allocated to the activity). (R4)*

R5 also highlights the need to clarify objectives for students:

> *Define some points better, such as what you are working on in that PS, what goals you want them to achieve, what knowledge your students already need to know, and what they should learn from that. (R5)*

The preceptor teacher observed that despite the difficulty in mediating discussions without "giving the answer," the Residents engaged in conversations among themselves and requested his support on several occasions. He also noted that for the Residents, the implementation of PBL enabled reflection on the practice of science through knowledge mediation. For the Residents, arguing against hypotheses (brought by students) that were at odds with the physics studied in their undergraduate program was a significant challenge. Furthermore, the Residents identified how their bases for analyzing and explaining reality were based on a well-established line of reasoning, but this did not exempt them from the difficulty of arguing with high school students about a problem they had created.

These findings inform the discussion in the next section, where we contrast Residents' conceptions with previous PBL research.

4. Discussion

In order to identify the Residents' conceptions about learning objectives, methodologies, and learning assessment, we analyzed the teaching plans developed for the first five meetings in the elective course (Table 3), the responses to Questionnaire Q1 (Table 2), and the observations and field records of the preceptor teacher. All Residents demonstrated an understanding of the importance of the methodology being appropriate to the objectives and profile of the class in the reflection presented in Table 2 when answering Q1. However, this reflection is not always present in the teaching plan.

Therefore, we understand that when designing the objectives, the Residents are more concerned with what they want to teach. Nevertheless, the learning objectives should serve as a guide for the student, so that they know where their studies will take them, while the teaching objectives guide the teacher's actions (M. H. S. Silva & Lopes, 2016; Alt & Raichel, 2020). Thus, even though they think of instruments that can monitor student learning, these seem to be designed only for the teacher's analysis. It is worth remembering that in PBL, the design of the problem must be concerned with the intended learning objectives (Akçay, 2009; Alt & Raichel, 2020).

Furthermore, observation showed that only R1 and R4 were able to implement the proposed teaching plan. R1 had more classroom experience, and R4 presented a more detailed plan consistent with their reflections. The others, R2, R3, and R5, were unable to adequately implement their teaching plans, failing to conduct appropriate learning assessments, mainly because they failed to establish a connection between learning objectives, methodology, and learning assessment (Camargo, 2019).

Analysis of Q2 allows us to infer that the Residents were able to distinguish a problem situation that meets the necessary criteria for applying a methodology such as PBL from problems commonly presented in the classroom, as argued by Akben (2019). They report that the context of the PS allows for student engagement (Novikasari, 2020; Smith et al., 2022) and provides elements for finding a solution (Akben, 2019; Baptista, 2025). The Residents are able to perceive that the process of solving the PS leads to the construction of knowledge (Akçay, 2009; Aidoo, 2023), making the student the protagonist (Kuvac & Koc, 2018; Novikasari, 2020; Aidoo, 2023; Baptista, 2025), developing declarative, procedural, and attitudinal learning, as well as creativity and critical thinking, characteristics observed in the works of Akben (2019), Saputro et al. (2020), and Aidoo (2023).

However, two points remained conflicting: the first was the fact that they were unable to develop their own PS, even though they demonstrated a thorough understanding of all its characteristics. This result also appears in the work of Ekici (2016), Kuvac and Koc (2018), and Akben (2019), where they observed the difficulty of pre-service teachers in creating problem scenarios that are relevant, complex, and suitable for group work. Alt and Raichel (2020) also observe the difficulty in developing authentic and complex problems that stimulate critical thinking and problem-solving when working with trained professionals. The same account also appears in the research conducted by Smith et al. (2022) with PBL experts from different international contexts, including STEM-related fields. For the authors, the difficulty in creating appropriate problems reflects, in part, the need for teachers to develop new skills to design problems that are sufficiently open-ended, complex, relevant, and aligned with the learning objectives and students' capabilities.

The second point is related to breaking paradigms or personal beliefs about how to teach. This point is reflected in the Residents' need to "know" the solution to the problem, even though they know that working with PSs in PBL requires a new approach. Smith et al. (2022) noted that it was challenging, even for PBL experts, to adopt more contemporary practices, such as focusing on the learning process and student autonomy. According to Alt and Raichel (2020), many teachers may not be willing to redefine their traditional role as an authority or expert, which directly impacts the development of PBL. The difficulty of pedagogical change was also observed in the works of Ekici (2016), Akben (2019), and Kuvac and Koc (2018). For Ekici (2016), the difficulties faced by pre-service teachers when creating problems are related to the lack of experience, the difficulty in writing clear and understandable scenarios, and the determination of problems that lead students to investigation.

However, for all other researchers, the difficulty in developing PSs suitable for the PBL approach is related to the difficulty of thinking about teaching from a different paradigm. According to Akben (2019), teachers accustomed to working with structured and traditional problems have difficulty adapting to the creation and implementation of unstructured and challenging problems, which are essential to PBL. Kuvac and Koc (2018) argue that teacher resistance to change can hinder PSs and the implementation of approaches such as PBL. They emphasize that teacher education programs traditionally focus on providing theoretical knowledge, but that the goal of teacher education should be to provide learning experiences that involve perception, assessment of situations, judgment, and choice of actions, confronting teachers with the consequences of these choices. Alt and Raichel (2020) mention that the difficulty in creating authentic problems and implementing alternative assessment methods may be related to teachers' resistance to change. They also mention that formative assessment methods, such as self-assessment and peer review, challenge traditional power relations in universities, which may contribute to this resistance. Smith et al. (2022) point out that this transition can be challenging, especially in contexts where traditional pedagogical practices are deeply rooted.

During the application of PBL, questionnaire Q4 was answered by the Residents in order to help us understand how they perceived, up until that moment, the use of a problem situation in a PBL approach. All Residents reported that students were enthusiastic, curious, and motivated by the problem situations, despite concerns about the PBL format raised by some students, which can generate resistance to the approach (Ekici, 2016; Kuvac & Koc, 2018; Alt & Raichel, 2020; Smith et al., 2022; Aidoo, 2023). For Ekici (2016), students' lack of familiarity with the PBL approach can hinder their understanding of scenarios and problem-solving. Therefore, they considered the PS to be a single-answer question and expected the Residents and the professor to answer the question, as observed by the preceptor. From the preceptor's observation, it is clear that this resistance is linked to more structured teaching methods. This fact was observed in the work of Kuvac and Koc (2018), Alt and Raichel (2020), Smith et al. (2022), and Aidoo (2023).

Residents also reported that they had great difficulty in implementing PBL, although they understand that the teacher's role should be that of a facilitator. Both their reports and the observation of the preceptor teacher indicate that they sought to maintain surveillance of their actions, avoiding responding directly to students' questions. However, the Residents reported to the preceptor that the difficulty in leading the students' discussions towards solving the problem situation was related to their familiarity with the traditional teaching style in Physics classes, which focuses on problems that have an expected or known solution. For Kuvac and Koc (2018) and Akben (2019), acting as a facilitator and guide, rather than a direct instructor, requires specific skills, such as asking open-ended questions, providing constructive feedback, and creating a collaborative environment, which can be challenging for teachers accustomed to traditional methods. This change in pedagogical approach is not easy to achieve in practice, neither for pre-service teachers (Kuvac & Koc, 2018; Akben, 2019) nor for experienced teachers (Alt & Raichel, 2020; Smith et al., 2022; Aidoo, 2023).

Therefore, investment in training for the development of skills such as argumentation and metacognitive regulation are necessary for the PBL approach. A. C. Silva and De Chiaro (2018) observed that teachers' argumentative skills lead students to critical reflections that make all the difference in the PBL approach. Marthaliakirana et al. (2022) observed that the use of metacognitive prompts helped students plan, monitor, and evaluate their actions, promoting deeper and more reflective learning.

When asked about evaluation, R3, R4, and R5 consider that it should be carried out based on the way students engage in the process and apply their knowledge to solve the problem, which is a good path (Alt & Raichel, 2020; Smith et al., 2022). However, we observed that no Resident proposed the use of alternative assessment methods, such as rubrics and self-assessment, to promote students' active involvement in the learning process, as pointed out by Alt and Raichel (2020).

All Residents reported that they would make changes to the problem situations, some in the information provided (R1, R3, and R5) and others in the presentation structure (R2 and R4). Some reflections deserve to be highlighted. R2 reports that he learned from applying PBL and that considering changes in the PS was only possible because of this experience. The same was true in Ekici's (2016) study, where participants reported that practical application allowed them to identify flaws and continually learn how to use the method, in addition to gaining experience. Participants in the research conducted by Alt and Raichel (2020) reported in their reflective journals that the learning process encouraged them to think more deeply and critically about the educational problems addressed. Also, teachers who participated in the research by Smith et al. (2022) emphasize that the PBL process involves continuous reflection, reassessment, and adjustments to meet student needs and the learning context.

Another point worth highlighting is R5's reflection that the PS could contain more information, demanding more attention from students. This approach is corroborated by Smith et al. (2022), who understand that the problems best suited to the PBL context are so-called "ill-structured problems," which have multiple unknown elements, ambiguity in the concepts needed to solve them, several possible solutions, and no obvious path to finding a solution.

The preceptor's observations during the implementation of PBL and the Residents' reflections when responding to Q5 help us analyze the perceptions/learnings about the attitudes necessary to conduct a PBL program. Among the difficulties encountered, the Residents highlighted the following: maintaining student motivation, creating a problem situation, changing the pedagogical approach, students' lack of competence in research skills, and more time to work with students. The difficulty in keeping students motivated may be linked to the fact that they are accustomed to receiving well-defined tasks and expect to find answers directly, without the need to explore or question, as observed in the research by Smith et al. (2022). The research by Alt and Raichel (2020) indicates that demotivation was related to discomfort with the loss of control over learning and a preference for traditional methods, such as lectures, which was also observed by the Residents and the preceptor teacher.

The difficulty in creating problem situations is related to the need for change in pedagogical practice, as discussed here (Kuvac & Koc, 2018; Akben, 2019; Alt & Raichel, 2020; Smith et al., 2022). However, it is important to emphasize that Residents perceive the experience with PBL as enriching, not only for considering adaptations and improvements to the problem situation, but, most importantly, for reflecting on the necessary change in the teaching role within a PBL approach. In Ekici's (2016) research, pre-service teachers also reported that they gained experience and better understood how to apply the method, indicating a reflection on the active and adaptive role that the teacher must assume in Problem-Based Learning environments. Similar reports are found in the works of Kuvac and Koc (2018), Alt and Raichel (2020), and Smith et al. (2022), where despite the difficulties initially encountered by teachers, the experience in PBL made them change their pedagogical approach.

The reasons why students had difficulty conducting research and gathering relevant and necessary information to solve the PS can be explained by the fact that many of them were using the method for the first time, as observed in the research developed by Ekici (2016); were not accustomed to seeking information autonomously; and, initially, did not understand that they needed to ask questions to clarify the problem, as observed by Smith et al. (2022). Alternatively, this may have been because the Residents had difficulty formulating questions that stimulated investigation, as observed by Akben (2019). The need for more time to work with students was also highlighted in the work of Aidoo (2023) and Ekici (2016).

Regarding possible improvements to the problem situation, the Residents reported the following: improving the text (R1), the visual representations (R2), the details provided (R3), strategies/instruments to monitor students' progress (R4), and informing the learning objectives (R5). The first three proposals are linked to the elaboration and presentation of the problem situation, which is a relevant aspect highlighted in the works of Ekici (2016), Kuvac and Koc (2018), Akben (2019), Alt and Raichel (2020), and Smith et al. (2022). The last two are related, since clearly establishing objectives is essential in helping students construct their learning (M. H. S. Silva & Lopes, 2016) and establishing formative assessment (Camargo, 2019).

5. Conclusions

Our first research objective was to identify Residents' conceptions of learning objectives, methodologies, and learning assessment. We observed that Residents had difficulty aligning learning assessments with learning objectives, and that these objectives were not designed to allow students to monitor their learning but rather to define what or how to teach. This aspect may reveal why Residents have difficulty establishing assessment processes aligned with formative assessment, such as rubrics, feedback, peer review, and self-assessment.

The Residents also had difficulties in establishing a problem situation and conducting the intended learning development process in a PBL approach. However, despite the difficulties encountered by the Residents when implementing the PBL approach, the students developed the skills and learning expected. The difficulties reported by the Residents have also been observed in other studies with pre-service teachers (Ekici, 2016; Kuvac & Koc, 2018; Akben, 2019), teachers who are already in the field (Alt & Raichel, 2020), and PBL experts (Smith et al., 2022).

However, it is important to emphasize that establishing the possibility of implementing PBL in physics teaching in basic education is a necessary condition for learning this methodology. Moreover, establishing reflective processes is essential for pre-service teachers to confront the need to change their pedagogical paradigms to ensure learning occurs. In this sense, the Pedagogical Residency Program proved to be the ideal opportunity for this training and to analyze the Residents' perceptions/learning about the "attitudes" necessary to conduct a PBL program. Aspects such as supervision by a preceptor throughout the immersion in the school and follow-up meetings with the coordinator at the HEI are essential for this contact with methodologies that diverge from current teaching paradigms. The reflective questionnaires used in the research played a fundamental role in helping the Residents establish an understanding of the differences between traditional methodological approaches and PBL.

This research has some limitations, such as the inability to establish an adequate action plan with the Residents for the PBL implementation phase. Another limitation was the inability to involve this same group of Residents, based on their reflections and learning, in proposing, implementing, and analyzing a new PBL proposal. Time was also a limiting factor, both for the Residents to acquire knowledge of PBL-related aspects and for the HEI coordinator and the preceptor to provide feedback and more appropriate support to the

Residents. We understand that this research presents us with some important challenges in teacher training, which should be considered based on three strategies.

The first is the strategic study of teaching planning for the use of PBL. It is necessary to understand that the learning objectives in a PBL approach go beyond declarative learning, but involve skills such as critical and creative thinking, developing questions and hypotheses, conducting research using technological tools such as the Internet and Artificial Intelligence, and knowing how to share, discuss, and build knowledge collaboratively. To support this learning, it is necessary to develop formative assessment strategies, like rubrics and peer assessment, where feedback to students is the central point.

The second strategy is developing problem situations that consider previously defined objectives, are interesting and challenging, promote engagement, encourage students to think critically and creatively, and are aligned with students' learning level. Finally, the most challenging and perhaps most necessary strategy is the development of an appropriate pedagogical approach. The results obtained in this study, along with findings from other studies with pre-service teachers, highlight that metacognitive regulation and argumentative skills are needed to implement PBL. Metacognitive regulation makes the teacher constantly reflect on their practice, in addition to helping students set learning goals, reflect on their processes, and mediate new meanings based on existing knowledge (Alt & Raichel, 2020; Marthaliakirana et al., 2022; Baptista, 2025). Argumentative skills will allow the teacher to foster a cooperative learning environment, where students can express their opinions and work as a team, learning to develop their arguments based on scientific knowledge (A. C. Silva & De Chiaro, 2018; Baptista, 2025).

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The Impact of AI-Generated Instructional Videos on Problem-Based Learning in Science Teacher Education

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Abstract: Artificial Intelligence (AI) has gained significant prominence in science education, yet its practical applications, particularly in teacher training, remain underexplored. Specifically, there is a lack of research on AI's potential to support personalized professional development through automated analysis of classroom interactions and tailored feedback. As science teacher education requires skill development in complex scientific concepts within problem-based learning (PBL) contexts, there is a growing need for innovative, technology-driven instructional tools. AI-generated instructional videos are increasingly recognized as powerful tools for enhancing educational experiences. This study investigates the impact of AI-generated instructional videos, designed using established instructional design principles, on self-efficacy, task performance, and learning outcomes in science teacher education. Employing a within-subjects design, the current study included pre-test, post-test, and transfer assessments to evaluate learning durability and transferability, consistent with design-based research methodology. Moreover, this study compares the effectiveness of two AI-generated instructional video formats: one with an embedded preview feature allowing learners to preview key concepts before detailed instruction (video-with-preview condition) and another without this feature (video-without-preview condition). It specifically examines the role of preview features in enhancing these outcomes during training on scientific concepts with 55 Greek pre-service science teachers (n = 55; mean age 27.3 years; range 22–35). The results demonstrated that the videos effectively supported self-efficacy, task performance, and knowledge retention. However, no significant differences were observed between videos with and without preview features across all assessed metrics and tests. These findings also indicate that AI-generated instructional videos can effectively enhance knowledge retention, transfer, and self-efficacy, positioning them as promising assets in science teacher education. The limited impact of the preview feature highlights the need for careful design and evaluation of instructional elements, such as interactivity and adaptive learning algorithms, to fully realize their potential.

Keywords: artificial intelligence; instructional videos; narration; problem-based learning; science teacher education

1. Introduction

The digital transformation of education has redefined how knowledge is delivered, absorbed, and applied. In science teacher education, the challenge is imparting theoretical knowledge and cultivating essential skills, reflecting on critical thinking, collaborative problem-solving, and the ability to translate complex scientific concepts into engaging teaching practices (Koumi, 2013). Among the most impactful pedagogical strategies, problem-based learning (PBL) is still of great importance for its student-centered, inquiry-driven approach, encouraging learners to engage deeply in real-world problems (Akçay, 2009). PBL empowers future (pre-service) science teachers to experience firsthand the dynamic interplay between scientific inquiry and practical problem-solving, making it a cornerstone of effective science teacher training (Gumisirizah et al., 2024).

However, the shift to digital contexts, driven by technological advancements and global circumstances, has introduced complexities in implementing PBL effectively. Maintaining student engagement, fostering learning within problem-solving contexts, and providing contextualized problem scenarios are significant hurdles in digital settings (Lange & Costley, 2020). Traditional methods of instruction often fall short of offering the interactive and immersive experiences necessary for meaningful learning, particularly in science education. This gap necessitates innovative approaches that harness the power of emerging technologies to transform learning environments. Integrating instructional videos into the PBL context enhances learning by presenting real-world, information-rich scenarios that foster critical thinking and engagement. Kumar (2010) emphasized the value of interactive video anchors in contextualizing learning through authentic problem-solving activities, such as investigating environmental or historical challenges. These examples highlight the importance of tailoring video content to specific educational objectives. Rasi and Poikela (2016) demonstrated the multimodal potential of video triggers in PBL, aligning with modern students' participatory learning preferences. Their review confirmed that video triggers promote collaborative inquiry and self-directed learning when supported by appropriate infrastructure and educational alignment. Aidoo (2023) found that technology-integrated PBL empowers teacher educators to foster both independent and collaborative learning. Conversely, challenges such as resource constraints, time limitations, and varying competence levels among educators point to the need for professional development to optimize video-based PBL contexts. Gumisirizah et al. (2024) reported that supplementing PBL with video resources in physics education significantly improved student performance, particularly in private schools. These findings suggest that videos enhance PBL's effectiveness by providing accessible and contextually relevant learning aids. Son (2024) highlighted the role of interactive video simulations in developing preservice teachers' adaptive teaching skills, showcasing the potential of responsive, video-based instructional tools. Similarly, Taningrum et al. (2024) demonstrated that animated videos in sports education improved students' critical thinking and understanding of complex concepts. Therefore, studies underline the transformative potential of instructional videos in PBL contexts, emphasizing strategies such as curating authentic content, promoting collaborative learning, addressing implementation challenges, and leveraging narration to simplify complex topics and engage learners effectively.

One such transformative innovation is nowadays the integration of Artificial Intelligence (AI)-generated instructional videos into PBL contexts. These AI-generated videos, created using advanced natural language processing and machine learning algorithms, can dynamically adapt to educational needs. They offer a visually rich and interactive medium to present complex scientific phenomena, simulate real-world scenarios, and provide guided support during problem-solving activities (Pellas, 2024). Unlike static resources, AI-generated videos can be tailored to specific educational contexts, ensuring relevance and accessibility. For future science teachers, such videos can serve as both instructional tools and an example of how technology can enhance classroom learning (Pellas, 2023b; Saqr & López-Pernas, 2024). Integrating AI-generated instructional videos into PBL contexts offers transformative potential by enriching learning experiences through personalized, interactive, and visually engaging content. Leveraging Large Language Models (LLMs), these videos enable adaptive scaffolding and support collaborative problem-solving, making them particularly valuable in science teacher education (Pellas, 2023a).

Generative AI technologies also facilitate scalable, high-quality content creation by converting slides or images into hyper-realistic videos, expanding accessibility across diverse educational contexts (Bewersdorff et al., 2024; Shahzad et al., 2024). Research (e.g., Li et al., 2024; Pellas, 2023b) shows that AI-generated videos achieve comparable outcomes to traditional recordings, with enhanced retention rates and effective support for transfer tasks, which are associated with self-efficacy. Moreover, these tools foster self-directed learning and autonomy, equipping future science educators with the skills to explore and implement advanced strategies independently. A balanced approach, where AI complements human educators rather than replaces them, preserves the relational aspects of teaching while maximizing AI's potential (Arkün-Kocadere & Çağlar-Özhan, 2024). For science teacher training, AI-driven tools not only enhance content delivery but also model innovative instructional practices, fostering interdisciplinary engagement and future-ready teaching skills. By balancing innovation with ethical considerations, AI-generated instructional videos can redefine PBL settings, transforming science education and equipping educators with innovative capabilities (Bewersdorff et al., 2024; Pellas, 2023a; Taningrum et al., 2024). In particular, preview conditions embedded within AI-generated instructional videos can serve as essential scaffolding tools (Lim, 2024). Preview conditions assist in establishing clear goals, activating prior knowledge, and reducing cognitive load by familiarizing learners with key concepts before delving into complex tasks (Van Der Meij, 2017). By drawing attention to critical elements and stimulating curiosity, preview features enhance engagement and facilitate deeper processing, ultimately improving retention and task performance (Van Der Meij et al., 2018a).

As indicated above, the rapid integration of AI in education presents transformative opportunities, yet its practical applications in teacher training programs remain under-explored (Blummer & Kritskaya, 2009; Shahzad et al., 2024). Particularly, science teacher education demands innovative methods to prepare educators for technology-rich classrooms and equip them with the skills necessary to engage diverse learners. PBL settings offer promising frameworks for fostering critical thinking, collaboration, and real-world problem-solving skills (Pellas, 2024; Son, 2024). However, the effectiveness of AI-generated instructional videos within these environments, particularly in enhancing self-efficacy, task performance, and learning outcomes for pre-service science educators, is yet to be fully understood. Moreover, key instructional features—such as conversational narratives, visual demonstrations, and interactive elements—are crucial for maximizing the impact of AI-generated videos. These features align with established multimedia design principles, ensuring that the content is accessible, engaging, and tailored to diverse learning needs (Gumisirizah et al., 2024). By integrating such elements thoughtfully, instructional videos can act as a bridge between theoretical knowledge and practical application, fostering both confidence and competence among pre-service science teachers (Taningrum et al., 2024).

Among the most impactful pedagogical strategies, PBL is one of the most prevalent for its student-centered, inquiry-driven approach, encouraging learners to engage deeply in real-world problems (Akçay, 2009). PBL's emphasis on authentic problem-solving aligns particularly well with the challenges faced by science teachers in preparing students to engage with complex scientific concepts and real-world issues. PBL can also empower future (pre-service) science teachers to experience firsthand the dynamic interplay between scientific inquiry and practical problem-solving, making it a cornerstone of effective science teacher training (Gumisirizah et al., 2024). However, the shift to digital contexts, driven by technological advancements and global circumstances, has introduced complexities in implementing PBL effectively (Li et al., 2024; Magaji et al., 2024). Therefore, there is a need for innovative tools and strategies that can effectively support PBL in digital environments, particularly in science teacher education.

This study investigates the potential of AI-generated instructional videos to address these challenges. AI-generated videos can provide visually engaging and contextually rich scenarios that enhance student engagement in online PBL activities. The use of AI allows for the creation of dynamic and adaptable video content, enabling the presentation of complex scientific phenomena in an accessible and engaging manner. AI's capacity for natural language processing and avatar animation enables the creation of conversational and relatable learning experiences, especially in science education. In the context of complex PBL scenarios, preview conditions within AI-generated videos can be particularly valuable in reducing cognitive load by providing an initial framework for understanding the problem and its related scientific concepts. Preview can help activate prior knowledge relevant to the problem, facilitating more effective engagement in the initial stages of the PBL process, such as problem definition and hypothesis generation. This study aims to investigate the impact of AI-generated instructional videos, with and without preview features, on pre-service science teachers' ability to apply scientific concepts within a PBL context, their problem-solving performance, and their self-efficacy in tackling complex scientific problems. It not only contributes to the growing discourse on AI in education but also offers practical solutions to enhance science teacher training, ensuring educators are equipped with innovative capabilities of AI-generated instructional video to meet the demands of this contemporary education.

2. Background

2.1. Instructional Videos into PBL Contexts

The integration of instructional videos into PBL contexts has been shown to significantly enhance learning by providing real-world, information-rich scenarios that stimulate critical thinking and engagement. Kumar (2010) demonstrated that interactive video anchors, derived from cognitive theories, help students to contextualize learning by embedding students in immersive and authentic problem-solving situations. Examples such as analyzing pollution in a river ecosystem or investigating historical illnesses showcased how videos can effectively bridge theoretical knowledge with practical application. These examples underline the need for educators to thoughtfully curate or create video content tailored to specific learning objectives. In addition, Rasi and Poikela (2016) highlighted the multimodal and participatory affordances of video triggers and production in PBL, emphasizing their alignment with modern students' communication and content creation preferences. Their review of higher education contexts confirmed that video triggers support collaborative learning and self-directed inquiry when implemented under optimal conditions, such as proper technological infrastructure and alignment with educational goals. Instructional videos offer effective support within PBL contexts, particularly for science teachers tackling complex, open-ended problems requiring interdisciplinary knowledge integration. Without sufficient guidance, students may find the problem-solving process challenging. Instructional videos can provide targeted support at crucial junctures by prior works (Lange & Costley, 2020; Pellas, 2024):

- Introduction: Videos can introduce essential background knowledge and concepts necessary for understanding the problem context.
- During problem-solving: Videos can offer just-in-time support by demonstrating specific skills or procedures relevant to particular stages of the problem-solving process.
- Post-problem reflection: Videos can provide expert commentary or alternative solutions, facilitating deeper reflection and learning.

Despite these benefits, challenges such as limited resources, time constraints, and varying levels of teacher competence were noted, underscoring the need for targeted professional development to enhance the adoption of video-based PBL strategies. The effectiveness of video-enhanced PBL in physics education was investigated by Gumisirizah et al. (2024), who reported significant improvements in academic performance across various school settings. Students engaging with video-based PBL performed better than those in traditional or PBL-only settings, particularly in private schools. These findings suggest that video resources can amplify the benefits of PBL by providing accessible and contextually relevant visual aids. Son (2024) demonstrated that AI chatbot simulations enhanced preservice teachers' noticing expertise and movements, reinforcing the value of responsive teaching. Lastly, Taningrum et al. (2024) extended the application of animated videos in sports education, finding that problem-based learning videos significantly improved students' critical thinking skills and understanding of complex football tactics. The study concluded that animated videos can effectively simplify challenging content while encouraging analytical thinking.

The findings from the above studies emphasize the transformative potential of integrating instructional videos into PBL settings. Key strategies for maximizing impact include:

1. Curating authentic and relevant content: Instructional videos should simulate real-world scenarios that resonate with learners' experiences and challenge their problem-solving skills.
2. Promoting multimedia-supported learning: Video triggers and productions foster participatory and interactive learning environments that cater to diverse student preferences.
3. Addressing challenges: Science teacher education in programs and adequate technological support are essential to overcome barriers such as resource limitations and educator readiness.
4. Leveraging AI and animation: Advanced technologies like AI chatbots and animated videos enhance adaptability, interactivity, and engagement, especially in addressing complex or abstract topics.

By aligning pedagogical strategies with technological innovations, educators can create impactful, student-centered experiences within PBL contexts that prepare learners for real-world challenges. For instance, AI-generated instructional videos offer unique opportunities to enhance understanding of Newton's laws of motion by visualizing abstract principles through dynamic animations and real-world scenarios (Savinainen et al., 2004; Thornton & Sokoloff, 1998). For instance, a video could illustrate the first law (inertia) by showing an object at rest and an object in motion until acted upon by an external force. For the second law ($F = ma$), the video might depict varying forces applied to objects of different masses, demonstrating how acceleration changes in proportion. Finally, for the third law (action-reaction), an animation could simulate a rocket launch, highlighting the expulsion of gas and the equal and opposite force propelling the rocket upward. To promote active learning, the video could include interactive segments where students predict outcomes before animations play or solve related physics problems during pause points. These elements can make AI-generated videos a powerful tool for demystifying physics concepts and improving learners' performance.

2.2. Observational and Demonstration Learning in Video Training

Instructional videos have gained momentum due to their ability to engage learners through multimedia representation and interactive features (Simanjuntak et al., 2019). These types of videos offer notable advantages, such as multimedia representation, alignment between screen animation and task execution, and user-friendly modeling. Research (Lim, 2024; Semeraro & Vidal, 2022) has demonstrated their superiority as an instructional medium in software training, although limitations remain, such as passive information processing, lack of structural overview, and pace inflexibility. Nevertheless, the effectiveness of videos can vary significantly depending on their design and implementation.

The theoretical foundation for videos lies in Bandura's social cognitive theory, which emphasizes the importance of observational learning. By observing and imitating the actions of others, learners can acquire new knowledge and skills. Demonstration-Based Training (DBT) builds upon this theory by systematically designing instructional features to enhance learning outcomes. This theoretical underpinning posits that much of human knowledge is acquired through observing others' actions. DBT builds on these principles, employing systematically designed instructional features to enhance knowledge acquisition, skills development, and attitudes (Van Der Meij et al., 2018b). DBT aligns instructional features with Bandura's four observational learning processes: attention, retention, production, and motivation. To support attentional processes, which are critical for observational learning, features such as narration and highlighting were utilized (Hurzlmeier et al., 2021). Narration is synchronized speech with animation for clarity in video. Highlighting techniques, including color coding, and zooming, directed learners' focus on essential interface elements, improving readability and recognition (Newbold & Gillam, 2010). Empirical evidence supports the effectiveness of such visual cues in improving learning outcomes (Zhang et al., 2024) and examines the functions and designs of added cues in instructional videos (Wang et al., 2020). User control, allowing learners to pause, replay, or skip sections, is another vital feature. It enables self-paced learning, overcoming the passivity often associated with videos and fostering active engagement. Studies indicate that user control enhances knowledge transfer, particularly for low-ability learners or complex tasks (Pi et al., 2019). The pacing of videos also influences learning outcomes. This can pass too quickly risk cognitive overload, while overly slow pacing may reduce attention (Martin & Martin, 2015). Previous studies (Van Der Meij, 2017) suggested an optimal pacing strategy that balances these concerns, with shorter videos under three minutes proving most engaging. In this study, video lengths ranged from approximately 3 to 5 min, aligning with these findings.

Lastly, previews serve as essential tools in video-based training, functioning as advanced organizers that structure and guide learners' understanding of the subsequent demonstration (Van Der Meij & Van Der Meij, 2014). By providing a concise overview of the upcoming content, previews can significantly enhance learning outcomes. While research (Blummer & Kritskaya, 2009; Van Der Meij, 2017) on the specific impact of previews in multimedia learning is limited, studies on text comprehension offer valuable insights. Some studies have shown that initial summaries, similar to previews, can improve information retention, particularly when they actively engage learners. This suggests that a well-designed preview can capture learners' attention, motivate them, and reduce cognitive load.

Prior works (Lim, 2024; Hurzlmeier et al., 2021; Van Der Meij et al., 2018a) indicate some key guidelines for effective preview design:

1. Clear objectives: The preview should clearly state the instructional video's learning goals.
2. Conversational style: The narrative should be engaging and easy to follow, resembling a conversation.
3. Introduction of key concepts: Critical or novel concepts should be briefly introduced, priming learners for deeper understanding during the demonstration.

The preview condition in this study adhered to the above principles, providing a brief overview of the task, and highlighting key elements. This approach aimed to boost learners' self-efficacy and reduce cognitive load by familiarizing them with essential terminology and concepts before the detailed demonstration. The preview process can ensure that learners are well-prepared to absorb the information presented in video (Van Der Meij & Van Der Meij, 2014). The preview in this study adhered to the aforementioned principles, offering learners a concise yet structured introduction to the task at hand. By providing a brief overview and emphasizing critical components, the preview served as a cognitive scaffold, equipping learners with the foundational knowledge needed to engage effectively with the detailed demonstration. This preparatory phase is essential in establishing learners' self-efficacy, as it assures them that the task is approachable and within their capabilities (Rismark & Sølvberg, 2019). According to Bandura's theory of self-efficacy (2006), individuals who perceive a task as manageable are more likely to persist, perform effectively, and achieve positive outcomes.

In this context, the preview fulfills multiple functions. It familiarizes learners with essential terminology and key concepts, reducing the cognitive load associated with processing new information during the demonstration. By doing so, it allows learners to focus their mental resources on understanding task-specific actions rather than struggling with unfamiliar jargon or concepts (Costley et al., 2020). Additionally, the preview acts as an anticipatory guide, helping learners organize incoming information, establish a mental framework, and activate relevant prior knowledge. This alignment between the preview and the learner's cognitive schema fosters a sense of preparedness and confidence, both critical components of self-efficacy (Marshall, 2024). Furthermore, the preview's ability to simulate a clear and achievable task pathway reinforces learners' belief in their capacity to succeed. For instance, by introducing screen objects, procedural steps, and task goals in an accessible manner, the preview transforms potentially intimidating content into manageable chunks (Brame, 2016). This breakdown not only supports cognitive processing but also nurtures a positive mindset, encouraging learners to approach the subsequent videos with motivation and readiness (Ester et al., 2023). In essence, the preview primes learners for success by creating a low-stakes environment for initial exposure to enhance their attention and memory, ensuring they are psychologically and cognitively equipped to engage with the full demonstration (Schacter & Szpunar, 2015). The integration of such previews aligns closely with the pre-training principle advocated by Kulgemeyer (2018), who posits that teaching essential components before a task enhances understanding and retention. By proactively addressing potential barriers to comprehension, the preview creates a smoother learning curve and supports the overarching goals of self-efficacy development, cognitive load reduction, and instructional effectiveness, when it comes to instructional explanation of scientific topics.

However, the integration of AI in videos provides additional ethical considerations. AI tools were employed to streamline the design process and generate dynamic visuals, but these tools were evaluated to ensure the produced content was accurate, culturally inclusive, and pedagogically effective. Potential biases in AI algorithms were assessed to avoid perpetuating stereotypes or misinformation. To enhance learner engagement and accessibility, the videos were designed with natural, relatable visuals and conversational narration (Al-Zahrani & Alasmari, 2024). The AI-generated components were developed with transparency, emphasizing fairness and accountability. Measures were taken to provide learners with control over video interaction and to ensure the content's adaptability to diverse learning needs. Additionally, the ethical implications of AI tools in education, including data privacy and algorithmic decision-making, were carefully considered to align with both General Data Protection Regulation (GDPR) regulations and best practices for educational fairness (Hamad et al., 2024).

2.3. AI-Generated Instructional Videos into PBL Contexts

One of the primary advantages of integrating AI-generated instructional videos into PBL settings is their potential to enrich learning experiences. By leveraging LLMs, these videos can deliver personalized, visually engaging, and interactive content that resonates with diverse learners. This capability enhances engagement with scientific concepts and provides dynamic scaffolding for collaborative problem-solving tasks. Such tools are particularly valuable in science teacher education, where contextualized and adaptive learning resources are essential for cultivating practical teaching skills (Bewersdorff et al., 2024). Moreover, generative AI pipelines that transform slides or images into hyper-realistic videos enable scalable, high-quality content creation, making innovative educational tools accessible across varied contexts (Saqr & López-Pernas, 2024).

Studies have shown that AI-generated videos can achieve comparable learning outcomes to traditional recorded videos. While retention rates with AI-driven resources are often higher, their performance on transfer tasks aligns closely with that of human-instructor-led videos, demonstrating their viability as an alternative instructional tool. Li et al. (2024) advocated that AI-generated videos support self-directed learning by fostering autonomy and facilitating personalized guidance, particularly valuable for training science educators to independently explore and implement advanced teaching strategies. These capabilities position AI-generated content as a significant enhancement to traditional PBL methodologies, addressing the limitations of static instructional resources.

However, challenges remain in achieving optimal engagement and a sense of social presence in AI-generated instructional videos. For instance, Shahzad et al. (2024) indicated that learners often perceive these videos as less engaging or relatable compared to human instructors. Concerns such as distraction, discomfort, and a lack of connectedness highlight the importance of refining the human-like qualities of AI avatars and videos. Despite these limitations, Arkün-Kocadere and Çağlar-Özhan (2024), in their study pointed out that learners tend to overlook these issues when the content is intrinsically engaging or aligned with their learning goals. As generative AI continues to advance, these differences are expected to diminish, further normalizing the use of its content in education.

Ethical and pedagogical considerations also play a critical role in the integration of AI-generated instructional videos into education. A study conducted by Pellas (2024) revealed that creativity mediates the relationship between academic performance and attitudes toward machine learning, though its moderating effect was not significant. Problem-solving and critical thinking, while not mediators, significantly moderates the link between academic performance and machine learning attitudes. Pellas (2023b) also showed that challenges such as data privacy, algorithmic bias, and the potential over-reliance on technology necessitate robust frameworks to ensure responsible use in AI-generated video content creation. This study examines the impact of digital storytelling and generative AI platforms on narrative intelligence and writing self-efficacy in undergraduate students. A pretest–posttest study, Pellas (2023a) compared traditional platforms (e.g., Storybird, Storyjumper) with generative AI tools (e.g., Sudowrite, Jasper). Results showed that generative AI platforms significantly enhance narrative intelligence and writing self-efficacy, though no notable differences were found in creative identity. These findings underscore the potential of AI tools to support students' story creation and development skills. Lin et al. (2025) admitted that a balanced approach is essential, where AI complements the unique relational and adaptive capabilities of human educators rather than replacing them. This equilibrium preserves the educator's role as a mediator of learning experiences while maximizing the potential of AI-generated tools.

For science teacher education, the integration of AI-generated videos offers a dual benefit: enhancing content delivery and modeling innovative instructional practices. By engaging in AI-driven resources during their training, Qu et al. (2024) admitted that future educators gain insight into how technology can be leveraged to address diverse learning needs effectively. Additionally, the multimodal capabilities open new possibilities for delivering immersive, interdisciplinary learning scenarios, fostering deeper engagement in scientific practices and equipping teachers with adaptable, future-ready skills (Pellas, 2024).

While the above research studies were focused on instructional videos, observational learning, and PBL are extensive, a significant gap exists at the intersection of these domains, particularly concerning the use of AI-generated videos. Although previews have been shown to be beneficial in traditional video-based learning by activating prior knowledge and reducing cognitive load, their specific role within AI-generated instructional videos used in PBL contexts remains largely unexplored. Existing research has not adequately addressed how the unique characteristics of AI-generated videos, such as their dynamic content and potential for personalization, might interact with preview strategies to influence learning outcomes. Furthermore, there is a lack of empirical evidence examining the combined effect of previews and AI-generated videos on pre-service science teachers' self-efficacy and their ability to transfer learned concepts to novel problem-solving situations within a PBL activity. This lack of research is particularly relevant in science teacher education, where preparing future educators to effectively use technology in the classroom is crucial. Although AI offers promising tools for creating engaging and accessible learning resources, it is essential to understand how established instructional design principles, such as the use of previews, can be optimally integrated into these new technologies. Investigating this intersection can provide valuable insights into maximizing the effectiveness of AI-generated videos in PBL settings, ultimately contributing to improved science teaching practices and enhanced student learning. This study aims to address this critical gap by specifically examining the impact of previews in AI-generated instructional videos on pre-service science teachers' learning, problem-solving performance, and self-efficacy within PBL contexts.

3. Materials and Methods

3.1. Research Purpose and Questions

The purpose of this study is to explore the role of preview features in enhancing the effectiveness of AI-generated instructional videos, particularly within PBL contexts for science teacher education. As the integration of AI in educational technology grows, this research seeks to examine how AI-generated videos—especially those with preview segments—can revolutionize the learning process in teacher training environments. By comparing videos with and without preview features, this study provides a unique contribution to the field of AI-driven multimedia learning and instructional design, offering insights into how subtle design elements can impact educational outcomes. In addition, research (Bandura, 2006; Shaukat et al., 2024) has shown that higher levels of self-efficacy are associated with increased persistence, better problem-solving strategies, and improved academic performance. By enhancing students' self-efficacy through instructional videos users will be more likely to engage deeply with the material and approach physics problems with greater confidence and competence. Therefore, any increase in self-efficacy measured in our study would suggest not only an improvement in students' beliefs about their abilities but also a potential improvement in their actual academic performance.

This research employs a within-subjects design (Greenwald, 1976), a research methodology grounded in well-established educational frameworks, allowing for a more direct comparison of the effects of preview features on learners' (pre-service teachers) performance (Johnson et al., 2017; Reeves et al., 2005). Through this rigorous evaluation, the current study aims to generate evidence that can inform the design of more engaging, interactive, and effective learning experiences. Specifically, it investigates how the inclusion of preview features in AI-generated videos influences key factors such as self-efficacy, task performance, and overall learning outcomes. Incorporating principles from design guidelines for software training videos, such as the importance of contextualized previews to enhance understanding and retention (Arkün-Kocadere & Çağlar-Özhan, 2024; Bewersdorff et al., 2024; Gumisirizah et al., 2024), this study anticipates that AI-generated videos will improve participants' confidence and skill acquisition in teaching science concepts. Moreover, it is expected that preview features would further enhance these outcomes by providing learners with a brief but informative overview of the content, thus improving both the retention and transferability of the learned material. The findings of this study may inform future instructional video design, particularly in the context of science teacher education, and contribute to the broader understanding of how AI can be leveraged to support effective, technology-enhanced learning.

To investigate the impact of AI-generated instructional videos on pre-service science teachers' learning within PBL contexts, the following research questions (RQs) guided this study:

- RQ1: Do AI-generated instructional videos, with and without a preview feature, affect pre-service science teachers' ability to apply scientific concepts?
- RQ2: Do AI-generated instructional videos, with and without a preview feature, influence pre-service science teachers' immediate and delayed problem-solving performance?
- RQ3: Do AI-generated instructional videos, with and without a preview feature, impact pre-service science teachers' self-efficacy in addressing complex scientific problems?

This study intends to provide evidence-based insights into how AI-generated instructional videos, particularly those enhanced with preview features, can effectively enhance science teacher education through PBL settings.

3.2. Research Design

While AI has garnered significant attention in education, its application within teacher training, particularly concerning the effective design and utilization of digital learning resources, remains underexplored. Though AI-generated content for student use is gaining traction, the potential of AI to support teachers in creating, adapting, and integrating these resources into their instruction is an area ripe for investigation. For example, AI could be used to: (a) automatically generate diverse examples and practice problems for instructional videos; (b) provide real-time feedback to teachers on the design and delivery of video lessons; or (c) create personal recommendations for teachers on how to best utilize video resources within PBL contexts.

This study investigates the comparative effectiveness of AI-generated instructional videos with and without preview features on learning outcomes, self-efficacy, and knowledge transferability. Using a within-subjects design, where all participants experienced both video conditions, minimizes variability due to participant differences and aligns with design-based research principles emphasizing iterative refinement of educational interventions (Reeves et al., 2005). Following Greenwald's (1976) principles, learning was assessed using pre-test, post-test, and transfer assessments to evaluate learning durability and transferability, directly addressing the need for practical evaluations of design principles in instructional media (Lin et al., 2025). This approach bridges theoretical insights from instructional design with actionable recommendations for educators. Participants' learning of scientific concepts, such as Newton's laws of motion, was assessed as follows:

- Pre-test: A 10-item multiple-choice and 2-item short-answer test assessed baseline knowledge (e.g., 'Which of Newton's laws explains why an object in motion stays in motion unless acted upon by an external force?').

- Post-test: Administered immediately after the intervention, the post-test used a parallel format with reworded or scenario-based questions assessing the same concepts.
- Transfer test: Transfer was assessed by requiring participants to apply Newton's laws to a novel, real-world context—analyzing a video of a complex mechanical system (e.g., a bicycle braking system)—distinct from the training examples (e.g., simple projectile motion problems). This ensured measurement of genuine knowledge application rather than simple recall.

Participants completed a post-test immediately after finishing the online learning module. A delayed post-test was administered two weeks later to assess retention. This two-week interval was chosen to provide a more realistic measure of long-term retention, allowing sufficient time for potential memory decay and the influence of everyday experiences (Figure 1).

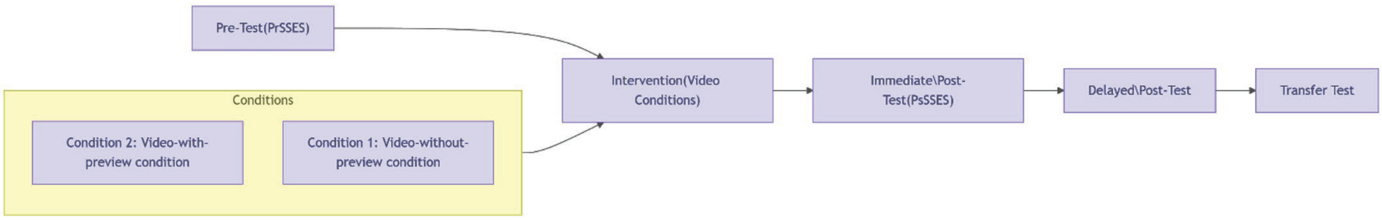

Figure 1. Flowchart of the research design.

3.3. Participants

Fifty-five Greek pre-service teachers participated in the study, comprising 31 females (56.36%) and 24 males (43.64%). Their average age was 27.3 years (SD = 3.56, range: 22–35). Most participants had 4–5 years of teaching experience (42.77%, n = 23), followed by less than 4 years (31.29%, n = 17), and first-year teachers (12.25%, n = 7). Their specialization areas included chemistry (32.73%, n = 18), biology (27.27%, n = 15), geology (21.82%, n = 12), and physics (18.18%, n = 10). All participants were experienced in using AI platforms, particularly in the context of media and information literacy.

The participants were selected based on their strong background in science education and prior exposure to AI-driven learning environments, ensuring their familiarity with instructional technology and innovative teaching methods. The majority (82.91%, n = 46) had completed traditional teacher training in Greece, involving a 4-year bachelor's degree or a 2-year master's degree, followed by a mandatory induction phase.

Most participants had 6 or more years of experience (53.98%, n = 29), with fewer having 4–5 years (42.77%, n = 23). The majority worked full-time (56.74%, n = 31). Approximately 22.51% (n = 12) were adjunct science teachers in public secondary schools, with the remaining 77.49% (n = 41) employed in private secondary schools. This sample also represented diverse educational contexts, with 37% (n = 20) teaching in rural areas and 63% (n = 35) in urban schools. Participants' motivation to participate was driven by professional development opportunities (78%, n = 43) and a shared interest in integrating AI into science education.

Participants were recruited from pre-service teacher education programs at three prominent Greek universities. Recruitment was conducted through a multi-pronged approach to maximize reach and ensure a representative sample. These emails provided a concise overview of the study's purpose, the estimated time commitment (approximately 2–3 h), information about data confidentiality, and a clear statement of voluntary participation. The email also included a link to an online platform (e.g., Google forms) where interested participants could access the informed consent form.

Inclusion criteria for participation were as follows: (a) current enrollment in a pre-service science teacher education program at one of the participating universities; (b) access to a computer with reliable internet access; and (c) willingness to participate in both data collection sessions. Participants were not offered any direct compensation, but their participation was framed as a valuable opportunity for professional development and contributing to the advancement of research in educational technology.

A total of approximately 80 email invitations were sent, resulting in 55 completed responses and a response rate of approximately 69%. This response rate is considered moderate and suggests a reasonable level of engagement with the study. While we acknowledge that any non-response may introduce some selection bias, the achieved sample size is sufficient for the planned statistical analyses. We address the potential limitations related to response rate in the discussion section.

3.4. Instruments

3.4.1. Training Materials

Participants were trained in key concepts reflecting Newtonian mechanics. The instructional videos covered specific concepts, including Newton's three laws of motion—inertia, force and acceleration, and action-reaction pairs. These concepts were chosen because they are fundamental to understanding basic physics principles and are essential for teaching introductory physics at the secondary level. The learning objective was to enable pre-service teachers to visualize Newton's laws in terms of analyzing and explaining the motion of objects in various real-world scenarios (Savinainen et al., 2004; Thornton & Sokoloff, 1998). This objective directly informed the design of the post-test and transfer test, ensuring alignment between instruction and assessment.

A. Instructional AI-generated videos: This study integrates AI-generated instructional videos into PBL for science teacher education, leveraging the IDEA (Interpret, Design, Evaluate, Articulate) framework by Lin et al. (2025) to enhance the effectiveness of training materials. Each of the four treatment phases has been restructured to align with the IDEA principles, ensuring a comprehensive, pedagogically grounded approach to developing pre-service science teachers' skills.

Treatment phase 1: Observing and explaining natural phenomena

- Interpret: Participants are guided to interpret and understand natural phenomena by observing and analyzing scientific events such as the phases of the moon, changes in shadow length, and the motion of objects under various forces. Teachers provide context for these tasks, helping students identify key observational goals and comprehend the significance of the phenomena. Newton's laws are introduced through AI-generated scenarios, such as a ball rolling on different surfaces to demonstrate inertia and force. AI tools offer culturally and contextually relevant visual prompts and scenarios to scaffold understanding. This focus on interpretation laid the groundwork for the transfer task, which required participants to interpret a complex mechanical system.
- Design: Participants collaborate with AI tools to develop detailed observation plans. For instance, they may design templates to measure and record motion data, such as acceleration or force diagrams. These tools support multi-lingual and multimodal interactions, allowing students to generate text-based or visual representations of their observations.
- Evaluate: Participants critically analyze their observation data against Newtonian principles. AI feedback systems help highlight inaccuracies or areas of improvement, promoting reflection. Peer discussion sessions, guided by AI-generated insights, en-

able collaborative evaluation of findings, fostering deeper understanding of concepts such as inertia and action-reaction pairs.

- Articulate: Participants provide their interpreted observations and reasoning to peers through presentations or reports. AI assistance ensures clarity and precision, offering real-time feedback and generating culturally relevant explanations to support their arguments, particularly around Newton's laws.

Treatment phase 2: Conducting Experiments and Analyzing Results

- Interpret: Participants are introduced to experimental scenarios, such as testing the effects of mass on acceleration or analyzing the forces acting on an inclined plane. Teachers guide students to understand the purpose, methodology, and significance of these experiments. AI-generated videos include dynamic animations and visual overlays to enhance comprehension of experimental setups and protocols involving Newton's laws.
- Design: Using AI tools, each participant designs experimental workflows, including hypotheses, variables, and data collection methods. AI offers real-time assistance by suggesting modifications to ensure safety and experimental validity, tailoring feedback to students' cultural and educational contexts. Experiments emphasize key principles such as force, mass, and acceleration.
- Evaluate: Participants evaluate their experimental results by comparing their findings with expected outcomes derived from Newton's laws. AI-powered analytics tools guide this process, identifying trends and highlighting discrepancies. Peer assessment sessions, supported by AI-generated discussion prompts, further refine their understanding of concepts such as force interactions and equilibrium.
- Articulate: Participants can articulate their experimental findings through interactive presentations, supported by AI-generated visual aids such as graphs, tables, and infographics. These outputs enable effective communication of results to diverse audiences, fostering scientific literacy with a focus on Newtonian mechanics.

Treatment phase 3: Advanced PBL in science education contexts

- Interpret: The main researcher introduces complex scientific challenges, such as designing a water filtration system or analyzing the dynamics of a pendulum. AI helps students interpret these problems by breaking them into manageable components, using simulations to visualize underlying principles, including Newton's laws.
- Design: Participants design solutions using AI-generated tools to create and refine prototypes or simulate outcomes. For example, they might model a pendulum's motion to study forces and acceleration or simulate vehicle collisions to understand action-reaction pairs. AI tools provide iterative feedback, ensuring designs are scientifically sound and feasible.
- Evaluate: Participants test their solutions using AI-driven simulations and evaluate the results. They reflect on the success of their approaches and identify areas for improvement. AI-generated comparisons with best-practice solutions help them understand gaps in their designs and how Newton's principles apply.
- Articulate: Participants can present their problem-solving processes and outcomes to peers and instructors, supported by AI-generated explanatory content. Real-time AI translation and contextual feedback help them effectively communicate complex ideas, particularly those related to Newtonian mechanics.

Treatment phase 4: Interactive features and technical considerations

- Interpret: The main researcher guides students to understand the importance of using digital tools for effective learning. The interactive features of the AI-generated videos, such as pausing, rewinding, and adjusting playback, are demonstrated to help students optimize their learning experience. Videos include real-time examples of Newton's laws in action to reinforce understanding.

- Design: Participants design their learning schedules and practices around these interactive features. AI provides personalized suggestions, such as recommending specific playback settings for segments illustrating complex Newtonian principles.
- Evaluate: Participants reflect on the utility of the interactive features in improving their comprehension and retention of Newton's laws. Peer feedback and self-assessment help identify which features are most effective for different learning styles.
- Articulate: Participants articulate their experiences with the interactive features through written or verbal feedback, supported by AI prompts. This phase encourages how these tools enhance their learning of fundamental physics concepts.

By integrating the IDEA framework into the chapters, this approach emphasizes a holistic and student-centered methodology. It ensures that students not only acquire scientific knowledge and skills but also develop critical thinking, collaboration, and communication abilities essential for effective science education. The key examples implemented focus on providing Newton-specific examples that explicitly relate to his laws of motion. In the preview videos, examples now address friction and inertia (Newton's First Law) and action-reaction pairs (Newton's Third Law). Demonstration videos showcase concepts like force and acceleration (Newton's Second Law) and the conservation of momentum and collisions (Newton's Third Law). The practice files offer opportunities to apply these laws by calculating force and acceleration (Newton's Second Law), analyzing forces on an inclined plane, and exploring projectile motion (incorporating multiple laws). Furthermore, instructional content videos and practice files connect to Newton's laws, providing more detailed examples to give a better sense of their content.

A. *Preview videos:* The preview videos provide concise overviews of the scientific phenomena or experimental techniques covered in each chapter. The narration begins conversationally, posing a problem or question to engage learners (e.g., *"Have you ever wondered why a rolling ball eventually stops?"* or *"What happens when you push a stationary object?"*). These videos include brief demonstrations of critical steps, enhanced by animations and zooming to emphasize key details. For example, a preview video might show a ball rolling across different surfaces (carpet vs. smooth floor) to illustrate the concept of friction and how it relates to Newton's First Law (inertia). Another example could show a brief animation of a rocket launching to introduce the concept of action-reaction pairs (Newton's Third Law). The average duration of preview videos is 1.30 min, with a five-second pause at the end to help students process the information (range 1.15−1.60). These previews served as initial exposure to the concepts tested in the pre- and post-tests.

B. *Demonstration videos*: Demonstration videos deliver detailed step-by-step instructions for conducting experiments or solving scientific problems. Narration is structured to explain both actions and outcomes (e.g., *"We will now measure the acceleration of a cart as we apply different forces, demonstrating Newton's Second Law. First, we'll measure the mass of the cart…"* or *"Observe how the force applied to the cart directly affects its acceleration."*). These videos incorporate AI-enhanced visuals, such as showing force vectors acting on an object or graphing the relationship between force and acceleration, to reinforce learning. For instance, a video could demonstrate how changing the mass of an object affects its acceleration when a constant force is applied. Another example could showcase the collision of two objects, demonstrating the conservation of momentum and Newton's Third Law. Each step is followed by a brief pause to allow reflection, and the entire video concludes with a five-second pause. Demonstration videos have an average length of 1.77 min. These demonstrations directly addressed the content assessed in the post-test and provided concrete examples that aided in conceptual understanding relevant to the transfer task.

C. *Final video files:* Accompanying the video tutorials are practice files, designed to replicate the scenarios presented in the videos. These files include step-by-step instructions for conducting experiments, paired with before-and-after images or data tables to guide learners through each task. For example, a file might provide instructions for calculating the force required to accelerate an object at a given rate (applying Newton's Second Law) or analyzing the forces acting on an object on an inclined plane. Another example could involve analyzing the motion of a projectile, calculating its trajectory based on initial velocity and launch angle (incorporating concepts from Newton's laws). These tasks allow students to apply what they have learned from the videos, with the option of re-visiting the segments for guidance. These practice files offered opportunities for applying learned concepts, reinforcing learning and preparing participants for the application-focused aspects of the post-test and the transfer task.

The above framework aligns with the study's focus on science teacher education, emphasizing active engagement with scientific phenomena and problem-solving through AI-generated instructional content.

3.4.2. Self-Efficacy Scale

To evaluate self-efficacy, the validated *Standards Self-Efficacy Scale (SSES)* was utilized (Shaukat et al., 2024). This study explored the potential of the SSES to assess pre-service teachers' self-efficacy about teaching standards, separating into other two: the Pre-Self-Efficacy Questionnaire (PrSSES) and the Post-Post-Self-Efficacy Questionnaire (PsSSES). The psychometric properties of the SSES were examined to evaluate its validity and reliability. It consists of 29 items and is selected due to its individual item's internal consistency. This was designed to capture participants' confidence levels in completing specific tasks, both before and after engaging with a video. The former (PrSEQ) was administered before the video to assess baseline self-efficacy. Based on Bandura's recommendations for designing self-efficacy measures, the questionnaire included seven items. Each item provided a brief description of a task along with corresponding "before-and-after" screenshots. Participants were asked to rate their perceived competence in completing the task using a 5-point Likert scale, ranging from "strongly disagree" to "strongly agree."

This scale is widely used to assess teachers' beliefs in their ability to meet the demands of their profession. For the purpose of this study, we adapted the SSES to specifically measure pre-service teachers' self-efficacy related to applying Newtonian mechanics concepts within the context of a roller coaster design PBL activity. This adaptation involved rephrasing items to refer to specific tasks related to applying Newton's motion laws during the roller coaster design PBL activity. The adapted scale used a 5-point Likert scale ranging from "strongly disagree" (1) to "strongly agree" (5).

Pre-self-efficacy questionnaire (PrSSES): The PrSSES, administered before the intervention, consisted of seven items adapted from the original SSES. These items were designed to assess baseline self-efficacy related to basic understanding and application of Newton's Laws, such as interpreting motion graphs, understanding force vectors, and calculating basic forces. The PrSSES demonstrated strong reliability with a Cronbach's alpha of 0.83. These items established a baseline for participants' confidence in applying the foundational concepts of Newtonian mechanics. Examples of PrSSES items (relating to Newton's Laws) are the following:

1. "*I interpret a graph of velocity versus time to determine the acceleration of an object.*" (Relates to understanding motion and Newton's First Law/Inertia if the velocity is constant, and to Newton's Second Law if the velocity changes).
2. "*I identify the forces acting on a stationary object.*" (Relates to Newton's First Law and the concept of balanced forces).
3. "*I describe the force required to accelerate an object given its mass and acceleration.*" (Directly relates to Newton's Second Law: F = ma).

Post-self-efficacy questionnaire (PsSSES): The PsSSES, administered after the intervention, also consisted of seven items adapted from the original SSES. These items were designed to assess self-efficacy related to more complex applications of Newton's Laws, such as analyzing forces on an inclined plane, predicting projectile motion, and understanding the relationship between force, mass, and acceleration *within the context of designing a roller coaster*. The PsSSES also demonstrated strong reliability with a Cronbach's alpha of 0.81. These items measured participants' confidence in applying Newton's Laws in more complex scenarios, similar to those encountered in the PBL activity. Examples of PsSSES items (relating to Newton's Laws and the Roller Coaster Context) are the following:

1. "*I analyze the forces acting on a roller coaster car as it moves along an inclined track, including gravity, normal force, and friction.*" (Combines Newton's First and Second Laws in a realistic scenario).
2. "*I predict the speed of a roller coaster car at different points on the track using the principles of energy conservation and Newton's Laws.*" (Integrates multiple concepts and laws within the PBL context).
3. "*I explain how Newton's Third Law (action-reaction) affects the interaction between the roller coaster car and the track, especially during turns.*" (Directly relates to a key aspect of roller coaster design).

To comprehensively analyze self-efficacy changes, this study employed tools to capture participants' perceived abilities at two distinct stages. Given the Greek context of this research, the scales were rigorously translated into Greek using Brislin's (1970) back-translation method to maintain cultural and linguistic equivalence. Online questionnaires were distributed to assess participants' perceptions.

3.4.3. Task Performance Tests

The task performance tests were developed to evaluate the practical skills introduced in the AI-generated instructional video. Four distinct tests were administered: the pre-test, immediate post-test, delayed post-test, and transfer test, following the guidelines by Van Der Meij et al. (2018b). Each task was assessed on a binary scoring system: tasks completed entirely and correctly were awarded one point, while incomplete or incorrect tasks received zero points. The maximum achievable scores were nine points for the pre-test, immediate post-test, and delayed post-test, and four points for the transfer test.

A. Pre-Test, Immediate Post-Test, and Delayed Post-Test: The pre-test, conducted before the tutorial, consisted of seven tasks designed to evaluate participants' initial understanding and skills related to science phenomena. These tasks were carefully aligned with the content of the AI-generated instructional videos, focusing on key scientific concepts and processes, including:
    1. Adjusting variables in a simulation to observe changes in a scientific phenomenon.
    2. Identifying relationships between dependent and independent variables in an experiment.
    3. Interpreting data from graphs or tables representing scientific phenomena.
    4. Organizing observations into structured formats, such as diagrams or flowcharts.

5. Creating and labeling a model to represent a specific science concept.

These tasks established a baseline for evaluating participants' ability to comprehend and apply scientific concepts, as facilitated by the AI-generated instructional videos.

The pre-test included an instructional guide and seven science-related tasks. Each task was introduced with a brief description, supported by before-and-after visualizations illustrating the expected results. Participants were instructed to open corresponding simulation files, stored in their personalized computer folders, to perform the tasks. For instance, one task required participants to analyze a graph of velocity vs. time and determine the acceleration of an object. This task assessed their understanding of Newton's First Law (inertia) by requiring them to recognize that a constant velocity indicates zero net force and therefore no acceleration (connecting to Newton's first law). Another task asked participants to draw force vectors acting on a block sliding down an inclined plane without friction to connect with Newton's second law. This task assessed their understanding of Newton's Second Law (F = ma) by requiring them to identify the forces acting on the block (gravity, normal force) and their relationship to the block's acceleration. The pre-test was designed to have a maximum score of nine points.

The immediate post-test, administered directly after the tutorial, and the delayed post-test, conducted seven days later, followed the same structure as the pre-test. While the tasks and instructions remained similar, the content of the associated science simulations was adjusted slightly to ensure learners demonstrated conceptual understanding without repetition. While the pre-test asked participants to analyze a graph with constant acceleration, the post-test presented a graph with varying acceleration (Connecting to Newton's Second Law). This required a deeper understanding of Newton's Second Law and the relationship between force and changing acceleration. Connecting to Newton's Laws in combination, similarly, the inclined plane problem in the post-test included friction. This required participants to apply both Newton's First and Second Laws to account for the additional force of friction and its effect on the block's motion. These tests were also designed to have a maximum score of nine points.

B. Transfer test: The transfer test evaluated participants' ability to apply their knowledge and skills to science phenomena that were not explicitly addressed in the AI-generated instructional videos. This test aimed to measure adaptability, critical thinking, and independent problem-solving skills. The transfer test included a separate instruction file and four new tasks:
    1. Adjusting environmental variables in a simulation to observe changes in system behavior.
    2. Reorganizing data within a visual representation, such as a graph or chart.
    3. Identifying patterns in new experimental results.
    4. Creating a hypothesis and explaining its implications using unfamiliar scientific data.

Each task in the transfer test was paired with uniquely designed simulation files to ensure participants faced challenges extending beyond the tutorial's scope. This approach encouraged deeper cognitive engagement and the application of foundational scientific principles in new contexts. An appropriate example of connecting to Newton's Third Law and conservation of momentum was required. One task presented a scenario involving two colliding objects with different masses and asked participants to calculate the final velocities of each object. This task assessed their understanding of Newton's Third Law (action-reaction) and the principle of conservation of momentum. Connecting to multiple laws in a complex system. Another task asked participants to predict the trajectory of a projectile launched at an angle, considering the effects of air resistance. This required participants to integrate their understanding of all three of Newton's Laws to account for gravity, air resistance, and the resulting motion of the projectile.

By integrating these structured assessments, the study systematically evaluated the effectiveness of the AI-generated instructional videos in fostering understanding, retention, and transferable skills within the domain of science teacher education.

3.5. Procedure

The present study was conducted in a middle school computer lab, equipped with headphones for each participant. Experiments spanned two sessions over six days. During Session 1, participants were assigned ID cards and completed the PrSSES and a pre-test after a brief introduction. Following a short break, participants watched the video tutorial, practiced tasks, and completed the PsSSES, and an immediate post-test. This session lasted approximately 90 min (Figure 2).

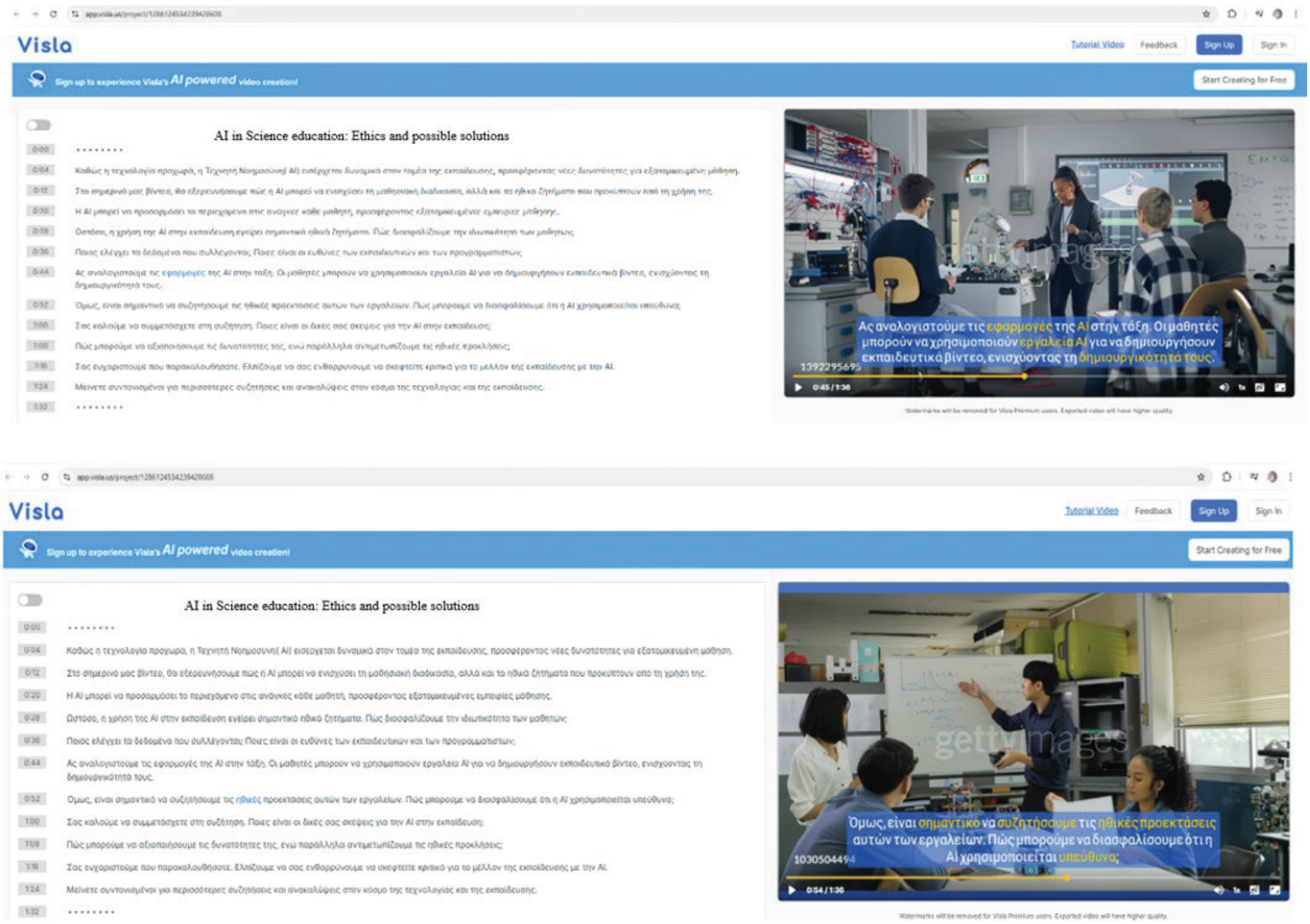

Figure 2. Participants create AI-generated instructional videos using Visla.

In Session 2, conducted a week later, participants completed a delayed post-test and a transfer test without access to the tutorial. This session lasted 45 min. Participants interested in pursuing careers within public or private schools can gain valuable research experience by exploring the potential of generative AI chatbots for education. This could involve:

- Evaluating existing tools: Analyzing the effectiveness of current AI-powered educational applications like ChatGPT, Claude, and Gemini to identify areas for improvement.
- Designing integration frameworks: Developing frameworks for seamlessly integrating AI into existing digital literacy curriculums.

Furthermore, all participants can enhance their practical skills by creating AI-supported educational resources tailored to diverse age groups and learning objectives. This process encompassed the following:

- Interactive multimedia content: Designing and developing educational videos and images enriched with interactive digital elements to enhance learners' digital literacy across various subjects.
- AI-generated video production: Utilizing platforms like Sudowrite (https://www.sudowrite.com, accessed on 8 December 2024), Visla (https://www.visla.us, accessed on 8 December 2024), or Jasper (https://www.jasper.ai, accessed on 8 December 2024) for creating engaging educational video content through AI assistance.

This study employed a within-subjects design, where all participants experienced both conditions: AI-generated instructional videos with a preview feature and AI-generated instructional videos without a preview feature. This design was chosen to minimize the influence of individual differences on the results, allowing a more direct comparison of the effects of the preview feature within the same participants (Greenwald, 1976). However, the lack of a separate control group receiving a different type of instruction limits the ability to contextualize findings against alternative instructional approaches. Therefore, the current study consisted of the following phases:

- Pre-test: Participants completed the pre-test, which assessed their baseline knowledge of Newtonian mechanics and related problem-solving skills. They also completed the PrSSES, measuring their perceived self-efficacy in problem-solving.
- Intervention (Video conditions): Participants were exposed randomly to two conditions of AI-generated instructional videos:
  - Condition 1: Video with preview: Participants watched AI-generated instructional videos on Newtonian mechanics with an embedded preview feature (video-with-preview condition).
  - Condition 2: Video without preview: Participants watched the same AI-generated instructional videos on Newtonian mechanics without the embedded preview feature (video-without-preview condition).

  A 15-min break was given between the two conditions to minimize carryover effects.
- Immediate post-test: After viewing both video conditions, participants completed the immediate post-test, which assessed their understanding and application of the concepts presented in the videos. They also completed the PrSSES again to measure any changes in self-efficacy.
- Delayed post-test: Seven days after the intervention, participants completed the delayed post-test to assess retention of the learned material over time.
- Transfer test: Immediately following the delayed post-test, participants completed the transfer test. This assessed their ability to apply the learned concepts to novel problems, specifically a roller coaster design PBL activity.

This counterbalancing ensured that any observed differences between the conditions were not due to the order in which they were presented. It is important to emphasize that the core instructional content of the AI-generated videos was identical in both conditions. Both videos covered the same concepts of Newtonian mechanics and provided the same demonstrations and explanations. The sole difference between the conditions was the inclusion or exclusion of the short preview segment at the beginning of the video. The instructional videos were generated using a variety of platforms for AI-generated video production. Each one was selected based on its ability to create dynamic, engaging content suitable for educational purposes. AI with detailed text scripts that outlined the key concepts of Newtonian mechanics, such as Newton's First and Second Laws of Motion, along with specific descriptions of the animations we wanted to accompany the explanations. For example, the script for Newton's Second Law included a description of a moving car and a force diagram to visually demonstrate the relationship between force, mass, and acceleration. Additionally, we specified visual elements such as color schemes, motion graphics, and the inclusion of text annotations to reinforce the concepts. The AI then generated video segments that included animated explanations, synthesized voiceovers, and text captions. The voiceovers were created using text-to-speech technology, ensuring clear and accurate pronunciation of the key terms and concepts. The animations were designed to be visually engaging and pedagogically appropriate, aimed at enhancing learners' understanding of the physics concepts. Once the videos were generated, they were thoroughly reviewed and edited by two physics educators to ensure both accuracy and pedagogical soundness. The educators verified that the content was correct from a scientific standpoint, ensuring that the animations effectively represented the physics concepts and that the voiceovers were coherent and appropriate for the target audience. Any errors in terminology or conceptual explanations were corrected, and adjustments were made to the animations to improve clarity and enhance educational value.

All tests were administered online using Google Forms. The videos were hosted on an individual server and were accessible through unique links provided to each participant. Participants were instructed to complete all phases of the study individually and without external assistance. The entire procedure, including all tests and video viewings, took approximately two hours to complete.

3.6. Data Collection and Data Analysis

Data were gathered through structured tasks aligned with the instructional videos. The tasks assessed participants' ability to comprehend and apply the concepts presented in the videos. Each task was scored based on accuracy, with zero points for incorrect or incomplete tasks and full points for correct completions.

Data analysis was performed using IBM SPSS 23. Baseline equivalence was assessed through independent-sample t-tests (for age, PrSSES, and pre-test scores) and Chi-Square tests (for gender distribution). Paired-sample t-tests were used to evaluate the effect of the tutorial on self-efficacy and test performance across time points. ANCOVAs were conducted to examine condition effects, with PrSSES and pre-test scores as covariates. The homogeneity of variance was checked beforehand. Significance was set at $\alpha = 0.05$, with effect sizes interpreted per Cohen's guidelines (small: $d = 0.2$, medium: $d = 0.5$, large: $d = 0.8$) (Cortina, 1993).

Data was analyzed using Paired-Sample t-tests to compare pre- and post-test scores within each condition. Additionally, ANCOVAs were conducted for pre-existing differences in participants' knowledge of the scientific concepts. Specifically, pre-test scores on the knowledge assessment were used as covariates. This was done because pre-test scores are a strong predictor of post-test performance and allow us to account for individual differences in baseline knowledge. This approach allowed us to isolate the effect of the instructional videos with and without preview features on learning outcomes, independent of participants' initial knowledge levels

The video tutorial (final video file) designed for this study serves as a key component in integrating AI-generated instructional content into PBL contexts for science teacher education. This process was specifically developed to align with Lin et al.'s (2025) IDEA framework for effective instructional video design, adapting these guidelines for science education. The treatment was organized into five phases, each progressively addressing more complex scientific phenomena and laboratory practices (Table 1).

Table 1. Summarizing the phases and data collection.

Phases	Activity	Data Collected	Time Point
Pre-Intervention	Completion of pre-test and Pre-Self-Efficacy Questionnaire (PrSSES)	Pre-test scores, PrSSES scores	Before Intervention
Intervention	Viewing AI-generated videos (with/without preview—counterbalanced)	Video viewing data (completion, time spent)	During Intervention
Immediate Post-Test	Completion of immediate post-test and Post-Self-Efficacy Questionnaire (PsSSES)	Immediate post-test scores, PsSSES scores	Immediately after Intervention
Delayed Post-Test	Completion of delayed post-test	Delayed post-test scores	7 Days after Intervention
Transfer Test	Completion of transfer test	Transfer test scores	After Delayed Post-Test

3.7. Ethical Considerations

The lead researcher (author) prioritized participant well-being and rights throughout this study, adhering to rigorous ethical guidelines. Ethical protocols encompassed obtaining informed consent, ensuring confidentiality and anonymity, and safeguarding participants' privacy and overall welfare while addressing the ethical, social, and educational implications of utilizing AI technologies in research and instructional design (Al-Zahrani & Alasmari, 2024). Participation was entirely voluntary, with all individuals providing informed consent before data collection and being informed of their right to withdraw from the study at any time without repercussion.

Specific to the development and use of AI-generated video tutorials, ethical considerations extended to the transparency and accountability of AI algorithms, ensuring the generated content was accurate, unbiased, and aligned with educational standards. Potential biases in AI training data were carefully evaluated to prevent unintended reinforcement of stereotypes or misinformation. Specific to the development and use of AI-generated video tutorials, ethical considerations extended to the transparency and accountability of AI algorithms, ensuring the generated content was accurate, unbiased, and aligned with educational standards. Potential biases in AI training data were carefully evaluated to prevent unintended reinforcement of stereotypes or misinformation. Additionally, the main researcher took measures to enhance the naturalness and relatability of AI-generated visuals and narratives, ensuring the content was engaging, culturally sensitive, and supportive of a positive learning environment (Al-Zahrani & Alasmari, 2024).

Before initiating the instructional intervention, participants were thoroughly briefed on the study's purpose (Hamad et al., 2024). They also signed a consent form detailing: (a) the potential implications of using the assessment platforms and AI-generated content, (b) the collection and handling of their data under GDPR, and (c) their unconditional right to withdraw from the study at any point without negative consequences. By addressing both traditional and AI-specific ethical considerations, the study aimed to uphold the highest standards of integrity and respect for participant autonomy. This study complied with the ethical guidelines outlined in the Declaration of Helsinki. Necessary permissions were secured from all participating institutions. Moreover, all subjects were fully informed of their right to withdraw from this study at any time without repercussions. Both verbal and written consent were obtained from each participant (Bush & Grotjohann, 2020).

4. Results

4.1. Descriptive Analysis

A total of 55 participants completed their AI-generated instructional video tasks. A chi-square test indicated no statistically significant difference in gender distribution between the two groups, $\chi^2(1, n = 55) = 0.49$, $p = 0.64$. A p-value of 0.64 is greater than the typical significance level of 0.05, indicating no statistically significant difference in gender distribution between the two groups. The participants' average age was 25.44 years (SD = 0.91), with ages ranging from 22 to 36. Similarly, an independent sample *t*-test revealed no significant difference in age between the two groups, $t(53) = 0.84$, $p = 0.58$. A p-value of 0.58 is also greater than 0.05, indicating no statistically significant difference in age between the two groups.

The PrSSES scores were comparable across the two conditions. Participants scored an average of 5.74 (SD = 1.41) in the video-with-preview condition and 5.81 (SD = 0.95) in the video-without-preview condition, $t(53) = 0.81$, $p = 0.45$. However, a significant difference emerged in the pre-test scores when participants were first assigned to different starting conditions. Participants who viewed the video-without-preview condition first achieved a higher mean pre-test score (M = 0.52, SD = 0.21) compared to those who viewed the video-with-preview condition first (M = 0.42, SD = 0.22), $t(55) = 3.44$, $p = 0.003$. This significant difference suggests that participants demonstrated greater initial ability in developing AI-generated video tutorials when starting with the video-without-preview condition compared to the video-with-preview condition. Consequently, the baseline task performance was not equivalent across conditions at the outset. The first plot in Figure 3 compares the pre-test scores between the video-with-preview and video-without-preview conditions, with error bars indicating the standard deviations. The second plot in the same figure shows the PrSSES scores for both conditions, again with error bars to represent the variability. The first plot highlights the higher initial scores when participants started with the video-without-preview condition, compared to the video-with-preview condition. The second plot illustrates the close similarity in self-efficacy perceptions (PrSSES scores) between the two conditions, with error bars representing standard deviations.

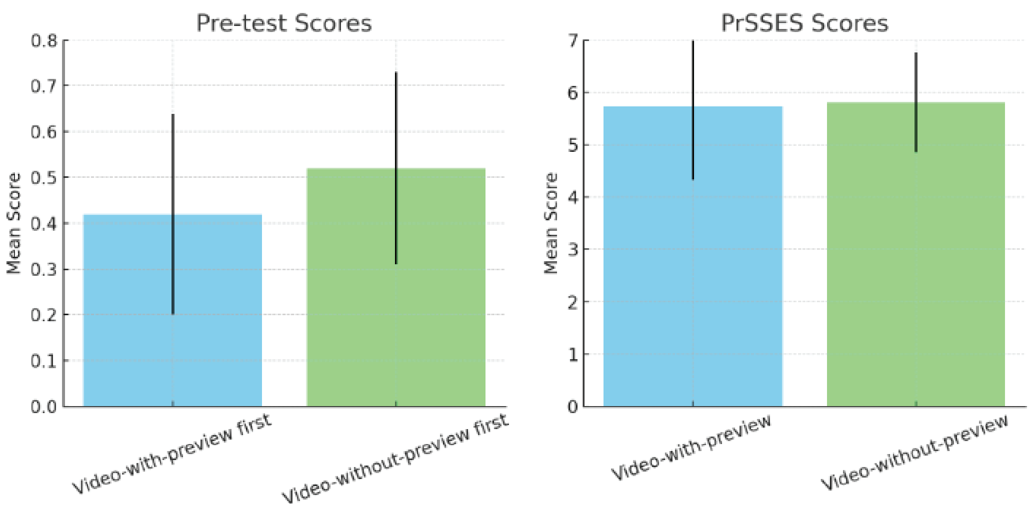

Figure 3. The Pre-test and PrSSES scores by condition.

Some key points of view based on the above analysis are the following:

1. Baseline differences in performance: Participants exhibited significantly higher pre-test scores when starting with the video-without-preview condition compared to the video-with-preview condition, indicating a disparity in initial task performance

capabilities. This suggests that further investigation is needed to address such baseline differences and ensure equivalent starting points for all participants, regardless of the order of conditions.

2. Consistency in self-efficacy perceptions: Despite differences in baseline performance, the PrSSES scores were comparable across the video-with-preview and video-without-preview conditions. This finding suggests that the AI-generated instructional videos were perceived similarly in terms of their ability to support self-efficacy across conditions, regardless of the order in which participants experienced the videos.
3. Implications for instructional design: The significant difference in pre-test scores suggests that the preview feature alone may not be sufficient to ensure equivalent learning conditions. It is important, therefore, to incorporate additional scaffolding strategies or tailored previews to accommodate the diverse starting points of learners, as observed in the baseline performance differences.
4. Generalizability of AI-generated tutorials: Participants showed similar levels of self-efficacy across both conditions, highlighting the broad potential of AI-generated instructional tools to enhance participant confidence, regardless of specific instructional design elements, such as the inclusion or exclusion of a preview feature.

4.2. Top of Form

Self-Efficacy Before and After Training

As illustrated in Figure 4, participants' self-efficacy significantly improved after completing the training (M_post = 6.66, SD_post = 0.72) compared to their self-efficacy before the training (M_pre = 5.72, SD_pre = 1.23), with t(53) = 5.37, p = 0.002 t(53) = 5.37, p = 0.002 t(53) = 5.37, p = 0.002. The effect size, calculated as Cohen's d = 0.96 indicates a large impact of the intervention. These findings confirm the hypothesis that the video tutorial positively influenced participants' self-efficacy. Additionally, the relatively high initial self-efficacy score (M_pre = 5.88), which exceeds the scale's midpoint, suggests that the word formatting tasks were perceived as relatively straightforward by most participants.

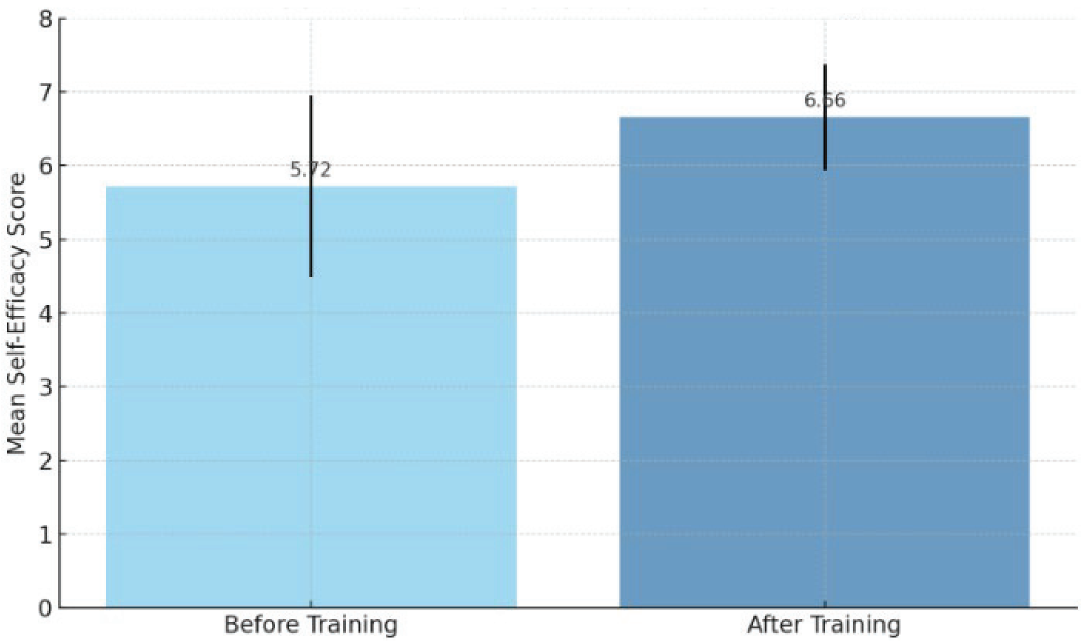

Figure 4. Self-efficacy results before and after training.

While the training significantly improved self-efficacy overall, analyses comparing the two video conditions (with and without the preview feature) revealed no statistically significant differences. A post-hoc power analysis conducted using G*Power with an alpha level of 0.05, an observed effect size of Cohen's d = 0.15, and a sample size of 55, indicated low achieved power (0.35). This suggests a low probability of detecting a statistically significant difference in self-efficacy between the two conditions, even if a true effect of that magnitude existed. Therefore, while the training effectively increased self-efficacy, the non-significant findings regarding the preview feature should be interpreted cautiously, as the study may have been underpowered to detect a small effect.

Regarding the impact of the experimental condition, ANCOVA tests revealed no significant difference between the participants in video-with-preview and video-without-preview conditions, $F(1, 54) = 1.73$, $p = 0.19$. This result does not support the hypothesis that self-efficacy improvements would be significantly greater in the video-with-preview condition compared to their counterparts in video-without-preview condition. Figure 4 illustrates the mean self-efficacy scores of participants before and after treatment, with error bars representing standard deviation. The increase in mean scores suggests a positive effect of the training on self-efficacy across both groups, although this increase was not significantly different between the conditions.

Based on the analysis above, three key points of view should be highlighted:

1. Overall self-efficacy improvement: Participants significantly improved their self-efficacy after training, with a large effect size.
2. Initial confidence: The pre-training self-efficacy scores were already above average, suggesting that the task was perceived as relatively manageable.
3. Condition comparison: No significant difference between instructional video-without-preview and video-with-preview conditions, implying both benefited similarly from the training.

4.3. Task Performances and Learning

Across the four assessments (pre-test, immediate post-test, delayed post-test, and transfer test), participants achieved the highest scores on the delayed post-test (M = 0.75, SD = 0.33), while the pre-test recorded the lowest scores (M = 0.41, SD = 0.22). A detailed descriptive analysis of the results for each test is presented in Figure 5, offering a clear visual comparison of the performance across conditions and test types. The visual and descriptive analysis in Figure 5 highlights the importance of different instructional conditions in enhancing learning outcomes and retention over time.

Some of the most notable points of view are the following:

1. Delayed post-test performance: The delayed post-test scores are the highest across all conditions, indicating a strong retention of the material over time.
2. Pre-test comparison of participants: (a) the pre-test scores are the lowest overall, showing significant room for improvement before the intervention and (b) the participants in video-without-preview conditions scored higher than the video-with-preview group in the pre-test, indicating an initial disparity in baseline performance.
3. Post-test insights: Participants in both conditions show improvement from the pre-test to the immediate post-test, but those in video-with-preview conditions' delayed post-test scores surpass their counterparts, suggesting a longer-term benefit of the preview condition.
4. Transfer test: Scores in the transfer test are consistent across conditions, suggesting that the intervention equally prepared both groups for applying learned concepts to new contexts.

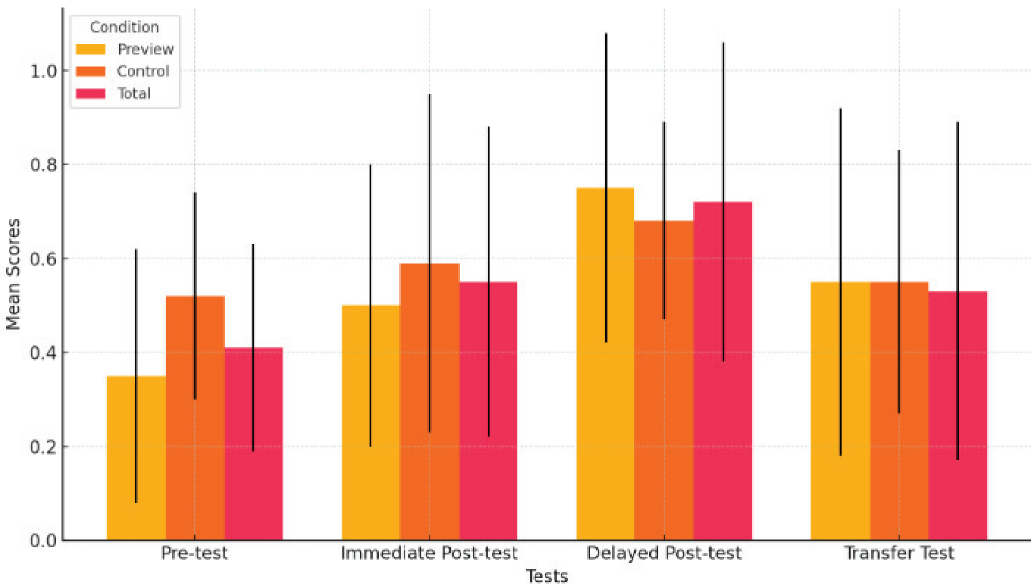

Figure 5. Performance across tests by condition.

One-sided paired-samples t-tests revealed that immediate post-test scores (M = 0.65, SD = 0.42) were significantly higher than pre-test scores (M = 0.41, SD = 0.33), t(53) = 4.58, $p < 0.001$, d = 0.65. This represents a moderate effect size. Similarly, delayed post-test scores (M = 0.69, SD = 0.24), t(53) = 7.95, $p < 0.001$, d = 1.65, and transfer test scores (M = 0.67, SD = 0.32), t(53) = 2.97, $p = 0.002$, d = 0.67, were also significantly higher than pre-test scores. These results confirm that the video tutorial positively impacted participants' task performance on the immediate post-test, delayed post-test, and transfer test (Figure 6).

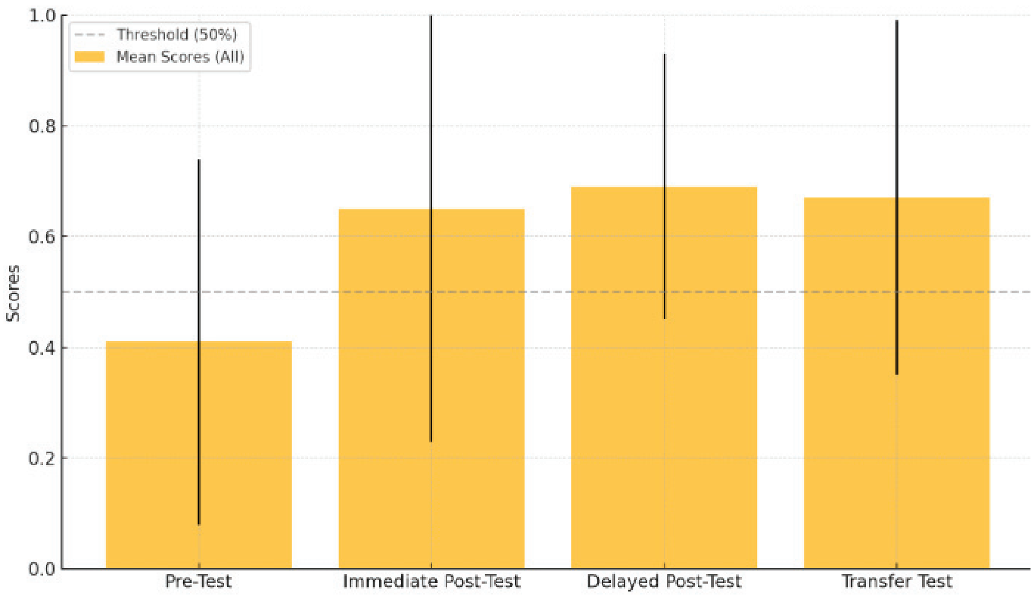

Figure 6. Overall task performance across tests.

The bar charts in Figure 6 show the mean scores for all participants across the four tests (pre-test, immediate post-test, delayed post-test, and transfer test), with error bars representing standard deviations. The performance increases steadily from the pre-test to the delayed post-test, emphasizing the effectiveness of the video tutorials.

An ANCOVA was conducted to examine the effects of conditions, with the pre-test scores included as a covariate. First, the assumption of homogeneity of variance was checked across all tests, and no violations were detected. A one-sided ANCOVA revealed the following:

- For the immediate post-test, the preview condition (M = 0.68, SD = 0.36) did not score significantly higher than the video-without-preview condition (M = 0.62, SD = 0.41), $F(1, 54) = 0.003$, $p = 0.54$.
- For the delayed post-test, the preview condition (M = 0.70, SD = 0.21) did not score significantly higher than the video-without-preview condition (M = 0.71, SD = 0.22), $F(1, 54) = 0.04$, $p = 0.51$.
- For the transfer test, the preview condition (M = 0.53, SD = 0.28) also did not score significantly higher than the video-without-preview condition (M = 0.51, SD = 0.29), $F(1, 54) = 0.22$, $p = 0.73$.

The bar charts compare the performance between conditions for the Immediate post-test, delayed post-test, and transfer test. Error bars show the standard deviations. While the preview consistently shows slightly higher means, the differences are not statistically significant. Therefore, the assumption that the preview feature in the AI-generated instructional video tutorial would lead to participants' performance improvement on the immediate post-test, delayed post-test, and transfer test cannot be supported (Figure 7).

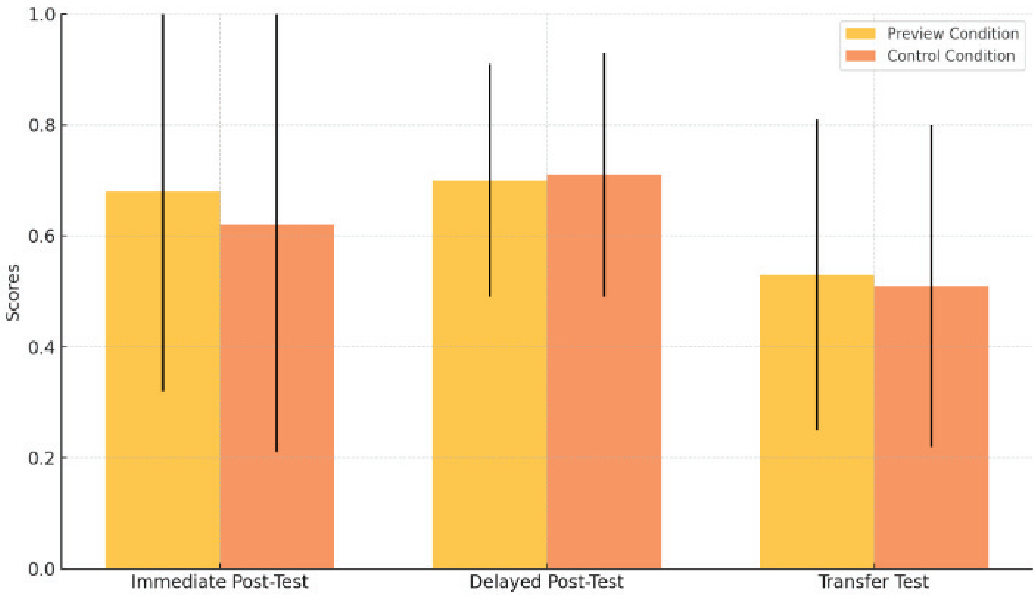

Figure 7. Results from the preview and conditions.

Based on the results presented above, the following key points should be considered:

- Improvement across all tests: The immediate post-test, delayed post-test, and transfer test scores were all significantly higher than the pre-test scores. This suggests that the intervention (AI-generated video tutorial) had a positive impact on participant task performance, improving their ability to complete both tasks immediately and overtime. Specifically, the large effect sizes in the delayed post-test (d = 1.65) and the moderate effect size in the transfer test (d = 0.67) emphasize the sustained benefits of the intervention. These results confirm that the video tutorial facilitated learning and retention of knowledge, extending beyond the immediate learning phase.
- No significant difference between conditions: Although the preview condition showed slight improvements in scores across the immediate post-test, delayed post-test, and transfer test, these improvements were not statistically significant when compared to video-without-preview condition. This suggests that the inclusion of a preview in the AI-generated instructional video did not have a notable additional effect on

performance relative to the video-without-preview condition. This indicates that other factors, such as the video content itself or individual differences, might be influencing task performance more than the preview alone.

- AI-generated instructional video 's effectiveness: Despite the lack of significant differences between conditions, the overall improvement in task performance from the pre-test to the subsequent tests (immediate, delayed, and transferred) supports the effectiveness of the AI-generated video tutorials in enhancing participants' understanding and task execution. The video tutorials, whether with or without a preview, appear to be a useful tool for promoting learning outcomes.
- Potential limitations of the preview effect: The absence of significant findings regarding the preview conditions may point to potential limitations in how the preview was implemented. While previews are generally helpful in setting up context and expectations, it seems that the format, content, or delivery of the preview might not have been optimized in this case to enhance task performance. Future research could explore different approaches to delivering previews or investigate other factors that could interact with the preview to better support learning.

In summary, the key aspects of these results are that AI-generated video tutorials have a positive effect on learning outcomes, but the specific role of a preview in enhancing performance remains unclear and warrants further exploration. These findings suggest that while AI-generated video tutorials are effective at enhancing participant performance, further investigation is needed into the precise mechanisms that make them successful. Research can further focus on refining the preview strategies, examining the role of other instructional features (such as interactive elements), or exploring the impact of learners' prior knowledge and motivation on tutorial effectiveness.

5. Discussion

This study aimed to examine the impact of AI-generated instructional videos on the learning outcomes of participants (pre-service science teachers) in PBL contexts, with particular emphasis on the role of preview content and its effect on pre-service science teachers' self-efficacy, task performance, and retention. The results presented here provide valuable insights into the effectiveness of AI-generated videos and the associated instructional features, such as the preview, in enhancing learning for future science educators.

Regarding RQ1, this study's results demonstrate that the use of AI-generated instructional videos significantly enhanced participants' task performance, as evidenced by the improvements observed in the immediate post-test, delayed post-test, and transfer test scores. These results are also consistent with those from previous studies (Arkün-Kocadere & Çağlar-Özhan, 2024; Pi et al., 2019; Rasi & Poikela, 2016), showing a clear increase in performance from the pre-test (M = 0.41) to the subsequent tests, with the delayed post-test (M = 0.75) achieving the highest scores. This pattern is consistent with the notion that AI-generated videos provide learners with a clear and engaging medium for acquiring and retaining knowledge, reinforcing the positive impact of multimedia learning (Gumisirizah et al., 2024; Son, 2024). The fact that the transfer test scores were also significantly higher than the pre-test suggests that the participants were not only able to remember information but were also able to apply it to novel situations. These results aligned with a portion of researchers (Arkün-Kocadere & Çağlar-Özhan, 2024; Li et al., 2024; Semeraro & Vidal, 2022) and showed that multimedia learning environments, particularly those employing AI technology, can enhance both the retention and application of learned material. Importantly, the improvement in transfer tasks emphasizes the potential of AI-generated videos to foster critical thinking and real-world problem-solving skills, which are essential for future educators.

The preview, as an instructional feature, was expected to play a significant role in setting up the learners' cognitive framework and promoting higher self-efficacy and performance (Bandura, 2006). However, the results of the answer RQ2 did not support the hypothesis that the preview condition would lead to a significantly higher task performance compared to the video-without-preview condition. Both the immediate post-test, delayed post-test, and transfer test results showed no significant differences between the preview and video-without-preview conditions, suggesting that the preview did not have a substantial effect on task performance, which comes in line with findings from previous works (Al-Zahrani & Alasmari, 2024; Brame, 2016). This finding is somewhat surprising given the theoretical backing for the preview's role in enhancing learning outcomes. In line with Lin et al.'s (2025) IDEA framework, the preview was designed to introduce participants to key concepts and reduce cognitive load. While the preview may have reduced cognitive load and provided context for the learners, it seems that its impact was not strong enough to create significant differences in performance. One possible explanation is that the format or content of the preview did not effectively engage participants in active cognitive processing, as suggested by previous research (Aidoo, 2023; Kumar, 2010). Alternatively, the effectiveness of the preview might depend on other factors, such as learners' prior knowledge or the instructional design of the tutorial itself. The null effect of the preview condition also highlights the complexity of instructional design in AI-generated video tutorials. Although the preview provided some context and clarity, it may not have been sufficiently engaging or tailored to the individual needs of the participants. Future research could explore variations in how previews are presented—perhaps incorporating interactive elements or asking participants to predict outcomes based on the preview, which might foster more active engagement and, consequently, better learning outcomes (Lange & Costley, 2020; Pellas, 2024; Saqr & López-Pernas, 2024).

Another key aspect of this study was the impact of the AI-generated video tutorials on participants' self-efficacy regarding RQ3. The results indicated that participants' self-efficacy scores significantly improved from the pre-test (M = 5.72) to post-training (M = 6.66), with a large effect size (d = 0.96). This finding underscores the positive influence of video tutorials on participants' confidence in their abilities to perform the tasks associated with the tutorial. The improvement in self-efficacy is consistent with previous research (Li et al., 2024; Shahzad et al., 2024), which has shown that multimedia instructional tools can enhance participants' perceived competence and motivation (Van Der Meij et al., 2018b). Interestingly, the comparison between conditions did not reveal significant differences in self-efficacy scores, suggesting that while video tutorials overall contributed to an increase in self-efficacy, the preview did not appear to provide additional benefits over the video-without-preview condition. This could suggest that the inherent benefits of the instructional videos themselves, such as clear instructions and demonstrations, were sufficient to boost participants' confidence without the need for a preview. Therefore, this finding stresses the importance of refining instructional elements to maximize their impact on participants' outcomes.

While the training itself led to significant improvements in self-efficacy and overall task performance, no statistically significant differences were observed between the AI-generated instructional videos with and without the preview feature across any of the assessed metrics (self-efficacy, immediate and delayed task performance, and transfer). The effect sizes for these comparisons were small to negligible: Cohen's d = 0.15 for self-efficacy, Cohen's d = 0.65 for immediate task performance, Cohen's d = 1.65 for delayed task performance, and Cohen's d = 0.67 for transfer. These small effect sizes suggest that the preview feature had a minimal practical impact on learning outcomes, as Sullivan and Feinn (2012) suggest.

Several factors may explain these non-significant findings. One possibility is that the preview did not provide sufficiently novel or crucial information beyond what was already presented in the main video content. Furthermore, participants may not have effectively utilized the preview, perhaps skipping it or not fully engaging with its content. The design of the preview itself may have also played a role. Future iterations of the preview could be improved by optimizing its timing (e.g., presenting it before complex sections), focusing its content on the most critical information, and incorporating interactive elements to promote active processing. An adaptive preview that tailors its content to individual learner needs could also be explored. These changes could enhance the preview's effectiveness and potentially lead to more significant learning gains.

6. Implications

The results of this study have several important implications for the design, implementation, and evaluation of AI-generated instructional tools in educational contexts, particularly in science and PBL settings. First, the findings confirm that AI-generated videos are a viable and effective medium for supporting learning, particularly in fostering retention and transfer of knowledge. The improvement demonstrated in participants' delayed post-test and transfer test performance highlights the potential of AI-driven multimedia tools to promote deeper learning outcomes, including the application of knowledge in science teacher education. By leveraging AI technologies such as adaptive avatars and natural language processing, these tools can provide a dynamic, engaging, and potentially personalized approach to content delivery that aligns with diverse learner needs. AI-generated instructional tools can also play a transformative role in bridging gaps in resource-limited educational settings. Their scalability and ability to deliver high-quality, consistent content make them a valuable asset for institutions seeking to expand access to high-quality education. This is particularly relevant in teacher training programs, where such tools can enhance pedagogical practices and prepare future educators for integrating technology into their classrooms.

The mixed findings regarding the preview feature offer valuable lessons for instructional design. While previews are theorized to set expectations and reduce cognitive load by providing an overview of key concepts, this study suggests that their efficacy depends on additional contextual factors. Instructional designers must carefully evaluate how features like previews are implemented. For example, interactive previews that prompt learners to make predictions or actively engage with the material may yield stronger learning outcomes compared to passive content delivery. Similarly, scaffolding strategies, such as linking preview content to specific tasks or goals, could enhance their relevance and impact. This underscores the importance of iterative design and testing in AI-generated instructional tools. Designers should consider learner feedback, content complexity, and pacing when integrating such features. Moreover, incorporating adaptive learning algorithms that adjust preview content based on individual learner profiles or prior knowledge could make these tools more responsive and effective.

On the one hand, the substantial improvement in self-efficacy observed across conditions brings to light a crucial advantage of AI-generated instructional tools, which is their ability to boost learners' confidence in their abilities. This finding is particularly significant in PBL contexts, where self-efficacy is a key predictor of success. AI tools that integrate motivational elements, such as encouraging feedback from avatars or personalized progress tracking, can further enhance learners' confidence and engagement. On the other, the lack of differential effects between the video-with-preview and video-without-preview conditions suggests that the core design of the video tutorials, including clear demonstrations and step-by-step guidance, was sufficient to support self-efficacy. Future developments could explore how additional features, such as reflective questions or gamified elements, might further amplify this effect.

7. Limitations and Directions for Future Research

While this study provides valuable insights into the use of AI-generated instructional videos, several limitations should be noted. The sample size, though adequate for this analysis, may limit the generalizability of the findings, and future research with a larger and more diverse sample could provide more robust conclusions. Additionally, while the study focused on the impact of video tutorials on self-efficacy and task performance, future research could explore other variables, such as participants' motivation, engagement, and perceptions of the technology.

Another potential avenue for future research is the examination of the long-term impact of AI-generated video tutorials. While the delayed post-test indicated sustained learning benefits, the retention and application of skills over a longer period remain an important area to explore. Longitudinal studies could assess whether the positive effects of AI-generated tutorials persist over time or if additional instructional interventions are required to maintain high levels of engagement and performance.

This study's findings open up avenues for future research. For instance, the role of the preview warrants further investigation. Future studies could experiment with different types of previews, such as interactive previews or those that involve active participation, to determine whether these approaches can more effectively support learning outcomes. Additionally, examining how individual learner characteristics, such as prior knowledge or learning styles, interact with the preview and other instructional features could provide further insights into optimizing AI-generated tutorials. Studies should also explore the role of interactivity, adaptive features, and learner agency in AI-generated instructional tools. For example, incorporating real-time feedback mechanisms or allowing learners to navigate content non-linearly could lead to more personalized and impactful learning experiences. Investigating how these tools can be adapted for diverse educational contexts, such as cross-disciplinary PBL programs or culturally specific learning environments, would further broaden their applicability. Lastly, this study's findings underline the need for longitudinal research to evaluate the long-term impact of AI-generated instructional tools on learners' knowledge retention, skill application, and overall academic performance. Such studies can provide deeper insights into how these tools shape learning trajectories over time and inform best practices for their integration into curricula.

8. Conclusions

The present study aspires to bridge the gap between the theoretical potential of AI-generated instructional video tutorials and its practical application in science training programs. The findings aim to provide a foundation for designing innovative pedagogical strategies that integrate AI-generated videos into PBL settings, enhancing both the learning experience and the professional preparedness of future science educators. The current study contributes to the evolving narrative of how technology reshapes education, empowering teachers to inspire the next generation of scientists and critical thinkers. It also aligns with broader educational goals of fostering digital competence among future educators. As schools increasingly adopt technology-enhanced learning environments, science teachers must understand and utilize advanced digital tools effectively. By experiencing AI-driven instructional resources in their training, future teachers gain not only subject-specific knowledge but also a deeper appreciation of how technology can be leveraged to address diverse learning needs. AI-generated instructional tools hold tremendous promises for transforming education, but their success hinges on thoughtful design and evidence-based implementation. By addressing the nuanced challenges highlighted in this study, educators and designers can harness the full potential of these tools to foster meaningful, sustained learning outcomes.

In conclusion, this study contributes to the growing body of research on the use of AI-generated instructional videos in science teacher education. The results indicate that these tools are effective in enhancing participants' learning outcomes, particularly in terms of knowledge retention and transfer tasks. While the preview did not have a significant impact on task performance, the overall positive effects of the AI tutorials for science education themselves suggest that they can be a valuable resource in future teacher training programs. This study also contributes to broader educational goals of fostering digital competence among future educators. Digital competence for educators encompasses a range of skills, knowledge, and attitudes related to the effective and responsible use of digital technologies in teaching and learning. This includes not only the ability to use digital tools but also the capacity to critically evaluate digital resources, integrate technology into pedagogical practices, and foster students' digital literacy.

The current work directly contributes to pre-service teachers' digital competence by providing them with hands-on experience using and evaluating AI-generated instructional videos. This experience enhances their ability to integrate digital resources into their pedagogical practices (Göltl et al., 2024). By comparing different versions of the instructional videos, participants are encouraged to consider the impact of specific design features, such as the preview, on learning outcomes, thus developing their evaluative skills related to digital content. Furthermore, this study contributes to a broader understanding of the pedagogical potential of AI in education. By experiencing AI-driven instruction, pre-service teachers gain insights into how these technologies can be leveraged to enhance learning and support different learning styles.

While this study provides valuable insights into the effectiveness of AI-generated instructional videos in teacher training, several avenues for future research remain. Future studies should investigate the effectiveness of interactive and adaptive previews, incorporating elements such as short quizzes or personalized content based on learner needs. Employing eye-tracking techniques could also provide valuable insights into how learners interact with the preview feature. Furthermore, exploring the use of gamification and personalized feedback within the video tutorials could further enhance learner engagement and motivation. Finally, future research could explore broader applications of AI in teacher training, such as using AI to provide automated feedback on teacher practice or developing AI-powered training simulations for classroom management.

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Article

Assessing Student Teachers' Motivation and Learning Strategies in Digital Inquiry-Based Learning

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Abstract: Over the past two decades, teachers have adopted several teaching and learning strategies for motivating students to learn chemistry. Learning chemistry in context enables students to develop richer crosscutting learning experiences relevant to contributing to solving problems. A qualitative case study method was adopted to examine student teachers' experiences in digital inquiry-based learning. Questionnaires with closed-ended and open-ended questions were used to evaluate student teachers' motivational orientations and learning strategies during a general chemistry course for one month. The results show that student teachers utilized varied perspectives such as self-efficacy, task value, and intrinsic goals to elaborate their learning for knowledge construction and application when performing collaborative tasks. The approach enables students to receive maximum support and feedback from instructors who use pedagogical styles to self-direct them during class discussions, which enhances their active participation in learning with the learning materials. The findings provide a practical insight into instructional strategies in delivering chemistry concepts when students are motivated to use and adopt varied learning strategies.

Keywords: context-based teaching; inquiry-based learning; student teachers; motivation; digital learning; chemistry education

1. Introduction

One growing challenge in chemistry education has been the issue of students usually perceiving organic chemistry concepts as challenging [1–3]. This negative perception and attitude is attributed to ineffective approaches, such as teachers' didactic approaches to deliver chemistry concepts [4,5]. Studies show teaching chemistry concepts with teacher-led approaches leads to students learning in isolation [4], resulting in weaker understanding of concepts due to low self-concept and critical thinking [6,7]. As a result, there are concerns that teachers do not utilize effective instructional approaches or learning strategies that help students develop critical thinking skills.

Focusing on the current crucial component of chemistry education research, learning chemistry is critical in helping students develop logical thinking and problem-solving skills [8] that allow students to make career decisions [9]. Researchers have identified effective instructional approaches and classroom teaching interventions to address this challenge to enhance students' critical thinking development [10–12] to prepare them for future employment. Recent science transformations have seen teachers shift from traditional chemistry teaching to active learning practices with relevant context-based approaches [13]. Delivering chemistry concepts in context enables students to connect their learning experiences to foster scientific literacy [14].

Current studies show that teaching chemistry concepts with context-based approaches improves students' attitudes towards chemistry [15] and makes them attain deep learning to "think critically, solve a problem, and transfer ideas, knowledge, and skills in new situations" [16–18]. Teaching chemistry in context-based approaches focuses on connecting the content to real-world situations so that students can understand the concept of phenomena or situations [19]. Further, King [20] reported that context-based learning enhances the development of understanding, enabling students to gain crosscutting learning experiences and relate them to real-life contexts.

One teaching approach that follows context-based learning experiences is inquiry-based learning [21]. Inquiry-based learning (IBL) is a multifaceted student-centered, self-directed teaching approach in which instructors guide learners to partake in a series of activities to take learning responsibilities [22] to construct knowledge from problem-solving activities. According to Lee et al. [23], IBL involves a series of techniques instructors use to promote students' active learning through problem identification, investigations, and solution generation. Through inquiry learning, students undergo scientific activities by observing, questioning, reviewing, gathering, analyzing, interpreting data, predicting, and drawing conclusions [24]. The IBL is reported to enhance students' conceptual understanding, leading to the development of new skills for knowledge acquisition of the nature of science [25,26]. Schwartz et al. [26] argue that an IBL approach emphasizes not entirely transferring knowledge but fostering inquiry skills and understanding the nature of science. A study by Orosz et al. [27] found that a guided inquiry-based approach helps students develop scientific skills as they scaffold through science learning activities. Due to the efficacy of the approach, several studies have been conducted to highlight several ways in which certain factors such as motivation and learning styles enhance students' learning success in IBL environments.

Students' Motivation and Learning Strategies in IBL

Several studies have investigated students' motivation to use learning strategies in IBL. A literature body has acknowledged the importance and value of motivation, goals, abilities, and learning styles in the IBL environment [28–30]. However, enhancing these motivational beliefs and learning strategies is facilitated by educators when designing their IBL lessons [31]. Research has shown that educators' role as facilitators in IBL empowers students to take responsibility for the learning process [32,33]. Educators guide students by creating opportunities that motivate students to learn and improve their scientific skills [34]. In the IBL, educators also provide resources and appropriate feedback that facilitates students learning progress to self-direct and elaborate their learning [22,35,36].

Studies show that students' motivation positively impacts their academic performance in science [37,38]. Oskarsson and Karlsson [39] argue that less motivated students see school science as less engaging, making them lose interest and see no relevance or connections of science learning to future jobs. Han [40] found that students' genuine interest in learning science involves activating and maintaining their affective enjoyment and cognitive engagement which enhances their motivation to learn. This shows motivation is vital in determining students' interests, scientific competence, and future science career choices. Addressing this challenge, teachers have adopted varied strategies to engage and motivate learners in their courses. Teachers use strategies such as collaborative learning to interact and explore information to construct knowledge [41]. In a collaborative learning environment such as IBL, teachers instruct and guide students to use prior knowledge to construct and apply new knowledge [42]. Researchers recommend that in thriving IBL environment requires collaboration and interaction among students and instructors to foster idea-sharing through discussions [43,44]. Studies show that students who self-regulate their learning can create learning goals and expectations to learn a task [29,30] and change their motivation and learning strategies to achieve such goals [45,46]. Researchers have argued that highly motivated students put much more effort into learning new tasks through self-efficacy and elaborating strategies compared with less motivated students [28,47]. Because demotivated students cannot concentrate on staying focused, they try to skip challenging tasks and finally give up, potentially affecting their learning. As such, instructors set up learning activities in a way that motivate students to seek information by interacting with peers to generate answers to problems [48]. Through IBL, students engage with peers in active learning that enhances their application of the knowledge to develop critical thinking skills for problem-solving [49]. Students in active learning environments are self-confident and usually seek solutions to problems to work out more complex tasks [17]. This indicates the importance of active learning environment enabling teachers to create opportunities for students to learn using different learning strategies.

A body of knowledge has emphasized the importance of motivation and learning strategies in learning [28,29,50]. These studies have hinted that motivational beliefs and learning strategies enable students to understand concepts that lead to learning success. How students use these motivational orientations and learning strategies in learning chemistry remains unknown. Therefore, this study explores how student teachers' motivational and learning strategies foster their organic chemistry learning. This study sought answers to the following research questions:

1. What are student teachers' dispositions towards motivation and learning strategies towards chemistry learning?
2. What are student teachers' views in learning chemistry in IBL classrooms?

2. Research Methodology

This study employed qualitative case study methods involving an in-depth inquiry of student teachers' experiences in digital inquiry-based learning. The design was appropriate as it enabled the researchers to collect in-depth data on implementing blended learning. Questionnaires with closed-ended and open-ended questions were used to collect data from the participants.

2.1. Participants and Sampling

During the pandemic, instructors faced many challenges, including engaging students to learn and learn specific subject matter. As such, the researchers aimed to recruit teacher educators using IBL to support students' digital learning practices. Convenient sampling was used to identify three classrooms of 143 student teachers from colleges of education enrolled in a general chemistry course. These student teachers were selected because of easy access and the availability of course instructors to participate in this study. The course content follows a blended learning approach (face-to-face lecture instructions and out-of-class online learning) to explore different chemistry concepts. The student teachers comprised 46 males and 97 females, aged 16 years to 30 years. The participants were enrolled in the Bachelor of Education programs, offering different major subjects with different study backgrounds and focusing on primary education, home economics, and early childhood streams.

2.2. Teaching and Learning Process

We adopted the 5E conceptual framework to design and plan the learning activities in an instructional sequence [51]. Through the framework, students were taken through the five phases, engage, explore, explain, elaborate, and evaluate, as shown in Table 1.

Table 1. Teaching and learning processes and activities in the 5E phases.

Phases of IBL	Teaching and Learning Activities
Engage	Students introduced organic chemistry concepts through questioning, scenarios, or problem-based to arouse their interest, e.g., classification of organic compounds, e.g., what are organic compounds and their uses

Table 1. *Cont.*

Phases of IBL	Teaching and Learning Activities
Explore	Educators guide students to construct their understanding of the naming of organic compounds by reflecting on guiding questions and principles, e.g., students follow and reflect on writing chemical formulas and naming of hydrocarbons and alcohols using the guiding rules
Explain	Students articulate their views on subject matter, e.g., share understanding during group discussions, e.g., participate in group discussions with peers on given tasks on naming, properties, hydrocarbons, alcohol, etc.
Elaborate	Educators review the lesson and provide more information through class discussions to brainstorm to build students' understanding of the subject matter, e.g., practice more examples of naming, reactions of hydrocarbons and alcohols, carboxylic acids, and aldehydes
Evaluate	Students complete individual and group tasks, and educators provide feedback, e.g., students take quizzes and conduct group presentations on naming organic compounds

2.3. Data Collection

The data were collected over a regular class session for four weeks through questionnaires. The purposely developed closed-ended questionnaire was adopted from the Motivated Strategies for Learning Questionnaire (MSLQ) developed by Pintrich and De Groot [52]. The MSLQ test contained 81 multiple-choice items. To suit the purpose of this study, three factors (intrinsic goal orientation, task value, and self-efficacy) were selected from the motivation scales. In the learning strategies, critical thinking abilities, elaboration, and peer learning were selected. According to Pintrich and De Groot [52], defining intrinsic goal orientation in the MSLQ as a student's perception of participating in a course/task challenges them to enhance curiosity and a mastery of learning. Task value refers to students' assessment of their interest, the importance, and the usefulness of the tasks, leading to more participation in the learning. Self-efficacy is a self-assessment of a student's ability to master a task. Elaboration strategies help learners to keep "information into long-term memory through the building of interconnections to integrate and connect new information with prior knowledge". Help seeking refers to students learning how to manage their learning by seeking assistance from peers and instructors. Peer learning refers to collaborating with peers to dialogue to clarify course material and reach insights that one may not have attained on their own. The questionnaire was based on a Likert scale scored on a level of 1 as "Strongly disagree, SD" to 5 as "Strongly agree, SA" and open-ended questions. The open-ended questions enabled the researchers to collect varied views, perspectives, and understandings to supplement the information gathered from the questionnaire. According to the research questions, the questionnaire and focus group items were categorized to solicit views and experiences of the motivation, learning strategies, and general perceptions of their IBL. In validating the questionnaire, two experts from the colleges of education and the University of Cape Coast agreed on the content validity after adding some questions. The instrument was shared with participants via WhatsApp, and some parts were offered to be completed on paper to enhance a high response rate. In total, 125 (response rate of 87%) student teachers completed and returned the questionnaires.

2.4. Data Analysis

Responses to the questionnaire were analyzed using SPSS. Descriptive statistics were used, and the results of the findings and student teachers' views and experiences with IBL were presented in frequencies and percentages for easy visualization. The responses were scaled down by combining Strongly Disagree (SD) and Disagree (D) as disagree and Strongly Agree and Agree into *agree*. The Neutral (N) was not included in the analysis as it shows the students' indecision to either agree or disagree. The open-ended responses were analyzed manually using qualitative content analysis [53]. The responses were extracted, transcribed, defined, and emerged themes identified. The themes were coded and revised to remove any overlaps.

3. Results and Findings

3.1. Research Question 1: What Are Student Teachers' Dispositions Towards Motivational Orientations and Learning Strategies of Chemistry Learning in IBL Settings?

This research question sought to find out which motivational dimensions and learning strategies enhance chemistry learning.

3.1.1. Motivational Orientations

The perceptions of student teachers' disposition towards motivation and learning strategies in IBL chemistry are shown in Table 2. The table was constructed to present the frequencies and percentages facilitating the participants' perceptions regarding motivational orientations and learning strategies in the context of chemistry education.

Table 2. Student teachers' dispositions towards learning strategies.

Item	Responses n (%)				
	SA (%)	A (%)	N (%)	D (%)	SD (%)
Intrinsic goal orientation	51 (35.7)	41 (28.7)	24 (16.8)	14 (9.8)	13 (9.1)
Task value	49 (34.5)	33 (23.2)	37 (26.1)	17 (12.0)	6 (4.2)
Self-efficacy	67 (46.9)	25 (17.5)	30 (21.0)	8 (5.6)	13 (9.1)
Critical thinking	72 (50.3)	27 (18.9)	17 (11.9)	11 (7.7)	16 (11.2)
Elaboration	74 (51.8)	24 (16.8)	18 (12.6)	11 (7.7)	16 (11.2)
Peer learning and help seeking	49 (34.3)	39 (27.3)	30 (21.0)	13 (9.1)	12 (8.4)

Key: Strongly Disagree, SD; Disagree D; Neutral, N; Agree, A; Strongly Agree, SA.

Results from Table 2 show that 89 (62%) student teachers agreed to all the motivational orientations, indicating a positive disposition of motivation in learning chemistry, while 24 (17%) did not have stronger motivational beliefs. In comparing the individual motivational orientations, respondents' assessment of task value showed that 82 (58%) agreed that the learning materials, activities, and tasks were interesting, important, and useful to their learning. In contrast, 23 respondents (16%) disagreed that the learning activities were to the statement. Similarly, for respondents' opinions on intrinsic motivation, 92 (64%) responded that they believed the approach was more engaging and enhanced their curiosity to become active learners, while 27 (19%) disagreed with that statement. When asked how they used their self-efficacy, 92 (64%) agreed that the IBL approach enabled them to develop abilities, skills, and confidence to learn, understand, perform, and master the learning tasks including tests and assignments. In comparison, 21 (15%) disagreed that self-efficacy enhanced their learning.

3.1.2. Learning Strategies

Results from Table 2 show that 95 (64%) of the respondents agreed with most of the learning strategies orientations, indicating a stronger positive disposition towards the use of varied learning strategies, while 26 (18%) disagreed that they had stronger learning strategies beliefs. Respondents' assessment of peer learning and help seeking showed 88 (62%) of respondents agreed that collaborating with peers and seeking assistance enhanced their understanding of the subject matter, while 25 (18%) disagreed that peer learning and seeking was essential to their learning of chemistry. While 98 (69%) of the respondents believed their ability to retain "information into long-term memory through the building of interconnections to integrate and connect new information with prior knowledge", 27 (19%) respondents did not believe that the approach helped them to integrate and connect new information with prior knowledge to learn. When asked about how they used their critical thinking, 99 (69%) of the student teachers agreed they used their prior knowledge to link new situations to solve problems, while approximately 27 (19%) of the participants disagree with the statement, “Students could apply previous knowledge to new situations to solve problems”. In facilitating a clear visualization of participants’ perceptions regarding motivational orientations and learning strategies in the context of chemistry education, a graphical representation was used as shown in Figure 1.

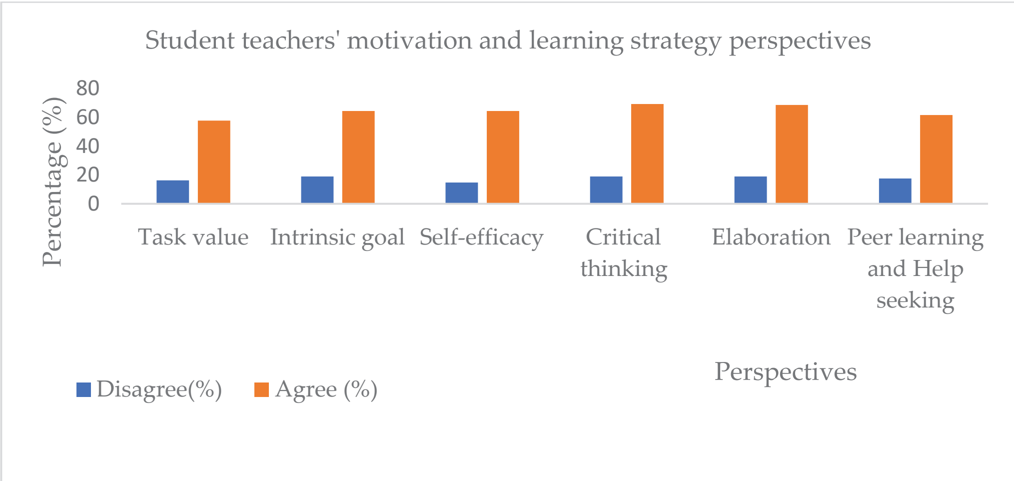

Figure 1. Percentages of student teachers’ dispositions towards motivation and learning strategies.

3.2. What Are Student Teachers’ General Views on Learning Chemistry in the IBL Classroom?

Participants were asked their views on the question: What did you like/not like most about learning in the online IBL environment? Their positive views about the approach were grouped into four themes, namely:

Category 1: Teachers’ support

Regarding educators’ support, 10 (8%) student teachers responded that they liked the presence of the tutors during the learning. They felt the presence of the tutors supported them during the class discussions and the out-of-class sessions. Most students agreed that the approach helped build good teacher–student relationships when interacting and communicating through the Google Docs platform. Through the learning platform, they could ask questions and receive feedback from tutors that enhanced their understanding of the subject matter. To strengthen this finding, one student stated,

> *The discussions and interactions with the tutor make the approach promotes learning support from the teacher-learner relationship.*

Another student added,

> *“. . .the tutors identified students with learning needs and provided them with the support that motivated them to learn more.”*

On the other hand, some (3%) student teachers could not utilize the platforms as regularly as expected, thus missing essential discussions and interactions with the tutors. One participant stated

> *there was a lack of effective communication and interaction since you can’t ask questions when you don’t understand, and the educator wasn’t always available.*

Category 2: Collaboration and peer learning

Regarding students’ collaboration and peer learning, 10 (8%) student teachers noted the approach was effective as they could interact and communicate with peers during the group learning activities. The student teachers felt they collaborated on work with peers, which helped establish a good rapport. Some comments from participants include,

> *I have a face-to-face interaction with colleagues, which helps me remember things that were taught.*

> *Doing the tasks as group work was good because we get help from our friends if you do not understand something.*

Category 3: Use of the learning materials

Students (6%) had positive views and attitudes towards the video lectures. Findings from the survey showed that student teachers found the video lectures very helpful in enhancing their learning. One participant wrote that

> *. . .by watching the videos, a basic understanding of the subject matter was established and developed further, which helped students to review for examination.*

In addition, the student teachers indicated that the materials, e.g., videos, were exciting and motivating, enhancing their learning. They explained that the video content was more prosperous. One student teacher indicated,

> *I believe there was more understanding in the video lessons, and it broadened my scope of learning I also got to know more examples vividly using this approach.*

On the other hand, some students (4%) indicated that the video lectures were not helpful. They complained that some of the video activities were complicated and that,

> *Sometimes the videos were difficult, and unable to understand the concept of the lesson*.

Besides students (2%) being unable to comprehend the video's content, the video quality was not appealing to some participants. One student teacher wrote,

> *The voice in videos was unclear, making it boring to watch and sometimes confusing me the most*.

Category 4: Independent and active engagements for learning

The student teachers reported that learning was more engaging and made them active learners. Regarding their class engagement, 7 (6%) student teachers indicated that IBL enabled them to practice the learning content by reflecting on the learning materials. Student teachers believed that having more time to practice the content outside the classroom positively enhanced their active participation and confidence to learn. For instance, one participant argued,

> *I am more engaged and gain a deeper understanding of content instead of primarily memorizing and recalling facts and ideas*.

Another student teacher said,

> *Learning chemistry in a blended learning environment increased my motivation to participate and engage in the class. We were encouraged to read the materials, ask probing questions, and discuss with peers to share ideas instead of having the tutor give us the facts.*

Further, 6 (5%) student teachers also indicated how the learning activities were designed to allow them to decide what and how to learn. They argued that by having access to digital tools, they could review the learning materials and practice the learning tasks ahead of regular class time. This accessibility option enabled students to learn and practice more of the assigned tasks. Excerpts from their responses read,

> *Inquiry learning allows students to learn on their own time so you can have more time to read and practice the assigned tasks.*

> *I feel comfortable learning in the inquiry settings because the learning activities in the videos were captivating which enabled me to prepare better for the topic.*

4. Discussion

This study examines student teachers' perspectives on motivational orientations and learning strategies in a digital IBL chemistry course. Data on student perceptions of the IBL approach were collected through closed and open questionnaires. Findings from the data showed student teachers were motivated and used different learning strategies in the online IBL environment. This shows that the level of motivation students obtain determines the amount of effort placed into the learning.

Motivated students go into the classroom with a well-prepared mind, stay focused on the task, take responsibility for their learning, perform tasks on time, and deal with challenges. Some studies have argued that inquiry-based learning enhances students' learning efficiency, motivation, and interest in chemistry concepts [54]. Findings from this study showed that student teachers' higher task value beliefs see the subject matter as very meaningful and helpful. Student teachers' evaluation of the learning activities and tasks was measured by their interest, importance, and usefulness for their learning. They recognized that the learning materials and activities were helpful for their learning because they facilitated their understanding of the content. Most of the student teachers agreed that the video lessons and lectures were very helpful as they enhanced opportunities for individualized learning after reviewing them many times [17]. Similar findings are reported in the literature on how beneficial task value aids students' chemistry learning outcomes [29].

Research shows that students with higher intrinsic goal orientation place more importance on understanding learning tasks [30,55], changing attitudes towards their learning. Students' teachers believed their attitudes towards science learning and their intrinsic goal orientation enhanced their usage of blended learning. Similar findings have reported [40,56] that students' interest in learning science increases when they activate their active participation and maintain their affective enjoyment and cognitive engagement, which enhances their motivation to learn. Evidence shows that students' interest in learning is focused on capturing the cognitive attention that helps them to master science content taught in the classroom [40]. Students' ability to self-regulate their learning activities enables them to progress in their learning. These self-regulatory efforts develop into critical skills that enhanced students learning success [57]. It is therefore important for teachers to help students identify learning goals, needs, and materials and choose appropriate learning strategies to succeed. This indicates that ideas of active learning facilitate and improve a student's motivation to perform better.

Another interesting finding is the way student teachers use their self-efficacy abilities to master the tasks. The student teachers felt that their confidence in their abilities played a significant role in their learning and that they judiciously used the learning technologies and materials. One of the ideas of constructivist learning is for the learner to actively engage and participate in developing independent thinking in the learning process by coherently organizing facts and knowledge. The student teachers' positive thinking on their capabilities of learning the content and achieving success on the tasks enhanced their understanding of the subject matter. They believed that their self-efficacy influenced active participation and engagement, which helped them learn from their peers. Through their higher self-efficacies, they could accept challenging tasks, disregard distractions, control anxieties, and persist until goals were met for successive learning outcomes [58]. A critical characteristic of IBL is allowing students to self-account, make decisions, and feel responsible. This finding is consistent with prior research [59], that giving students such freedom of learning enables them to use their self-efficacy to utilize, set goals for themselves, and learn tasks successfully. This shows that the students improved their self-efficacies by using varied learning activities to manage their anxieties and change challenging situations.

Studies show that thrives in IBL environment through learning collaboration and interactions and discussions with peers and instructors to foster idea-sharing [43,44]. Peer learning and collaboration among students and teachers is supposed to develop when groups are exposed to problem-based learning. An interesting finding is that some students indicated that they could collaborate well with peers when discussing ideas systematically or managing aspects of their group work that interfered with the scientific content. Through active collaborative learning strategies, student teachers discussed problem-solving activities involving analyzing, synthesizing, and drawing conclusions. The findings show that digital integration in IBL enabled students to collaborate, interact, and explore information for knowledge construction and application [41]. Through the learning activities, student teachers were more engaged in activities to dialogue and brainstorm and clarify course materials. They felt that through the collaborative learning discourse with peers and sometimes teachers, they were enabled to reach insights that they may not have attained on their own. These situations enhanced their learning and thinking skills from the kind of support given by peers and instructors [17]. Again, students engaging in active learning activities were motivated to seek and understand new knowledge through learning collaborations to find solutions [23,49] and integrate new knowledge [60]. This shows that students' motivation promotes their active engagement to use varied learning styles when participating in an IBL class.

Another interesting finding in this study was students' ability to use cognitive and metacognitive strategies such as elaboration to construct new knowledge. Lynch [61] emphasized that individuals' beliefs in their abilities to elaborate and organize their tasks with peers for support enhances the development of critical thinking to be able to succeed in a course. Students' prior knowledge helped manage ideas by enabling them to connect prior knowledge and previous experiences to build new knowledge which served as the basis for subsequent learning. Since the student teachers came to class with some knowledge from the pre-class activities, they had opportunities to participate in discussions. This finding indicate that students had an opportunity to engage in individualized learning at their own pace and review pre-learning materials [17]. Studies show that when learners are engaged in inquiry-based activities several times, their reasoning about scientific phenomena changes through an inductive learning process [44]. This indicates that students' prior knowledge of a subject is critical and that instructors should identify and build on it to enhance the construction of new knowledge. Therefore, educators are encouraged to provide students with high-quality pre-class learning materials to support their learning sufficiently.

Learning science through inquiry is different in that it demands high active participation, intellectual effort, and personal responsibility from students to self-direct their learning [34,36,62]. Inquiry learning allow students to ask questions that have the potential to direct the learning for knowledge construction either through debate or discussion to help evaluate their understanding [63]. Miller et al. [64] assert that when students investigate and organize knowledge themselves, they better understand the knowledge built around them. This indicates that students higher cognitive questioning ability are essential in developing their critical thinking and problem solving since they can be used to diagnose students' understanding of the subject matter, which can be an improvement for future instructions. The choice of instructional pedagogical practice is motivated by specific intent. Using inquiry-based instructional approaches enables teachers to meet the diverse needs of students based on their cognitive levels [23,60]. Within an inquiry classroom, students ask questions, design investigations, collect data, and draw conclusions based on their investigation. In this study, the teacher facilitated the learning process by instructing students to use prior knowledge to construct new knowledge leading to the development of thinking skills. This suggests that to orient students towards inquiry, teachers need to guide students to develop the required skills to engage in scientific inquiry [42]. Therefore, the teacher becomes a facilitator, creating the necessary opportunities for students to learn effectively.

Educators use varied teaching strategies and aids in engaging students to learn as a way of motivating them. Teachers use motivation and engagement to help students learn science to improve their scientific skills. In the IBL environment, teachers guide students in organizing information and facts, assemble experiment results, and make reasonable claims and conclusions based on the data collected. Some studies have acknowledged that educators engaging in students' learning activities, technological tools, and interactions enhance students' success [65]. It is argued that teachers' active role in supporting students in using technology and participating in the classroom empowers and makes students develop positive attitudes by taking responsibility towards learning [32,33]. Similarly, other studies have reported that teachers' presence in an online learning environment motivates and provides intensive guidance and feedback to students to learn and accomplish tasks [35]. Student teachers felt that receiving positive feedback from educators when they experienced challenging situations helped them use their skills and capabilities to manage and overcome their anxieties. Similar findings were found [22,35,36] explaining that the vital role of teachers' provision of appropriate feedback facilitates students' learning progress to self-direct and elaborate their learning.

In addition, students' active engagement and learning occur when they develop knowledge through concept building and reflections on the discourse positively impacts their learning [66]. Positive learning engagements provide a good connection between students' prior knowledge, interests, and science learning experiences. Student teachers felt the flexible learning opportunities provided a strong foundation for students and teachers to participate in meaningful class discussions. By so doing, they could ask questions that connected what they learned and how to apply it. The student teachers had the opportunity to watch the videos more than once, provided many contributed to their understanding of the content as they could pause and reflect on their ideas. Aidoo et al. [17] argues that engaging students with digital inquiry learning provides opportunities of learning flexibilities which makes them active learners as they can take control of their learning at their own convenience. With flexible learning allowances, learners' can review learning activities and generate high-level factual questions from their prior knowledge. Consequently, teachers should provide opportunities for students to activate prior knowledge from learning experiences to make relevant connections with new information [33]. These findings are based on previous studies emphasizing the usefulness of high-quality prior learning activities and materials, e.g., videos for students' learning success [66,67]. This suggests that the effective use of an inquiry-based approach by students requires adequate knowledge and experience.

5. Conclusions and Recommendation

In conclusion, this study has indicated the importance of using different motivational and learning strategies to support students' chemistry learning in the IBL context. The descriptive analysis of this study shows the benefits of IBL in chemistry education and teacher training. This study has limitations in that it was conducted in only three sites, and the sample size does not represent most of the teacher education institutions in Ghana. Therefore, further research is recommended to investigate the effects of motivation and learning styles on students' chemistry learning. Such findings could provide comprehensive information on how motivational orientation and learning strategies influence students' chemistry learning.

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Article

Problem-Based Learning as a Strategy for Teaching Physics in Technical–Professional Higher Education: A Case Study in Chile

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Abstract

This study examines the implementation of problem-based learning in the teaching of physics within the context of technical–professional higher education in Chile. The research aimed to evaluate meaningful learning, competency development, and student satisfaction. The study involved 122 first-year students enrolled in technical programmes related to the field of mechanics. The findings revealed significant improvements in both conceptual and propositional learning, as well as in the development of technical competencies such as problem-solving, information selection, and teamwork. Additionally, high levels of student satisfaction were observed, indicating that problem-based learning not only enhances learning but also fosters greater engagement and motivation among students. These results highlight the potential of problem-based learning to transform the teaching of physics in technical–professional higher education settings, aligning academic content with practical applications and providing students with relevant and high-quality education.

Keywords: problem-based learning; technical–professional higher education; physics teaching

1. Introduction

In Chile, technical–professional higher education is provided both at universities and at institutions exclusively dedicated to technical programmes, such as professional institutes and technical training centres. This type of education trains highly skilled professionals, whose contribution is vital for strengthening the productive sector and promoting the sustainable development of the country. As argued by Wheelahan and Moodie (2024), these institutions are fundamental for fostering collective capabilities and promoting inclusive development, becoming essential local actors for regional progress. From the perspective of institutional logics, these organisations face educational and productive challenges defined by three main orders: the state, the market, and the professions (Zoellner, 2024). In this context, the state ensures equitable access to education, the market demands competencies aligned with productive needs, and the professions require standards that ensure quality and legitimacy.

In terms of structure, although these programmes share a competency-based approach and an average duration of four to five semesters, they differ according to the type of institution that delivers them. Technical training centres and professional institutes are

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exclusively dedicated to technical–professional education, whereas universities combine this offering with undergraduate, postgraduate, and research programmes. From a social perspective, this educational modality plays a key role in ensuring access to higher education for students from socio-economically vulnerable backgrounds, due to its largely non-selective nature, which reinforces its function as an instrument of equity and social mobility (Esmar & Poo, 2022).

With a focus on short-cycle programmes oriented towards the productive sector, technical–professional higher education facilitates early entry into the labour market, particularly for students belonging to the lowest income quintiles. In fact, 71% of these students are the first in their families to access higher education, and 76% belong to the three lowest household income quintiles (Ministerio de Desarrollo Social y Familia, 2024).

Physics courses are typically offered in the early semesters of technical programmes, especially in disciplines such as mechanics, construction, design, and technology. Subjects like applied physics, mechanical physics, or principles of physics form the foundation for understanding and solving problems specific to these technical specialisations. However, Chilean secondary education student performance in science subjects has historically been low, as evidenced by national and international standardised tests. For example, the results of the 2018 PISA test showed that Chilean students scored below the OECD average in scientific competencies, with a significant proportion performing below Level 2, considered basic (Ministerio de Educación de Chile, 2019). These challenges are more pronounced among students from low- and middle-income socioeconomic backgrounds, with a steady decline in performance since 2012. Similarly, the results of the 2021 University Transition Test revealed significant disparities between students from public schools and those from private institutions, as well as between students from the humanities–scientific track and those from the technical–professional track (Subsecretaría de Educación Superior, 2021). These disparities pose significant challenges to the education system and directly impact higher education outcomes.

In addition to these issues, there is a need to foster active learning in technical training to develop essential skills such as critical thinking, problem-solving, planning, teamwork, and action (Subsecretaría de Educación Superior, 2023). Competence-based education prioritises developing skills like problem-solving, teamwork, and information management (Ministerio de Educación de Chile, 2017). However, these competencies, which are essential for technical professionals, are not always effectively developed through traditional methodologies, underscoring the importance of implementing active learning methodologies.

Active methodologies have gained prominence in higher education, as demonstrated by a Scopus database search, conducted by the authors, using the keywords ‘Active’, ‘Learning’, and ‘University’. This search, limited to open access articles, identified 297 articles published in 2024 that included these terms in their titles, abstracts, or keywords. Moreover, a growing trend in publications was observed from 2019 to 2023 for this search.

Problem-based learning is an active methodology proven effective in developing skills and attitudes (Gil-Galván et al., 2020). Studies have shown that students perceive problem-based learning as a motivating tool that facilitates the construction and integration of knowledge more effectively than traditional methodologies (Alreshidi & Lally, 2024; Delgado Trujillo & de Justo Moscardó, 2018; Gil-Galván et al., 2020). It has been associated with improved academic performance and higher student satisfaction rates (Rodríguez & Fernández-Batanero, 2017). Furthermore, problem-based learning promotes transversal competencies such as teamwork, critical thinking, and autonomous learning, which are crucial for future professional careers (Sepúlveda et al., 2021; Urrutia-Heinz et al., 2020).

Despite the growing interest in problem-based learning, its impact on physics teaching within technical–professional higher education remains under-researched. Most published studies have focused on other disciplines or educational levels, leaving a gap in understanding how this methodology can transform physics teaching in technical settings. A search in the Scopus database, using the keywords 'active', 'learning', 'university', and 'physics', identified 28 open access articles published between 2019 and 2024. Of these, 16 focused on university students, covering areas such as engineering education (three articles), basic sciences (two), introductory physics (six), and STEM degrees, health sciences, architecture, and technology (five). Additionally, four articles addressed secondary education research, and four studies analysed the preparation of future teachers and university lecturers. Some articles also explored mixed contexts, such as undergraduate physics students and secondary education (one) or university degrees in architecture and engineering (one). Finally, two studies focused on specific technical disciplines, such as chemistry and environmental physiology. These findings highlight the need to further explore the impact of problem-based learning on physics teaching in technical–professional education, thereby contributing to the development of knowledge in this specific area.

This study therefore seeks to contribute empirical evidence on the potential of problem-based learning to improve physics education in technical–professional contexts, and aims to address this gap by answering the following research questions: (1) How does the problem-based learning methodology impact students' conceptual and propositional learning in physics teaching within technical–professional education in Chile? (2) In what ways does problem-based learning contribute to the development of transversal competencies, such as problem-solving, information management, and teamwork, among students in technical–professional programmes? (3) What is the level of student satisfaction with the problem-based learning methodology, and how do they perceive its impact on their motivation and academic engagement? (4) What evidence exists that problem-based learning can enhance meaningful learning in the technical–professional context by aligning academic content with practical applications?

These questions are grounded in a constructivist perspective of learning and seek to evaluate the pedagogical potential of problem-based learning within the framework of meaningful learning.

2. Theoretical Framework

Building on the issues raised in the introduction and aiming to address the research questions outlined, this theoretical framework presents the conceptual and empirical foundations underpinning the use of problem-based learning in the teaching of physics within technical–professional higher education. It draws upon theories of meaningful learning and constructivist pedagogy to justify the selected methodological approach.

2.1. Physics Education in Technical–Professional Higher Education Training and Meaningful Learning

In the context of technical university education, it is essential to move beyond traditional approaches that limit students to specific occupational roles. As Höhns (2022) points out, it is necessary to promote an education that connects academic content with practical applications, enabling students to develop broader and more relevant perspectives for their professional future. In this regard, preparing students with the competencies required to face the challenges of a constantly changing productive and technological environment, as well as the need for continuous learning, necessitates the promotion of meaningful learning. This type of learning, as described by Ausubel et al. (1983), is characterised by the integration of new knowledge into existing cognitive structures, facilitating students' contextual application of what they have learned and enabling the resolution of discipline-specific problems. In technical–professional higher education training, the study of topics such as kinematics and dynamics is fundamental for fields like mechanics and construction. Physics courses in technical higher education typically address concepts like time, distance, measurements, vectors, velocity, motion, Newton's laws, equilibrium, and energy. These contents are not only foundational for understanding classical physics principles but also have direct applications in technical specialties, such as metrology, thermal machinery operations, structural design, and the understanding of mechanical systems involving movement and forces in machinery and constructions, among others.

However, students often face difficulties in learning these topics due to preconceived misconceptions, such as the direct association between force and motion or the confusion between velocity and acceleration, as noted by Pozo and Gómez (1998). These preconceived notions, widely studied and common in everyday life, often misalign with scientific principles, creating significant barriers to understanding physics. According to Wandersee et al. (1994), as cited by Mufit et al. (2018), misconceptions occur across all areas of physics and at various educational levels. This is consistent with the findings of Guerra-Reyes et al. (2024), who highlight that these misconceptions hinder the development of critical thinking and logical–mathematical reasoning in disciplines such as physics, particularly in complex topics like kinematics, dynamics, and thermodynamics.

From Ausubel's perspective, meaningful learning occurs when students connect new ideas with prior knowledge in a non-arbitrary and substantial way (Ausubel et al., 1983). To achieve this, educational materials must logically relate to the student's cognitive structure, and pedagogical strategies should facilitate this connection. Prior organisers and carefully selected materials can promote long-term retention and facilitate the practical application of concepts in situations relevant to their technical specialties.

According to Ausubel, meaningful learning manifests in three forms: representational, conceptual, and propositional. Representational learning involves assigning meaning to symbols and basic concepts, serving as the foundation for more complex learning. Conceptual learning integrates new concepts with prior knowledge, enhancing understanding and application. Finally, propositional learning focuses on linking new propositions to existing cognitive structures, enabling problem-solving. When achieved through discovery, this type of learning allows students to generate meaningful propositions derived from posed problems, contributing not only to the understanding of concepts but also to transforming them into new propositions that are significant for problem-solving. In technical–professional training, this approach aids in developing key competencies, such as problem-solving and the contextualised application of knowledge, aligning with the objectives outlined in the Chilean Technical–Professional Qualification Framework, which emphasises preparing students to face labour market challenges (Ministerio de Educación de Chile, 2020).

2.2. Problem-Based Learning

Problem-based learning has proven to be an effective methodology for enhancing conceptual understanding of physics (Kanyesigye et al., 2022; Mrani et al., 2020; Sulaiman et al., 2024), as well as for developing essential skills such as critical thinking, communication, and teamwork (Hastuti et al., 2024; Kurniawan et al., 2024; Ndiung & Menggo, 2024; Suprapto et al., 2024). This active methodology focuses on students who are presented with problems that lack a single solution, encouraging them to solve these in groups under the guidance of a tutor acting as a facilitator rather than a primary knowledge transmitter (Morales Bueno & Landa Fitzgerald, 2004).

Problem-based learning originated in medical education during the 1960s but has evolved into a pedagogical approach with broader epistemological foundations. Savin-Baden and Major (2004) highlight that problem-based learning is not only a didactic methodology but also a situated practice grounded in constructivist and postmodern perspectives. This approach promotes the active construction of knowledge around authentic problems, with the student playing a central role as a reflective and autonomous subject. Furthermore, its expansion has coincided with a structural transformation in higher education, characterised by increased student diversity and a growing demand for flexible and contextualised approaches. In this context, problem-based learning represents not only a methodological innovation but also a response to new ways of conceptualising learning, teaching, and the relationships between university, society, and industry (Savin-Baden & Major, 2004).

Its benefits include increased motivation (Bruna et al., 2019), deeper learning, and improved attitudes towards studying (Alreshidi & Lally, 2024; Pu et al., 2019), as well as enhanced confidence, a sense of responsibility, and interpersonal skills (Ndiung & Menggo, 2024). By working on real-world problems, students experience learning that is more connected to professional reality, which increases their motivation by helping them understand the relevance of their future work (González Javier et al., 2009). Furthermore, problem-based learning fosters critical thinking through the continuous analysis of information (Suprapto et al., 2024), and develops essential skills for identifying and solving problems, providing significant opportunities for creativity (Escribano & Del Valle, 2008), active participation, and peer interaction (Kurniawan et al., 2024).

In addition to fostering the learning of disciplinary content, problem-based learning also promotes essential interpersonal skills, such as cooperation and effective communication. From a constructivist perspective, group work constitutes not only a means but also an object of learning. As Walsh (2005) argues, group development in problem-based learning progresses through various stages—formation, conflict, norming, and performing—which require reflective intervention by the tutor to facilitate cohesion, trust, and peer learning. This approach allows collaborative work to be understood not merely as an external condition, but as a critical pedagogical dimension that directly influences the quality of the learning constructed.

From a pedagogical standpoint, problem-based learning promotes the socially mediated construction of knowledge. Boud and Feletti (1997) emphasise that the principle of articulation implies that students must explain and share their learning with their peers, fostering collective understanding and strengthening cooperation. This interaction not only deepens learning but also facilitates the development of communication and collaborative skills, which are essential in technical and professional contexts.

Nguyen et al. (2024) highlight that the effective implementation of problem-based learning requires strategic curricular planning that considers both the design of authentic problems and the alignment of teaching materials and assessment. These aspects are fundamental to ensuring that this methodology has a significant impact on the development of key competencies in students.

In general, the problem-based learning workflow begins with recognising the topic, followed by problem formulation, supervision, monitoring, and presentation of results (Morales Bueno & Landa Fitzgerald, 2004; Varela-Guntiñas, 2016). In this context, the introduction of brief assessments before the reporting phase can be an effective strategy to improve academic performance, as it fosters self-directed learning and prepares students for more productive discussions (Bestetti et al., 2017). Assessment integrates both learning outcomes and the skills and attitudes acquired during the process, utilising various formats (Gutiérrez Ávila et al., 2012).

From a contemporary perspective, assessment in the context of problem-based learning should not focus solely on academic outcomes, but rather incorporate the analysis of processes, critical reflection, and active student participation. Moore and Poikela (2011) propose a typology comprising three fundamental purposes of assessment in problem-based learning: assessment for accountability (aimed at measuring outcomes and efficiency), assessment for development (focused on providing useful information to improve practice), and assessment for knowledge (intended to generate deep understanding of learning or change management). In particular, developmental assessment, which is formative in nature, seeks the continuous improvement in teaching and learning processes, emphasising the quality of the educational environment and the student experience. This perspective encourages the use of participatory strategies such as self-assessment and peer assessment, which strengthen the ownership of the learning process by those involved. In line with this approach, the present study incorporated specific rubrics to assess the process of problem-solving and collaborative work, enabling the analysis of dimensions such as problem understanding, information management, and group interaction.

Despite its benefits, the literature also points out certain challenges, such as unequal group work (Cujba & Pifarré, 2024), variations in how faculty perceive their role as facilitators—which can significantly differ between experienced and less-prepared teachers, affecting the effectiveness of the learning process (Sunarno et al., 2024)—and issues in peer evaluation and self-assessment, especially when students lack experience or an understanding of their importance. Additionally, there are persistent barriers such as rigid curricula and a culture more focused on content than methodologies, which can create resistance to change (Escribano & Del Valle, 2008). Moreover, its implementation may limit the amount of content covered, making it necessary to design problems that guide learning (Marcinauskas et al., 2024).

Despite the demonstrated benefits of problem-based learning, limited research has explored its integration into technical–professional physics education—particularly from the perspective of meaningful learning. This study therefore seeks to contribute to filling this gap by providing empirical evidence in this specific context.

Problem-based learning has a set of characteristics that promote meaningful learning, as it is based on constructivist philosophy. This methodology assumes that each student constructs their own knowledge by using relevant, carefully designed materials and drawing on prior experience to exchange initial ideas with peers or the teacher. A correspondence is presented in Table 1.

Table 1. Correspondence between meaningful learning and problem-based learning.

Meaningful Learning (Ausubel's Theory)	Problem-Based Learning	Description
Integration of prior knowledge	Activation of prior knowledge through the problem	The significant problem facilitates the connection with prior knowledge, allowing students to anchor new concepts into their cognitive structure.
Relevant material connected to prior experience	Real and contextualised problem	Contributes to the student's education, not only in their area of specialisation but also in the development of skills relevant to the academic environment.
Structured and non-arbitrary learning	Structured development of investigation and solution of the problem	The process follows guided steps that help orient students and provide continuous feedback.
Long-term learning (retention and future application)	Synthesis and presentation of the final response	The final presentation serves as a synthesis of learning, facilitating retention and the application of knowledge in future contexts.

In summary, the theoretical foundations of this study lie in the constructivist paradigm and the principles of meaningful learning, with problem-based learning serving as a pedagogical strategy aligned with these principles. The coherence between the theoretical foundations and the research design supports a rigorous analysis of students' conceptual and propositional understanding, transversal competency development, and satisfaction. These theoretical underpinnings directly inform the research questions posed and guide the selection of instruments and procedures, ensuring that the evaluation captures the multidimensional nature of learning in technical–professional physics education.

This theoretical grounding is further operationalised in the Methodological Section through the design of rubrics and data collection tools aligned with the dimensions of meaningful learning and collaborative problem-solving.

3. Materials and Methods

This section presents the methodology designed to address the four research questions related to the impact of problem-based learning on (1) conceptual and propositional learning, (2) the development of transversal competencies, (3) students' satisfaction, and (4) the potential for meaningful learning through real-world problem integration.

3.1. Sample

This study targeted first-year students enrolled in the subject 'Introduction to Physics' at a technical–professional higher education institution in Chile during the 2022 academic year. The sample consisted of students from three sections of the course, selected from a total of seven sections offered by the university in technical programmes in the field of mechanics.

This subject is taught in the first semester of a total of four semesters that constitute the duration of the programmes and does not require prior coursework as a prerequisite. A total of 122 students participated, of whom 38 were enrolled in the University Technician in Industrial Mechanics programme and 84 in the University Technician in Mining and Metallurgy programme.

The participants were selected based on their direct admission from secondary education, without additional entrance examinations, ensuring a sample representative of the typical demographics of students in these programmes. The sample included 112 men and 10 women, aged between 18 and 29, reflecting the gender distribution commonly observed in technical–professional fields related to mechanics and mining in Chile.

3.2. Design

The activities associated with problem-based learning were carried out over five weeks, comprising two weekly in-person sessions of 3.5 h and one independent study session of 1.75 h outside the classroom.

The statements of Problems 1 and 2 included in this study are the same as those given to the students. They were originally written in Spanish and subsequently translated into English for the manuscript. During a previous round of review, based on comments from other reviewers, minor adjustments were made to the English version to enhance clarity, while preserving the original pedagogical content.

A limited but meaningful implementation of problem-based learning was conducted in order to allow for an in-depth observation of the effects of this methodology on conceptual learning, problem-solving, and collaborative work.

The problems used in the intervention were selected based on the contents of the course syllabus, with the aim of ensuring alignment with the intended learning objectives.

They were validated through expert judgement, which assessed their relevance, clarity, and conceptual coherence.

The problems were presented to students within a structured learning sequence that included preparatory readings and guiding questions designed to activate prior knowledge and promote critical reflection. The use of a Formula 1 car in Problem 1 was intended to present a familiar and engaging scenario for the students, stimulating their motivation. The activity required students to select a real video, analyse the observed motion of the car, extract relevant data, construct tables and graphs, and finally interpret the results—thus promoting active, contextualised, and meaningful learning.

In Problem 2, students were invited to contrast Aristotle's historical explanation of falling bodies with the current scientific view, in order to highlight the evolution of scientific knowledge and the importance of using measuring instruments, which are an essential component of technical practice. The aim of this problem was not to approach the phenomenon from Aristotle's model, but to foster critical reflection on the evolution of scientific knowledge. The comparison between Aristotle's explanation and the modern scientific view enabled students to distinguish intuitive or common-sense reasoning from reasoning based on empirical evidence and measurement tools, thereby strengthening their scientific reasoning.

Students' teamwork was monitored by the lead researcher during the in-person sessions. Furthermore, the overall instructional plan included a weekly sequence outlining the tasks to be completed both inside and outside the classroom, along with specific guidance for independent study. The main form of feedback was provided during the process evaluations, through the use of predefined rubrics.

The main activities included the following:

- Initial Diagnosis: Application of a pretest to evaluate prior knowledge.
- Problem Development:

Problem 1: Construct graphs to describe the motion of a Formula 1 car over a time interval during which it undergoes uniformly accelerated rectilinear motion.

Problem 2: Aristotle once proposed an explanation for the falling of objects. What is the current scientific explanation? What information is available today that was not in Aristotle's time?

- Final Evaluation: Application of a post-test and a student satisfaction survey.

The partial implementation of problem-based learning was chosen to ensure feasibility within the course's institutional and curricular structure. This approach enabled a focused evaluation of its pedagogical effects while maintaining alignment with other course components, thereby facilitating comparison and integration within the broader instructional framework.

3.3. Procedure

At the beginning of the semester, students were informed that they would participate in a pedagogical intervention based on active methodologies, integrated into the regular development of the course. It was clarified that the results would be analysed anonymously, without any association with names or personal data. During an introductory session, the course syllabus was presented, including the general schedule, contents, assessment activities, and key dates. One session was specifically dedicated to introducing the problem-based learning methodology, its objectives, general structure, and expected forms of active participation. Brief examples of similar problems were provided, and the steps of the problem-solving process were explained.

The intervention was led by the first author, who assumed the role of learning facilitator: promoting collaborative work, posing open-ended questions, and offering formative feedback without giving direct answers. The same person was responsible for assessing the students using pre-defined rubrics. Throughout the intervention, the institutional Moodle platform served as the main support space. It hosted problem statements, rubrics, Supplementary Materials, and enabled submission of intermediate and final group work. No specialised digital tools for problem-solving in physics were used, as the focus was on conceptual argumentation and teamwork.

The results presented are derived from three parts, each with a different methodological focus:

(1) Evaluation of Learning Achieved: To analyse the impact of the educational intervention, a pre-experimental design complemented by a descriptive analysis of the results was used. Changes in learning were measured by comparing the results obtained in a pretest and a post-test, applied before and after the intervention.

Analysis of the Development of Transversal Competencies: The development of competencies such as problem-solving, teamwork, and the use and identification of information was evaluated. This analysis was carried out through the application of specific rubrics designed to measure both the acquisition and application of these competencies within the context of problem-based learning.

Determination of Satisfaction Levels: To evaluate the level of student satisfaction with the Problem-Based Learning methodology, an exploratory descriptive study of a non-experimental quantitative type was implemented. This analysis was based on a survey that covered dimensions such as academic experience, proposed didactics, and teaching practice using an initial satisfaction questionnaire consisting of 23 questions.

Given the specific focus of this study, a subset of 14 questions considered most representative and relevant to the objectives was selected.

3.4. Evaluation Instruments

The evaluation events, the instruments used, the applied methodologies, and the expected outcomes are summarised in Table 2 below.

Table 2. Evaluation instruments and associated competencies.

Information	Instrument	Method	Expected Outcome	Evaluated Competencies
Diagnosis (Pretest)	Questionnaire	Questionnaire	Determine students' prior learning in terms of conceptual and propositional knowledge.	Scientific and mathematical reasoning and problem-solving
Problem Process (1 and 2)	Rubric	Group work	Evaluate and provide feedback on group processes during problem-solving.	Problem-solving, information management, teamwork
Problem 1	Rubric	Group work	Evaluate learning achieved through problem-solving.	Problem-solving, information management, teamwork
Problem 2	Rubric	Group work	Evaluate learning achieved through problem-solving.	Problem-solving, information management, teamwork
Post-test	Questionnaire	Questionnaire	Determine students' learning outcomes in terms of conceptual and propositional knowledge.	Scientific and mathematical reasoning and problem-solving
Survey	Likert scale	Survey	Assess whether the methodology was well-received by students.	Collaborative work

Each instrument was aligned with a specific research question: the pretest and post-test targeted conceptual and propositional learning (RQ1), the rubrics assessed transversal competencies such as problem-solving and teamwork (RQ2), and the student satisfaction survey explored perceptions of motivation and engagement (RQ3). Additionally, the integration of real-world problems sought to evaluate the potential for meaningful learning through practical application (RQ4).

3.5. Details of the Evaluation Instruments

(1) Pretest and Post-Test:

To evaluate the prior and final knowledge of students, a specific instrument was designed for this research. The pretest and post-test included 23 questions related to kinematics and dynamics content based on the Introduction to Physics course syllabus. These were divided into two main categories: (1) Conceptual learning: Understanding fundamental concepts such as measurement systems and equivalences, and (2) Propositional learning: Solving practical problems and analysing graphs. Although the pretest and post-test included multiple-choice and short-answer questions, commonly found in traditional assessments, the items were contextualised to reflect real-world applications and aligned with the conceptual areas addressed during the intervention. For example, students were asked to convert units using authentic examples (e.g., converting inches to metres), interpret physical graphs related to motion, apply vector addition, estimate measurement errors, and explain scientific principles such as gravitational acceleration or equilibrium using diagrams. This contextualisation was intended to foster transfer of learning and applied reasoning.

Sample questions included:

What measurement systems do you know for measuring length?

Consider the equivalence: 1 m = 39.37 inches. How many metres equal 520 inches?

In uniformly accelerated rectilinear motion, which of the following X(t) graphs best represents position as a function of time?

The instrument was validated through expert judgment, who assessed each item in terms of validity, clarity, and relevance, obtaining an average content validity coefficient of 0.91. Subsequently, Cronbach's alpha coefficient was calculated, yielding values of 0.84 for the pretest and 0.91 for the post-test, confirming high internal consistency for both applications.

The pretest results informed the planning of activities. Specifically, prior organisers, such as text readings, video viewing, and group activities, were employed to reinforce initial concepts and guide students toward key topics.

Evaluation of Problem 1 and Problem 2 Processes:

A single process evaluation rubric was designed based on five key dimensions: (1) Understanding the problem/project, (2) Identification and selection of information and tools, (3) Recognition of methods or strategies, (4) Proposing relevant solutions, (5) Collaborative work. Each dimension included specific indicators describing performance across four levels, scored from 0 to 3 points, where 0 indicated insufficient performance and 3 indicated outstanding performance. For example, in 'Understanding the problem/project', the highest level (3 points) was achieved when the group fully understood and addressed the problem in its context, while the lowest level (0 points) indicated a lack of understanding or inappropriate addressing of the problem.

The rubric was validated by expert judgment for validity, clarity, relevance, and coverage, obtaining average scores of 4.33 or higher on a 5-point scale. Expert recommendations were incorporated into the final version of the rubric.

Final Evaluation of Problem 1:

A final rubric based on four key dimensions was designed: (1) Use of information, (2) Identification of motion variables, (3) Motion evaluation, (4) Collaborative work.

The rubric followed the same scoring criteria as the process rubric and was validated similarly.

Final Evaluation of Problem 2:

This rubric also included four dimensions: (1) Use of information, (2) Identification of differences in explanations, (3) Accurate evaluation of information, (4) Collaborative work.

Expert validation yielded high average scores, with recommendations incorporated into the final rubric.

Satisfaction Survey:

To analyse student satisfaction with the implemented methodology, a 5-point Likert-type questionnaire was used, with responses ranging from 'strongly disagree' (0 points) to 'strongly agree' (4 points). The questionnaire included 17 representative questions divided into three main areas: (1) Academic experience, (2) Proposed didactics, (3) Teaching practice.

Expert validation ensured the instrument's validity, clarity, and relevance, with all criteria scoring an average of 4 or higher on a 5-point scale. The final questionnaire had a Cronbach's alpha of 0.98, indicating high internal consistency.

For this article, 14 questions were selected based on their relevance and representativeness regarding the study's objectives, ensuring comprehensive evaluation of the three main dimensions.

The design of the instruments was guided by the theoretical framework, particularly by the dimensions of meaningful learning (conceptual and propositional understanding) and collaborative problem-solving, thus ensuring conceptual alignment across all phases of the study—from data collection to interpretation.

4. Results

This section presents the findings of the study in relation to the four research questions. The results are organised into three subsections: the impact of the intervention on conceptual and propositional learning (RQ1 and RQ4), the development of transversal competencies and group performance during problem-solving (RQ2), and student satisfaction with the implemented methodology (RQ3).

4.1. Impact of Problem-Based Learning on Conceptual and Propositional Learning in Technical–Professional Contexts (RQ1 and RQ4)

This subsection addresses RQ1 and RQ4, which focus on the impact of problem-based learning on students' conceptual and propositional learning in physics, as well as on evidence of meaningful learning through the articulation of academic content with practical applications in technical–professional contexts.

The effectiveness of the pedagogical intervention was evaluated through quantitative analysis, employing paired *t*-tests and Wilcoxon signed-rank tests. These statistical methods were chosen to assess changes in learning outcomes before and after the intervention, in line with the objective of quantifying the impact of problem-based learning on students' application and understanding of physics concepts. The paired *t*-test was used to detect significant changes in mean scores, assuming a normal distribution, while the Wilcoxon test addressed any non-normal distribution, ensuring the robustness of the findings.

The results are detailed in Tables 3 and 4. Table 3 presents the initial and final mean scores, along with standard deviations, for both conceptual and propositional learning. Conceptual learning scores increased from an initial mean of 63.88% to a final mean of 81.88%, with a notable reduction in the standard deviation from 23.39 to 10.67. The results for propositional learning showed an even more pronounced improvement, with mean scores rising from 14.93% to 68.53% and a reduction in the standard deviation from 9.65 to 8.74. These results are graphically represented in Figures 1 and 2, illustrating the distribution of scores before and after the intervention.

Table 3. Changes in means and standard deviations of learning.

Category	Initial Mean (%)	Final Mean (%)	Initial Standard Deviation	Final Standard Deviation
Conceptual Learning	63.88	81.88	23.39	10.67
Propositional Learning	14.93	68.53	9.65	8.74

Table 4. Statistical test results.

Category	Statistical Test	t-Value	*p*-Value	Wilcoxon (*p*-Value)
Conceptual Learning	Paired *t*-test	−5.38	0.001	0.007
Propositional Learning	Paired *t*-test	−17.97	0.00001	0.00001

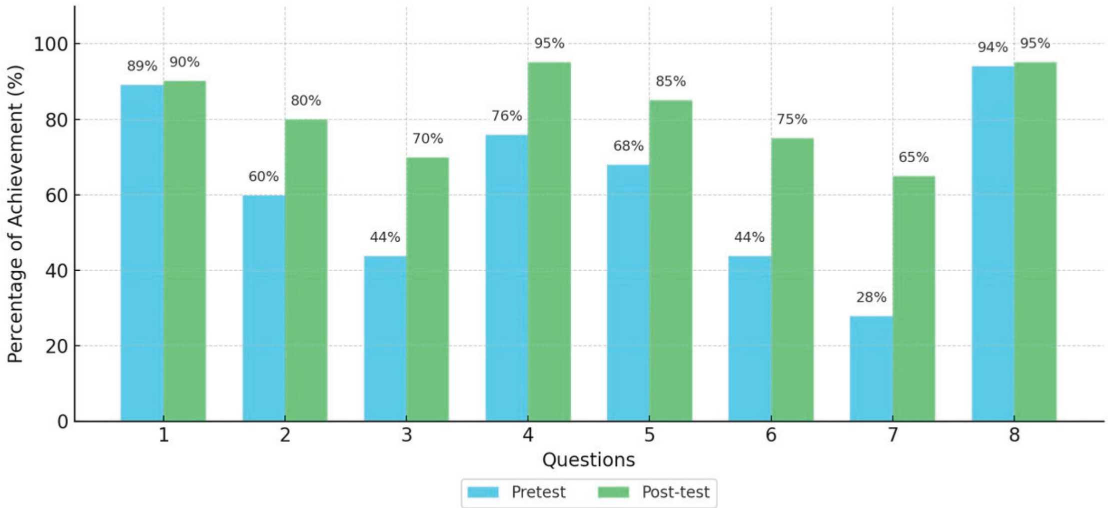

Figure 1. Comparison of pretest and post-test results for conceptual learning.

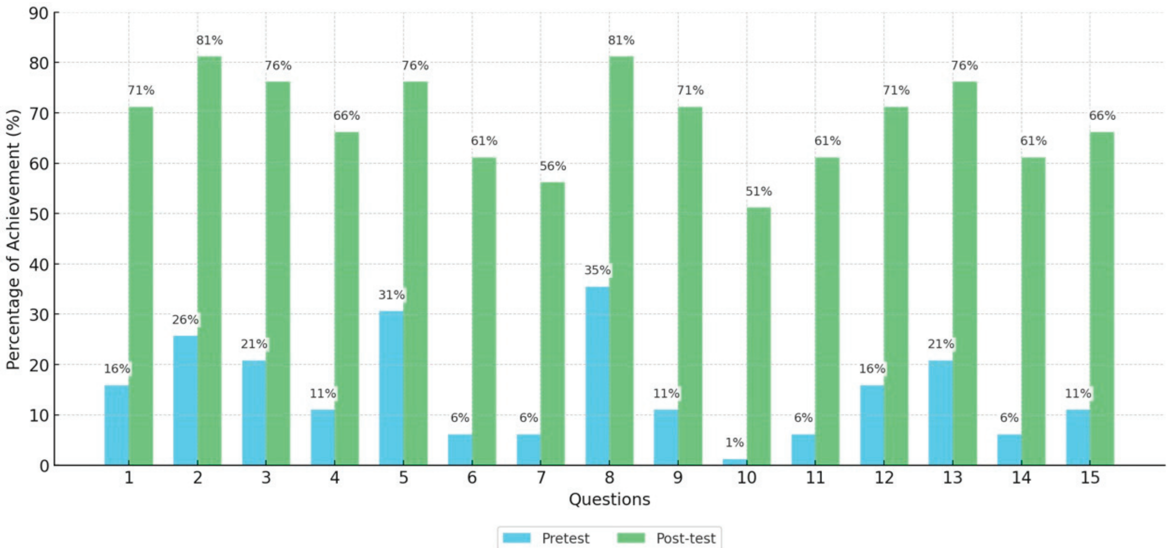

Figure 2. Comparison of pretest and post-test results for propositional learning.

Table 4 presents the results of the statistical tests, showing a t-value of −5.38 and a *p*-value of 0.001 for conceptual learning, and a t-value of −17.09 with a *p*-value of 0.00001 for propositional learning. The Wilcoxon test corroborated these findings, with *p*-values of 0.007 and 0.00001, respectively. These results indicate statistically significant improvements in both types of learning, suggesting that problem-based learning may be effective in strengthening the understanding and application of physics concepts.

These statistically significant improvements provide robust evidence that problem-based learning fosters meaningful learning, both conceptually and propositionally, by enabling students to understand and apply physics content in situations relevant to their technical–professional training.

4.2. Development of Transversal Competencies and Group Performance in Collaborative Problem-Solving (RQ2)

In response to Research Question 2 (RQ2), this section presents the analysis of the development of transversal competencies in the context of collaborative work during the resolution of contextualised physics problems.

Process evaluation of problem 1

Table 5 presents the calculated means for each dimension evaluated during the development of Problem 1.

Table 5. Means by dimension for process evaluation (Problem 1).

Dimension	Problem Understanding	Information Identification and Selection	Method Recognition	Proposing Relevant Solutions	Collaborative Work
Mean	2.45	2.23	2.32	2.23	2.45

Correlation analysis using Pearson's correlation coefficient indicated a strong positive relationship between problem understanding and collaborative work (r = 0.78). This suggests that groups with better problem comprehension tended to work more effectively as a team. Similarly, information identification and selection showed a strong correlation with collaborative work (r = 0.70), reinforcing the idea that effective collaboration enhances the ability to select relevant information and apply appropriate strategies.

Final evaluation of problem 1

As in the process evaluation, Table 6 presents the results, showing the means for each evaluated dimension.

Table 6. Means by dimension for final evaluation (Problem 1).

Dimension	Information Use	Motion Variables Identification	Motion Evaluation	Collaborative Work
Mean	2.19	2.26	2.23	2.37

The findings were consistent with those from the process evaluation, with a strong interrelationship between information use and collaborative work (r = 0.76). These findings highlight the value of the methodology not only in terms of theoretical knowledge acquisition but also in the development of practical skills such as collaboration and problem-solving.

Process evaluation of problem 2

Table 7 shows the means obtained for the dimensions evaluated during the development of Problem 2.

Table 7. Means by dimension for process evaluation (Problem 2).

Dimension	Problem Understanding	Information Identification and Selection	Method Recognition	Proposing Relevant Solutions	Collaborative Work
Mean	2.26	2.03	2.19	2.06	2.29

The analysis of Problem 2 confirmed that better problem understanding is closely related to effective collaborative work (r = 0.74), reinforcing the positive impact of problem-based learning.

Final evaluation of problem 2

Table 8 presents the calculated means for each dimension in the final evaluation of Problem 2.

Table 8. Means by dimension for final evaluation (Problem 2).

Dimension	Information Use	Identifying Differences	Accurate Information Evaluation	Collaborative Work
Mean	2.16	2.13	2.16	2.32

Correlation analysis for Problem 2 revealed a strong relationship between information use and collaborative work (r = 0.75), reinforcing the importance of teamwork for proper information evaluation and management. Similarly, the evaluation of information showed a strong correlation with collaborative work (r = 0.69), suggesting that students who work effectively in groups are better able to apply concepts and critically evaluate available information.

Taken together, the results suggest that collaborative problem-solving within the framework of problem-based learning fosters the development of transversal competencies such as teamwork, critical thinking, and information management. This provides empirical evidence of its relevance in technical–professional education, in line with the constructivist approach that underpins this methodology, whereby knowledge is socially constructed through peer interaction and the resolution of authentic problems (Boud & Feletti, 1997; Morales Bueno & Landa Fitzgerald, 2004).

4.3. Student Satisfaction with the Implemented Problem-Based Learning Methodology (RQ3)

Table 9 presents the average scores for each evaluated item, organised into three dimensions that reflect students' perceptions and overall assessment of the implemented problem-based learning methodology.

In the Academic Experience dimension, students positively valued the methodology's effectiveness in improving learning in physics, although they perceived less novelty in the problem-based approach. This dimension had an average score of 3.5. Regarding Proposed Didactics, students emphasised the clarity of objectives and strategies used, with an overall average of 3.7. Finally, in Teaching Practice, the professor's guidance, ability to maintain group interest, and effective communication were highly rated, achieving an average score of 3.9.

Table 9. Results of the student satisfaction survey on problem-based learning.

Question	Mean
Academic Experience	
1. I find the problem-based approach innovative.	3.1
2. Working with problems/projects contributes to meeting the objectives of the physics course.	3.1
3. Projects improve learning in physics.	3.9
4. Problems contribute to collaborative work.	3.6
5. Problems support future professional development.	3.8
Proposed Didactics	
6. Knowing the objectives before starting the problems was important.	3.9
7. Knowing the work format and times beforehand was important.	3.8
8. Communication among peers was easy.	3.5
9. The material and bibliography available in the virtual classroom helped guide the problem-solving process.	3.8
10. The evaluation method allows understanding the levels of achievement reached by the group.	3.7
Teaching Practice	
11. Formative assessment was constructive and timely for developing the final problem.	3.8
12. The professor's guidance was appropriate for the activity.	3.9
13. The professor maintained our interest throughout the problems.	3.8
14. The professor maintained good communication with students in and out of class.	3.9

A statistical analysis revealed a moderate to strong correlation between the evaluated dimensions, with a Pearson correlation coefficient of 0.61. This value suggests a moderate to strong relationship between the analysed variables, indicating significant associations among the questionnaire areas. These results support the validity and relevance of the instrument for measuring student satisfaction with the implemented methodology.

This finding suggests a consistent pattern in students' responses across the dimensions, reinforcing the instrument's internal coherence and its suitability for assessing satisfaction with the implemented approach.

These findings are consistent with learner-centred pedagogical principles, which emphasise students' motivation, engagement, and autonomy as key components of meaningful learning (Pozo & Gómez, 1998; Ausubel et al., 1983).

5. Discussion and Conclusions

This study was conducted to evaluate the impact of problem-based learning on the teaching of physics in Chile's technical–professional education, a domain that requires the cultivation of both technical and scientific skills. As evidenced in the literature review, this area remains underexplored in terms of pedagogical methodologies for teaching and learning.

Physics teaching is crucial in this type of education, especially in careers in the techno-scientific field that are constantly evolving, requiring learning approaches that equip students to address problems in a dynamic environment. Low academic performance in science, particularly in vulnerable socio-economic contexts, is a pressing issue. Results from standardised and large-scale tests reflect these learning gaps, emphasising the urgency of implementing more active and meaningful pedagogical strategies.

The main objective of this study was to evaluate whether problem-based learning could enhance conceptual and propositional learning and the development of transversal skills and student satisfaction. Through an evaluation designed using a mixed-methods approach that combined quantitative and qualitative methods, the results indicate significant improvements in these areas, along with a high valuation of the implemented methodology.

The results of this study confirm that problem-based learning is an effective methodology for promoting meaningful learning in the teaching of physics, as proposed by constructivist approaches to learning (Freeman et al., 2014; Hernández-Ramos et al., 2021). In terms of conceptual learning, Hernández-Ramos et al. (2021) highlight that PBL fosters conceptual understanding by connecting content to meaningful contexts. Similarly, Freeman et al. (2014) document that active methodologies significantly enhance academic performance, supporting the improvement observed between the pretest and post-test.

Regarding conceptual learning, an average increase of 18% was observed between the pretest and post-test results, representing a statistically significant improvement. This enhancement can be attributed to the constructivist nature of problem-based learning, which facilitates the understanding and application of concepts through active problem-solving.

The results for propositional learning were even more remarkable, with a 53.6% increase. This advance reinforces the idea that this methodology is particularly effective for fostering a deeper understanding of concepts that are often challenging for students. These findings align with previous studies that indicate problem-based learning is superior to traditional approaches in areas where students' misconceptions conflict with correct scientific principles (Morales Bueno & Landa Fitzgerald, 2004; Rodríguez & Fernández-Batanero, 2017).

In terms of the development of transversal skills, such as problem-solving, teamwork, and information selection, significant improvements were also observed. Positive correlations between problem understanding and collaborative work ($r = 0.78$ in Problem 1 and $r = 0.74$ in Problem 2) suggest that deeper problem understanding promotes more effective collaboration. These results align with research demonstrating that this methodology fosters positive interdependence and creates a more dynamic and participatory learning environment (Nguyen et al., 2024). Nevertheless, it is worth stressing that some students were unfamiliar with or lacked prior experience in group work, which could also contribute to the results obtained in this aspect. From a teaching point of view, it is essential to recognise and allow adjustment periods to facilitate group dynamics.

Moreover, the integration of rubrics for process and collaborative work assessment was grounded in the need to promote formative practices consistent with the principles of problem-based learning. Within this pedagogical framework, self-assessment and peer assessment were used as educational strategies that, according to Walsh (2005), encourage students' critical reflection on their own learning and that of their peers, thereby reinforcing both individual and collective responsibility in the learning process. These strategies also enable tutors to collect qualitative insights into group dynamics and to guide responsive interventions as needed.

These results align with the literature that highlights the importance of formative assessment in problem-based learning, particularly in supporting students' metacognitive development and collaboration skills throughout the problem-solving process (Moore & Poikela, 2011; Gutiérrez Ávila et al., 2012).

Another important aspect is student satisfaction. This is a central topic in educational research, as it is closely linked to the quality of learning and academic success. The results of the Likert-scale questionnaire show that students positively valued the methodology, particularly in terms of academic experience and its contribution to improving their learning (mean = 3.9), understanding the proposed didactics, and the instructor's practice. These findings support the idea that problem-based learning not only improves learning outcomes but also increases motivation and engagement among students (Ramos & Condotta, 2024), which is crucial in the technical–professional context, where students tend to be more oriented towards practical rather than theoretical aspects (Lárez Hernández & Jiménez, 2019).

This study seems to show that problem-based learning is an effective pedagogical tool for improving both meaningful learning and competency development in the teaching of physics within technical–professional higher education. The results support that it not only enhances conceptual and propositional learning, but also fosters essential transversal skills for the workplace, such as collaboration and problem-solving.

The implementation of problem-based learning provides an effective solution to the identified challenges by addressing learning gaps among technical–professional education students. Furthermore, high levels of student satisfaction indicate that problem-based learning not only has a positive impact on learning but also increases motivation and engagement as highlighted by Ramos and Condotta (2024), which are essential aspects for the long-term success of these students in a work context that demands practical and collaborative skills (Höhns, 2022).

From a broader perspective, the findings hold significant implications for the teaching of physics and other disciplines within technical and vocational education. Problem-based learning, by linking academic content with practical applications, provides a more relevant education aligned with the demands of the productive environment. These findings align with research that underscores the importance of equitable and authentic assessment practices in vocational education, where transparency and active student participation in the design and implementation of assessments play a central role (Sofía et al., 2022). This suggests that the methodology not only enhances learning outcomes but also better prepares students to face the challenges of the 21st century.

These results suggest that its implementation in technical–professional higher education programmes could be scalable at the national level, allowing for teaching more aligned with the needs of the productive sector. To maximise its impact, it would be advisable to integrate it into science curricula at the technical level, prioritising practical and collaborative training.

However, this study has some limitations that should be considered. The problems used in the intervention focused exclusively on the area of physics, which, although fundamental, limits the scope of the results. Future studies could explore a broader range of topics to evaluate how problem-based learning impacts other areas of learning. Additionally, the intervention period was relatively short, restricting the analysis of long-term effects on learning and competency development. A longer period would provide a more comprehensive perspective on the methodology's impact.

Although the pre-test and post-test assessed learning across the entire course, the instruments were aligned with the core conceptual areas addressed in the problem-based learning activities, which extended over several weeks and constituted a substantial portion of the instructional time. Therefore, although it is not possible to attribute the observed improvements exclusively to problem-based learning, it is likely that this methodology played a significant role in these gains. Future research could deepen this analysis by employing quasi-experimental designs that allow for a more precise isolation of its specific effects. It would also be pertinent to explore the impact of problem-based learning on students' employability and professional performance, providing further evidence of its relevance in technical and productive contexts.

In conclusion, this study provides a foundation for further exploration of active methodologies in technical training, contributing to better preparation, more tools, and a higher-quality, more relevant education for students.

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G.M.A.; supervision, I.M.G. and I.A.; project administration, G.M.A. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Written informed consent was not obtained because all data were anonymised prior to analysis, and thus, the requirement for written consent was waived. However, verbal informed consent was obtained from all participating students before data collection, ensuring their voluntary participation and confidentiality. No identifiable personal data are included in this study; therefore, written informed consent for publication is not applicable.

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Self-Regulation and Teacher Feedback in Problem-Based Learning on the Water Hardness

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Abstract: Problem-Based Learning has been recognized as a fundamental approach in Science Education. Studies show that the success of this approach depends on students' ability to self-regulate their learning and on teacher feedback. However, research on how these aspects interact in formal science teaching contexts remains limited. This study aims to address this gap by investigating two questions: (1) What self-regulation strategies are used by different student groups when solving a problem related to water hardness? (2) How do different types of teacher feedback influence students' problem-solving processes? The study involved 27 students and their Physics and Chemistry teacher. Students participated in an activity that required solving a problem related to water hardness. Data were collected through audio recordings, and the content of the transcriptions was analyzed. The results showed connections between self-regulation strategies and teacher feedback during the problem-solving process. Groups with high participation employed diverse self-regulation strategies, successfully solved the problem, and received varied teacher feedback. The group with the lowest participation received the least feedback from the teacher. Future research should focus on examining how different types of teachers' feedback during specific interventions for less-participative groups influence the development of their self-regulation strategies.

Keywords: problem-based learning; self-regulation; teacher feedback; science education; water hardness

1. Introduction

Over the past three decades, Problem-Based Learning (PBL) has been recognized as an important approach in Science Education (Akcay & Benek, 2024). The literature highlights several benefits of this methodology for students, such as developing critical thinking, decision-making, and communication skills (Hmelo-Silver & Barrows, 2006). When students work in groups, PBL also fosters the development of collaboration skills, idea negotiation, and tolerance (Leite & Afonso, 2001).

Several studies show that engaging students in PBL as a starting point for developing new learning (Leite & Dourado, 2013; Loyens et al., 2008) enables them to exercise their minds and experience a sense of satisfaction from the effort invested in finding solutions (Lambros, 2004). Furthermore, through problem-solving, students learn to reflect and act in challenging situations, applying knowledge that is developed and reinforced during the problem-solving process (Lambros, 2004). During problem-solving, students develop metacognitive skills related to planning, interpretation, reflection, and monitoring (Solaz-Portolés & Lopez, 2007). Throughout this development, new knowledge is incorporated into their cognitive structure and becomes available to address new problem situations, making them more autonomous, active, and creative in decision-making, both in the present and in the future (Lambros, 2004).

The success of PBL depends on students' ability to self-regulate their learning (English & Kitsantas, 2013). In fact, students with higher levels of self-regulation are more efficient at solving problems compared to those with lower levels of self-regulation (Hmelo-Silver, 2004). However, fostering the development of self-regulation processes during problem-solving can be challenging as students do not always understand these processes and often resist reflecting on their learning journey (Loyens et al., 2008). In an initial phase, the teacher may play a more active role, and students may rely more on external feedback from the teacher. Through co-regulation processes, students progressively learn to self-regulate independently by analyzing their own learning processes and making informed decisions (Azevedo et al., 2007; Dignath & Büttner, 2008). Teacher feedback plays an important role in supporting students' self-regulation when they are involved in PBL. This feedback should be adaptive, i.e., it must be adapted to the specific needs of students and groups at various stages of the problem-solving process (van de Pol et al., 2010).

Despite the recognized importance of students' self-regulation processes and teacher feedback in PBL, research on how these elements interact in formal science teaching contexts remains limited. This study aims to contribute to this understanding and address this gap in the literature by investigating the following questions: (1) What self-regulation strategies are used by different student groups when solving a problem related to water hardness? (2) How do different types of teacher feedback influence students' problem-solving processes?

2. Theoretical Framework

The term Problem-Based Learning (PBL) was introduced as an educational methodology at the Faculty of Medicine at McMaster University, Canada, during the 1960s (Barrows & Tamblyn, 1980). However, the theoretical foundations of learning through problems have already been introduced by other authors. For example, Dewey (1938) emphasized the role of problems in learning, highlighting that they create cognitive conflict in learners, allowing for the construction of understanding and serving as a natural organizer of learning processes. Also, Piaget's (1976) constructivist theory is aligned with PBL principles. The author emphasizes how learners actively construct knowledge through experiences that challenge their previous cognitive structures. Vygotsky's (1978) social constructivist view added another dimension to understanding PBL through the concept of the Zone of Proximal Development. According to Vygotsky's perspective, learners, when solving problems in collaborative processes, can achieve better results than they could individually, especially when supported by facilitators (Harland, 2003).

So, building on these theoretical foundations, in the literature, the term "problem" has been widely discussed by various authors (Schoenfeld, 2016; Jonassen, 2011). Among the various definitions, a set of common characteristics related to the individual's reaction to the situation presented can be identified. For example, according to Polya (2003), an individual encounters a problem when they face a question or situation for which they do not have an immediate solution, relying only on the knowledge they have available. Dogru (2008) also argues that a problem is an obstacle that can be overcome by someone with a clear purpose, i.e., is a situation that should present enough complexity to be a challenge but not be so complex that it becomes impossible.

However, it is important to consider that what some perceive as a problem may not be seen in the same way by others. Often, it is unpredictable how a given situation will be viewed by students as this depends on their individual approach, which, in turn, is influenced by their prior knowledge and maturity (Pozo, 1998). Thus, the same situation may be seen as exercise by some and as a problem by others. The distinction is based on the fundamental question of whether there is an immediate process to solve the situation. If the individual knows this process and can apply it, the situation is considered an exercise. Otherwise, it is considered a problem (Ponte, 2005).

Problem-solving in the classroom was first introduced consistently by Polya in 1945 within a mathematical context. Later, it was extended to other fields, including Science Education (Morgado & Leite, 2001). In the past thirty years, numerous studies have been conducted on problem-solving in educational contexts, specifically on students' cognitive processes when engaged with problems (Zimmerman & Schunk, 2011), the strategies students use to solve problems (Hmelo-Silver, 2004), the learning outcomes and skills developed by students (Savery, 2015), and others.

PBL is currently regarded as one of the key approaches to Science Education and is distinguished from other methodologies by its features, such as starting with a carefully designed ill-structured problem (English & Kitsantas, 2013) that is connected to students' everyday lives or simulates a real-world context (Leite & Afonso, 2001). There is no predetermined path for solving the problem, and its resolution is dynamic, allowing students to become accustomed to uncertainty (Qin et al., 1995). The problem serves as a means for students' learning, which they seek to solve in groups, while the teacher assumes the role of facilitator (Gallagher et al., 1995).

Additionally, it is important for students to employ self-regulation strategies when solving problems (English & Kitsantas, 2013). Self-regulated learning can be defined as a complex, multifaceted process involving cognitive, metacognitive, and affective strategies used by students to regulate their own learning (Zimmerman, 2002; Ng et al., 2024). In this constructive and active process, students set goals, monitor, regulate, and control their cognition, motivation, and behavior (Pintrich, 2000). Studies have shown that self-regulated learning plays an important role in students' academic success (Makhno et al., 2022; Park & Kim, 2022) and to develop their ability to solve problems (English & Kitsantas, 2013). For example, a study conducted by Malan et al. (2014) aimed to examine how the introduction of the PBL approach in classes influenced students' self-directed and self-regulated skills. The study involved 35 students and two mathematics and science teachers. The results showed that the PBL approach allowed students to use deep processing learning strategies and metacognitive self-regulation activities, including planning, diagnosing the problem, testing their outcomes, and adjusting and reflecting on their solutions. To achieve this, it was important to expose students to problems related to their interests, promote group work during problem-solving, and encourage the teacher's role as a facilitator of students' learning. Thus, the results of this study also highlight that in the problem-solving process, teacher feedback is fundamental.

According to Black (1998), feedback provided by the teacher should be short-term so that obstacles can be identified and discussed. According to the author, immediate feedback allows students to improve their knowledge and achieve better learning outcomes. Moreover, when feedback is given during activities, when the teacher holds students accountable for their learning process and provides them with adequate time to improve their work, students' satisfaction and motivation for the subject increase, as does their final evaluation (Black et al., 2003). For instance, a study conducted by Hmelo-Silver and Barrows (2006) aimed to examine the strategies used by a facilitator during a student-centered Problem-Based Learning group. The study involved an experienced facilitator and 35 higher education students. The results showed that the facilitator employed several strategies, such as using open-ended and metacognitive questioning, encouraging students' reflection, summarizing, helping students focus their inquiry, checking consensus on whether the whiteboard reflected the discussion, and encouraging the construction of visual representations.

3. Study Context

3.1. Metholodology

This is a qualitative study, adopting an interpretative orientation (Erickson, 1986). Interpretative research is a powerful tool for examining pupils' meaning construction and thinking. This is particularly important within this study as the study was based on a constructivist view of learning that considers that knowledge is constructed by individuals based on their interpretations of experiences and interactions with others (Carlson et al., 2003).

3.2. Participants

This study involved a teacher and 27 students from a school in the Greater Lisbon Metropolitan Area. The teacher holds a degree in Physics and Chemistry education and has twenty-two years of professional teaching experience. The students are from 8th grade and their ages varied between thirteen and fifteen. Of these 27 students, 15 are female, and 12 are male. In general, the students show an interest in Physics and Chemistry and are active participants in the classroom. The students were involved in solving a real-life problem related to water hardness and its influence on the condition of washing machine parts. They worked in groups, forming seven teams (six teams of four students and one team of three students) (Table 1).

Table 1. Teams that developed the learning sequence.

Group	Number of Students	Gender (M/F)
1	4	2 M; 2 F
2	4	2 M; 2 F
3	4	3 M; 1 F
4	4	1 M; 3 F
5	4	1 M; 3 F
6	4	2 M; 2 F
7	3	1 M; 2 F

The groups were organized by the teachers, and this method of working in groups was already familiar to the students.

3.3. The Problem of Water Hardness

The students were involved in an activity that required solving a problem related to water hardness in different regions of the country and the condition of washing machine parts. More specifically, the students were presented with the following context and problem: WashEngineering, a leading company in the manufacturing of washing machines, has hired your team of young scientists to solve a mystery. Identical machines, made on the same date and used with the same frequency, show very different levels of wear depending on the region of Portugal in which they are used. Your mission is to investigate the following question: Why do parts of identical machines degrade differently in various regions of the country? The company's management has also asked you to propose solutions to ensure the durability of the machines in all regions.

To support the students in solving the problem, two tables were provided: one with data on the condition of the machines after 6 years of use in each region of the country and another with the average water hardness by region. They were also allowed to conduct research on the internet. The problem-solving process lasted for a 90 min class. The students had not yet covered the scientific concepts related to water hardness in the classroom, so the problem served as the starting point for developing learning about this topic.

3.4. Data Collection and Analysis

The data collected through audio recordings took place in each of the working groups while they were solving the problem. As Patton (1990) describes, such recordings are important instruments when conducting qualitative research. During the group work, students engaged in group interactions and used self-regulation strategies to solve the problem. The teacher also interacted with the different groups, providing feedback. These recorded conversations served as an important data source for addressing research questions (Carlson et al., 2003). The study collected seven audio recordings in total, one from each working group. The researcher fully transcribed these recordings and analyzed their content (Cohen et al., 2007). Specifically, the method of constant questioning and comparison was used. According to Strauss and Corbin (1998), this method is an analytical process used to stimulate thinking about the properties and dimensions of categories. So, this method was used to code and categorize the data. For analyzing data concerning students' self-regulation strategies, we used categories described in the literature (Freire et al., 2013; Montague, 2008), and some categories emerged from the analysis of the audio records (Table 2).

Table 2. Categories concerning students' self-regulation strategies.

Categories	Description
To read for understanding (Ra)	Analyze the problem (Have I understood the problem? What am I supposed to do?) Identify the starting point (What do I already know and can mobilize to solve the problem?)
To paraphrase using own words (Pa)	Underline the important information. Put the problem in my own words (What am I looking for?)
To plan to solve the problem (Pl)	Decide the steps that are needed to solve the problem (What do I need to do? Which are the best options?)
To regulate the process of solving the problem (Rg)	Redefine strategies (Which other option do I have to solve the problem?) Mobilize knowledge (What do I know that can be useful for correcting mistakes or overcoming difficulties?) Add or search for additional information (What do I need to know more to overcome difficulties?) Call to others for help (e.g., teacher)
To check during and after solving the problem (Ch)	Check the goals and plan (Did I reach goals? Have I checked every step? Were strategies efficient?) Check that everything is correct (Is my answer correct? If not, did I go back?)

The level of students' participation during the problem-solving process was also assessed using the following criteria: (i) whether the problem was solved; (ii) the number of self-regulation strategies employed by the groups. Based on these two criteria, three groups were formed: high participation, referring to groups that successfully solved the problem and used more than twenty strategies, either the same or different; medium participation, referring to groups that successfully solved the problem and used between ten and twenty strategies, either the same or different; low participation, referring to groups that did not solve the problem and used fewer than ten strategies, either the same or different.

The teacher's feedback was analyzed based on the number and the type of teacher's feedback in each group. The categories related to the type of feedback were adapted from the study by Koyuncu et al. (2023) and Baptista et al. (2017), and additional categories emerged from the analysis of the audio recordings (Table 3).

Table 3. Categories of the teacher type of feedback.

Type of Feedback	Description
Encouragement (En)	Points out the positive aspects of students' intervention (well done) and encourages improvement of the work.
Prompting the mobilization of evidence, arguments, and justifications (EAJ)	Encourages answering "why" by mobilizing data, presenting arguments, and justifying the response.
Prompting the mobilization of scientific knowledge (SK)	Encourages the use of scientific knowledge. Identifies scientific inaccuracies and suggests strategies for improvement.
Prompting the presentation of clarifications and elaborations (CE)	Encourages answering "What is this?" and "What does this mean?"
Prompting the presentation of information and solutions (IS)	Encourages students to research information from various sources to present solutions to the problem.
Discussion guidance (DG)	Refers to group work and the discussion of ideas among group members.
Process guidance (PG)	Guidance on how to organize the response and which resources to use.
Confirming (Co)	Validates the students' response by expressing agreement (yes).

4. Results

4.1. Self-Regulation Strategies

The analysis of the audio recordings reveals that only one group did not complete the challenge (G2) and used a low number of self-regulation strategies (fewer than 10 strategies). The remaining groups had medium (G3, G4, G5, and G7) and high (G1 and G6) levels of participation (Table 4).

Table 4. Characterization of the student groups based on the completion of the problem-solving task and the level of participation of the groups.

	G1	G3	G4	G5	G6	G7	G2
Level of participation of the groups	H	M	M	M	H	M	L
Conclusion of the problem-solving	yes	yes	yes	yes	yes	yes	no

The results show that students used five types of self-regulation strategies during problem-solving: to read for understanding (Ra); to paraphrase using their own words (Pa); to plan to solve the problem (Pl); to regulate the process of solving the problem (Rg); and to check during and after solving the problem (Ch) (Table 5). The analysis of the groups' interactions reveals that around half of the students used the Rg strategy (46%) during problem-solving. This strategy involves actions such as analyzing the problem-solving process, redefining strategies, mobilizing knowledge, adding or searching for additional information, and seeking assistance from others (e.g., the teacher). In contrast, the least-used self-regulation strategy was to read for understanding (Ra), employed by only 7% of the students.

Table 5. Frequency and percentage of self-regulation strategies used by students during problem-solving.

Self-Regulation Strategy	Total
Ra	17 (7%)
Pa	21 (9%)
Pl	67 (28%)
Rg	109 (46%)
Ch	24 (10%)
Total	238 (100%)

This pattern differs across groups. For example, G2, which did not complete the problem-solving, as well as two groups with a medium level of participation (G3 and G5), did not employ the Ch type of self-regulation strategy. Furthermore, the groups that employed a higher number of self-regulation strategies, whether the same or different, and had medium to high participation levels were the ones that used all five types of self-regulation strategies (Table 6).

Table 6. Frequency of the types of self-regulation strategies used by each group of students.

Self-Regulation Strategy	G1	G2	G3	G4	G5	G6	G7	Total
Ra	3	3	2	3	2	2	2	17
Pa	4	3	2	2	4	3	3	21
Pl	12	4	7	9	10	17	8	67
Rg	29	6	14	12	7	23	18	109
Ch	10	0	0	4	0	8	2	24
Total	58	16	25	30	23	53	33	238

Groups G1 and G6, characterized by a high level of participation, began the problem-solving process using the Ra self-regulation strategy. That is, they started with problem analysis and brainstorming about what they already knew and could mobilize to solve the problem. Despite their similar starting points, G1 used this strategy more frequently than G6 and made greater use of the Pa, Rg, and Ch strategies. In contrast, G6 relied more often on the Pl strategy compared to G1. Compared to the other groups, these two groups most frequently employed the Pl, Rg, and Ch strategies. The following excerpt from G1's interactions provides examples of the self-regulation strategies they used (Table 7).

Table 7. Excerpt from G1's interactions.

	Excerpt	Self-Regulation Strategies
S1	We need to analyse the data from the two tables and establish connections. I think that's the first thing we should do. Don't you agree? And after comparing, we can carry out some research.	Pl
S2	Think, S1! I think we should start with research to figure out what's going on with the parts, and then we'll know more, giving us the knowledge to analyse the data in the tables.	Pl

Table 7. *Cont.*

	Excerpt	Self-Regulation Strategies
S1	But how do you want to research without knowing what to do first? I don't think we'll get anywhere like this. This doesn't seem right!	Ch
S3	Yeah. . . I also think we need to compare first, then do the research, and during the research, we can gather information to draw conclusions. We first need to look at the data in the tables.	Pl
	(. . .)	
S4	From the table analyses, we've already compared them, and it's because of the water hardness in different regions (. . .) Here it says that water hardness is a chemical characteristic and refers to the amount of mineral salts dissolved in water, such as calcium and magnesium ions. And that's why it accumulates in the machines.	Rg
S3	Accumulates? Accumulates what? Should we call the teacher? Teacher. . .	Rg
S1	We've already studied precipitates. Could this be one? (. . .) In this text, it says: Temporary hardness can be eliminated by heating water to its boiling point, which causes calcium carbonate and magnesium carbonate to precipitate. Permanent hardness, however, cannot be eliminated by boiling but can be removed by adding substances that prevent the reaction of calcium and magnesium ions with soaps: anti-scale agents.	Rg
S2	Oh! Right. . . The TV ad mentions those anti-scale agents. That's why we need to use them in machines. Look, we've got it! We figured it out! Machine parts degrade more in the south of the country because of water hardness. Isn't that, right? Yeah. . . the water is hard in the Algarve, according to the table values. And. . . we can use more anti-scale agents in the Algarve to prevent damage to the machines.	Rg Ch

The previous excerpt illustrates that G1 successfully developed a process of co-constructing knowledge by using three types of strategies: Pl, Rg, and Ch. It is evident from the excerpt that S1 initiated a cycle by introducing the steps they considered necessary for solving the problem. S2 then continued with the Pl self-regulation strategy but proposed an alternative way to organize the steps. S1 disagreed with S2's proposal and employed the Ch self-regulation strategy, encouraging the group to reflect and discuss whether S2's proposed steps would be the most effective solution. This is evident in the question, "But how do you want to research without knowing what to do first?" as well as the following statement: "I don't think we'll get anywhere like this. This doesn't seem right!" S3 then agreed with S1 and used the Pl self-regulation strategy to finalize the group's plan.

As the group continued to solve the problem, all four students also used the Rg self-regulation strategy. The excerpt shows that S4 introduced information obtained from online research. Then, when S3 struggled to interpret the information provided by S4, they decided to call the teacher for clarification ("Should we call the teacher? Teacher. . ."). The group's interaction became more complex, with S1 adding additional information and S2 integrating prior knowledge to address the problem, using the Rg self-regulation strategy. Furthermore, the statement "Look, we've got it! We figured it out!" by S2 indicates that they checked the solution and confirmed that they had reached a conclusion.

This excerpt shows that the group demonstrated effective self-regulation strategies. The students consistently defined the steps needed to progress in solving the problem, added information through online research, mobilized knowledge to overcome challenges, and successfully reached a conclusion.

Groups with a medium level of participation (G3, G4, G5, and G7) also exhibited differing patterns among themselves. G4 and G7 used all five types of self-regulation strategies and displayed a higher frequency of strategy use than G3 and G5. G5 is the only group that employed Rg less frequently than Pl, while G4 is the only group that used Ra less frequently than Pa. The following is an excerpt from the interactions of G4 (Table 8).

Table 8. Excerpt from G4's interactions.

	Excerpt	Self-Regulation Strategies
S13	So, what do we need to do? (. . .) Maybe it's one of the chemical reactions we've studied. I'm not sure I understand.	Ra
S14	[reads the problem again] I don't know if I've fully understood the problem or what we need to do. S15, do you have any brilliant ideas about chemistry?	Ra
S13	Right. . . we need to take on the role of scientists and figure out why machines in different parts of the country have some parts that are in good condition and others that aren't (. . .) we need to think about this and then come up with solutions, ideas for what we can do to prevent the machines from breaking down.	Pa
S15	I think that's it. Right, it's two things. Yes, two things. We need to see if there's a pattern based on location in the country and whether the parts degrade more or less and then figure out what we can suggest preventing the damage. Those are the two things we want to address, and now we need to decide what to do.	Pa
	(. . ..)	
S15	Let's start with the tables. In this table, where do the parts degrade more? [They analyse the table.] See, it's here in the Algarve and Alentejo, and there are fewer damaged parts in the North. Now, the other table is about water hardness. I don't know what this is. . . but the hardness is higher in the Algarve. Should we ask the teacher what water hardness means? Teacher, can you come over here?	Pl Rg
S13	You're right, S15. What we need to do is look at both tables and then draw our conclusions. We could also do an experiment with the chemical reactions to see in which region of the country the parts degrade the most.	Pl

G4 began problem-solving by using the Ra self-regulation strategy. However, at the beginning, the group did not have a clear understanding of the problem or what they needed to know, as evidenced by the initial contributions of S13 and S14. Therefore, it was central for them to use the Pa self-regulation strategy. Specifically, S13 and S15 were able to extract the important information and restate the problem in their own words. Using Pa helped them overcome their initial difficulty in understanding the problem and allowed them to define new goals and steps aligned with those goals, as seen when S15 remarked the following: “Those are the two things we want, and now we need to decide what to do”. The students then employed the Pl self-regulation strategy to outline the necessary steps for solving the problem and sought help from the teacher (Rg). Notably, their use of the Pl strategy involved building upon each other’s ideas, specifically from S15 to S13.

Regarding the group with the lowest participation (G2), many of their interventions were parallel. On several occasions, their interventions were disconnected, with no response to each group member’s contributions. In other words, one group member initiated a self-regulation strategy that was not linked to the strategy previously used by another group member. Additionally, they employed Rg without first using a Pl strategy, which led them to conduct internet searches that took them away from addressing the initial problem. The following excerpt from G2’s interactions (Table 9) illustrates this issue.

Table 9. Excerpt from G2’s interactions.

	Excerpt	Self-Regulation Strategies
S5	You are part of a group of scientists, and your mission is to investigate: why do parts of identical machines degrade differently in various regions of the country?	Ra
S8	What I’m going to do is be a scientist and check if the machine parts are degraded. I’ll see if they are damaged here in Lisbon or in Porto. What will I do? I’ll look for solutions to prevent the parts from degrading so much.	Pa
S6	[Researching on the internet] Washing machines, if placed in the wrong spot, can cause drainage issues, they get damaged, and the parts become defective. Teacher. . . [Calls the teacher]	Rg
	(. . .)	
S8	What we’re going to do is look at the two tables and find the answer to the problem.	Pl
S5	What we need to do is investigate: why do parts of identical machines degrade differently in various regions of the country? The company’s management has also asked you to propose solutions to ensure the machines’ durability in all regions.	Ra

In terms of self-regulation strategies, G2, despite S5 starting by reading the problem or part of the problem (Ra) and S8 restating the problem in their own words (Pa), the subsequent strategy used by S6, in addition to being disconnected from the Ra and Pa strategies used by S5 and S8, takes the group further away from solving the problem. Furthermore, instead of involving the group in their research, S6 opts to call the teacher, using the Rg self-regulation strategy. The next intervention by S8, using the Pl self-regulation strategy, could have helped the group move forward in addressing the problem. However, it is clear from S5’s next intervention that the group returns to understanding the initial problem, using the Ra strategy.

4.2. Teacher's Feedback

The analysis of the teacher's feedback reveals that she provided procedural guidance (21%), encouraged most of the groups (18%), prompted the mobilization of scientific knowledge (15%), prompted the mobilization of evidence, arguments, and justifications (13%), prompted the presentation of clarifications and elaborations (15%), confirmed students' ideas (10%), and provided discussion guidance (8%) (Table 10).

Table 10. Frequency and percentage of the teacher's feedback type.

Type of Feedback	Total
Encouragement (En)	11 (18%)
Prompting the mobilization of evidence, arguments, and justifications (EAJ)	8 (13%)
Prompting the mobilization of scientific knowledge (SK)	9 (15%)
Prompting the presentation of clarifications and elaborations (CE)	9 (15%)
Discussion guidance (DG)	5 (8%)
Process guidance (PG)	13 (21%)
Confirming (Co)	6 (10%)
Total	61 (100%)

Furthermore, the comparison of the feedback provided by the teacher to the different groups reveals that the number of interventions directed at the groups, as well as the quality of those interactions, is different (Table 11).

Table 11. Frequency of the teacher's feedback types by group.

Type of Feedback	G1	G2	G3	G4	G5	G6	G7	Total
Encouragement (En)	1	2	2	2	2	1	1	11
Prompting the mobilization of evidence, arguments, and justifications (EAJ)	2	0	0	1	1	3	1	8
Prompting the mobilization of scientific knowledge (SK)	2	0	1	2	1	2	1	9
Prompting the presentation of clarifications and elaborations (CE)	3	0	0	1	0	3	2	9
Discussion guidance (DG)	0	1	2	1	0	0	1	5
Process guidance (PG)	1	3	2	2	2	1	2	13
Confirming (Co)	1	0	1	0	1	1	2	6
Total	10	6	8	9	7	11	10	61

As for G2, with low participation and fewer self-regulation strategies used, it was the group with the fewest interactions from the teacher (6). The feedback provided by the teacher covered three types: PG, En, and DG. Compared to the other groups, G2 received the highest number of interventions from the teacher focused on the PG type of feedback. The following example shows three interactions between the teacher and G2 (Table 12).

Out of the groups G3, G4, G5, and G7, with medium participation, G7 had the same number of interactions as G1 (high participation), while for G3, G4, and G5, the number of interactions ranged from 7 to 9. These three groups received feedback En, SK, and PG type. G4 was the only one of the three groups that received feedback of the CE type. Feedback of the EAJ type was given to G4 and G5, the DG type to G3 and G4, and the Co type to G3 and G5. Below is an excerpt of the feedback given by the teacher to G3 (Table 13).

Table 12. Teacher's feedback to G2.

Excerpt	Teacher Feedback
Teacher: Very well, you've already done some research on the internet. Let me read [Teacher reads what the students have written]. Doing the research is important, but let's see if we are answering the problem. It might be better to use other search terms or define another way to start. Keep going...	EN
S6: Teacher, but what words could we use? Are the parts of the washing machine degraded?	
Teacher: What do the other group members think? Could it be? What do you think? S8, what do you think? Would starting with the research be the best option?	DG
S8: The machines are broken; we researched that.	
Teacher: You haven't looked at all the data you have in the activity yet. Look at the tables with the data you have, analyse them, and see how the data there can help you find answers and pathways. Start with analysing the tables.	PG

Table 13. Teacher's feedback to G3.

Excerpt	Teacher Feedback
Teacher: [The teacher reads the answer written by the students] We are on the right track, now let's move forward. You compared the two tables. But why is one water harder than the other? Why is it harder or softer? You can complete your answer and search for what is still missing.	EN SK
S10: Okay, Teacher. We will look it up on the internet and...	
Teacher: Then complete the answer. Work as a group, S12 help your team with the research.	DG

G7 and the two groups with high participation (G1 and G6) were the ones that received the most feedback from the teacher, i.e., the highest number of teacher–group interactions. G1, G6, and G7 were the three groups that received the most feedback of the CE type, and G1 and G6 also received more feedback of the CA and EAJ types. It is also noteworthy that the most-used type of feedback by the teacher for G1 was CE, and for G6, it was CE and EAJ. The following is an excerpt from the interaction between the teacher and G6 (Table 14).

It is evident from the previous excerpt that the feedback that the teacher provided to G7 allowed them to progress in solving the problem. More specifically, the teacher gave them feedback about the evidence and justifications they needed to include in their response ("you can justify your answer by looking at the numbers") and asked them to include scientific concepts in their answer ("the scientific meaning of this"). Additionally, the teacher encouraged clarification and elaboration of their response by questioning the students ("Are you sure about what you mean? What is this? Is that really it?"). To further support them in reaching a solution, the teacher provided process guidance about websites where they could research information on the variation of water hardness across the country. To conclude, the teacher states "Yes, now it's correct," confirming G6's response.

Table 14. Teacher's feedback to G6.

Excerpt	Teacher Feedback
Teacher: You started with the analysis of the tables. Can you justify your answer by looking at the numbers? Go ahead...	EAJ
S22: Is it about relating the numbers? We look at the average water hardness value and...	
Teacher: It's looking at the numbers, but then you need to go further and explain what it means. It's not enough to just relate them; you must understand the scientific meaning of it.	SK
S24: Okay, let's do this. (. . .)	
S23: [Calls the Teacher] Teacher, can you check if this is correct? [The teacher goes to the group]	
Teacher: Let me see what you wrote [reads what the students wrote]. I don't quite understand your answer: "Soft water increases the density of soap bubbles and is found in the North." Did you get this from the internet? Are you sure about what you mean? And what connection are you trying to make between the North of the country and soap bubbles? What is this? Is that really it? Try looking on another website, maybe the websites for the Northern and Algarve water companies might have something. That could be a good idea...	CE PG
(...) [The teacher goes to the group] Teacher: Let me read what you have [reads what the students wrote]. Ah! Yes, now it's correct.	Co

5. Discussion

The results show that the student groups participated in the problem-solving task about water hardness in different ways, with two groups exhibiting a high level of participation, four groups with a medium level of participation, and one group with low participation. Groups G1 and G6, which used self-regulation strategies more frequently (either repeating the same strategies or employing different ones), achieved the highest participation levels. In contrast, the group with the lowest participation was also the one that used fewer self-regulation strategies and did not complete the problem-solving (G2). These results align with previous studies showing that the diverse use of self-regulation strategies is positively correlated with students' success in PBL (Zimmerman & Schunk, 2011). Furthermore, the groups with the highest levels of participation demonstrated distinct patterns of interaction and knowledge construction compared to G2. While G1 demonstrated an effective process of knowledge construction with interconnected interventions built upon prior contributions, G2 exhibited parallel and disconnected interventions. This difference highlights the importance of group functioning, emphasizing the need for a good group dynamic to help students overcome the challenges they encounter throughout their work and collectively construct knowledge (Zhu, 2007). Thus, the results underscore the importance of collaborative knowledge construction in PBL, as highlighted in previous studies (e.g., Hmelo-Silver & Barrows, 2008).

Additionally, the results show that the self-regulation strategy most frequently used by the groups was regulating the process of solving the problem (Rg, 46%), followed by planning (Pl, 28%). In contrast, the least-used strategy, which was only employed by three groups (G1, G6, and G7), was checking during and after solving the problem (Ch, 10%). These results suggest that the groups with higher levels of participation are also the ones that developed their metacognitive abilities more, using verification strategies ("Did I reach goals? Have I checked every step? Were strategies efficient? Is my answer right?") (Freire et al., 2013; Montague, 2008). Most of the groups with a medium level of participation, as well as the group with low participation, did not mobilize this type of strategy, indicating difficulties in checking during and after solving the problem.

Regarding the teacher's feedback, the results show that the number and type of feedback provided by the teacher varied. The groups with the highest participation received more feedback from the teacher, while the group with lower participation received the least feedback. These results indicate that, on the one hand, the teacher adapted her feedback to the specific needs of each group. For the group with lower participation (G2), the focus was on process guidance and encouragement, while the groups with higher participation (G1 and G6) received more feedback geared towards clarifications and elaborations. This differentiation in the type of feedback is consistent with the "adaptive scaffolding" model proposed by Wood and Wood (2016), where the level and type of support are adjusted according to the competence demonstrated by the students. According to Lin et al. (2018), this adaptation is important for promoting students' progressive autonomy. However, on the other hand, in the case of G2, the interaction with the teacher was insufficient for them to reach a solution to the problem. These results suggest the need for the teacher to provide more frequent and targeted interventions for less-participative groups.

6. Conclusions

This study revealed connections between self-regulation strategies and teacher feedback during the problem-solving on water hardness. High-participation groups employed diverse self-regulation strategies, successfully solved the problem, and received varied teacher feedback. In contrast, the group with the lowest participation received the least feedback from the teacher, suggesting a bidirectional relationship: student participation influences teacher feedback, and teacher feedback affects student participation. This pattern emphasizes the importance of the teacher having more interactions with groups with lower participation to help them develop their self-regulation abilities. Additionally, this study highlighted the need for teachers to provide differentiated feedback based on each group's specific needs. The groups with higher participation received feedback directed towards clarifications and elaborations, while most of the groups with medium and low participation received more feedback aimed at encouragement and process guidance. Future research should further investigate these less-participative groups, developing specific interventions focused on PBL, and examine how different feedback influence types influence self-regulation strategy development in these student groups.

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Article

Inquiring in the Science Classroom by PBL: A Design-Based Research Study

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Abstract: The aim of this study has been the design and evaluation of a sequence of activities that promotes the development of scientific skills in secondary school. For this purpose, design-based research was conducted using a problem-solving methodology to learn as a tool to engage in scientific inquiry practice. The research was structured around the design, implementation, and evaluation phases, with specific tools created to assess both student learning outcomes and the validity of the TLS. These tools helped identify the performance levels achieved by students in the various stages of scientific inquiry, from formulating hypotheses to interpreting data, and also allowed for the evaluation of the teaching methodology's effectiveness. The results indicated that the TLS significantly enhanced students' scientific competence by promoting skills related to scientific inquiry, such as hypothesis formulation, variable identification, observation, data collection, and interpretation. Additionally, the use of a weather station as the central topic provided a context closely tied to the students' local environment, which facilitated deeper engagement and understanding. The evaluation revealed that students progressed in their scientific inquiry skills, moving from "pre-scientific" to "uncertain inquirer" performance levels. While challenges such as initial disorientation and difficulties in representing experimental data were observed, the overall performance of students demonstrated the success of the TLS. Furthermore, the students worked collaboratively, contributing their individual skills and experiences to achieve group goals. This study provides valuable insights into the potential of TLS as an alternative to traditional teaching methods, offering an innovative way to assess and enhance students' scientific skills. It also highlights the importance of teacher guidance in inquiry-based activities and suggests that future projects could benefit from allowing students to choose the topic, further enhancing their motivation and engagement.

Keywords: PBL; DBR; sequence of activities; inquiry; assessment; secondary education

1. Introduction

Science classes should be designed with the aim of helping students investigate their scientific concerns while learning what teachers must teach (Solbes et al., 2007). Prior studies revealed that students are interested in solving problems in their immediate environment; that is, if the scientific problems are contextualized in the students' environment, their interest grows (Caamaño, 2018; Fraser & Walberg, 2005; Rodrigues & Mattos, 2011; Swarat et al., 2012). In this respect, knowing whether students develop science process skills should be a topic that teachers assess. Therefore, an ideal teaching methodology could consist of students themselves posing problems contextualized in their own environments and based on their own interests or, at least, based on their environment necessities (Pozuelo-Muñoz et al., 2023). In this work, we present the design, development, and evaluation of a science teaching strategy based on a problem that needs to be solved by the students. The learning results of the participating students are evaluated, identifying the scientific skills developed and the degree of their achievement. The teaching methodology followed the problem-based learning (PBL) system in order to develop the practice of inquiry in the classroom. To investigate its development, design-based research (DBR) was implemented through the development of a sequence of activities (TLS), which is fundamental in a DBR.

2. Theoretical Framework

2.1. Problem-Based Learning

PBL is an educational method developed by Dewey (Dewey, 1938). The aim of PBL is to foster both content knowledge and problem-solving abilities in students (Wang et al., 1998). According to scholars like Hmelo-Silver (2004) and Merritt et al. (2017), PBL goals are organized into four categories: (a) content knowledge (building a broad and adaptable knowledge base, achieving academically, retaining information, and developing concepts), (b) procedural knowledge (enhancing problem-solving abilities and self-directed, lifelong learning skills), (c) collaboration (becoming effective team members), and (d) attitudes (developing intrinsic motivation to learn and staying engaged). PBL emphasizes learning through problem-solving and integrating knowledge in real-world contexts (Capraro & Slough, 2013), which helps develop competencies and skills (Bell, 2010).

Drake and Long (2009) explored a typical PBL framework, which consists of eight key components: the problem, small groups, a student-centered iterative inquiry process, resources, technology, community partnerships, communication of findings, and the role of teachers as facilitators. There is limited research on the impact of PBL in science education for secondary school students. However, some studies show promising outcomes, such as enhancing critical thinking skills (Anazifa & Djukri, 2017) and helping both students and teachers engage in scientific practices (Kolodner et al., 2003).

It is important to note that the problem is central to the learning process, acting as a catalyst for student motivation and activity (Chin & Chia, 2004). Therefore, the problem should be complex, related to real-life situations, and ill-structured, allowing for open-ended solutions and broad inquiry (Eherington, 2011; Merritt et al., 2017). Additionally, several researchers suggest that students should have the freedom to identify and address their own problems (Chin & Chia, 2004; Runco & Okuda, 1988). Once the problem is defined, students collaborate in small groups (Kolodner et al., 2003; Runco & Okuda, 1988; Wang et al., 1998), engaging in an iterative inquiry process that is strongly supported by the PBL approach (Chin & Chia, 2004). Taking the above into account, this work proposes research to evaluate the development of students' science process skills in inquiry by asking questions in a PBL context.

2.2. Design-Based Research

One of the most current lines of research in experimental science teaching is research based on the design of teaching–learning sequences (TLS) (Guisasola et al., 2021). Design-based research (DBR) aims to generate didactic knowledge about the teaching and learning of science through direct classroom intervention (Kortland & Klaassen, 2010). This research is interventionist in nature, theoretically grounded, iterative, process-oriented and pragmatic. Classroom interventions are carried out through the design of TLS, a set of structured activities adapted to the development of the school curriculum and student development, while also constituting an educational research activity (Méheut & Psillos, 2004). There are two fundamental characteristics that differentiate DBR from other research in the field of science teaching (Sánchez-Azqueta et al., 2019). The first focuses on the context of the activity as a fundamental pillar for understanding teaching practice in the classroom (Guisasola et al., 2021). This positions the objective of DBR as the characterization of specific situations and the development of classroom interventions that characterize the design of practice (Barab & Squire, 2004; Bell, 2004). The second characteristic, and the main difference between DBR and other methodologies, is that its implementation involves changes at the local level. That is, DBR implies a pragmatic research philosophy supported by methodological rigor (CherryHolmes, 1992; Philips, 2006).

Talking about DBR undeniably means talking about TLS, a series of classroom activities developed under prior study that aim to develop the relevant part of the curriculum while also serving as a research activity within science teaching (Méheut & Psillos, 2004). The existing formats for designing a TLS are diverse in nature (Furió-Más et al., 2003; Guisasola et al., 2021), but they basically focus on three phases: students must present their ideas and listen to those of others; activities are conducted to guide their ideas toward the academic concepts; and, upon completion of the sequence implementation, they must reflect on how their ideas have changed compared to their initial thoughts.

Design-based research (DBR) is proving to be an important line for the development of research in the field of experimental science didactics (Guisasola et al., 2021). This line of research is being supported by the scientific community in the field and each contribution on the topic helps to underpin advances in scientific knowledge, developed through the implementation of such research in the classroom (Kortland & Klaassen, 2010).

As (Guisasola et al., 2021) state, to establish a complete DBR, it is necessary to theoretically ground the research, design the teaching–learning sequence (TLS), develop it, and evaluate it. The results of DBR are directly linked to the quality of the sequence (Guisasola et al., 2021), so by evaluating the quality of the sequence, conclusions can be drawn about the designed research. It should not be forgotten that classroom research must fulfill a dual function: advancing knowledge on the topic under investigation and helping students develop knowledge and procedures inherent to science (Méheut & Psillos, 2004). This is an opportunity to work on scientific practices in the classroom at any educational stage (Crujeiras-Pérez & Cambeiro, 2018). Therefore, this research has a double objective. On the one hand, it is the design, implementation, and evaluation of a sequence of activities from which results are obtained through the DBR methodology. The objective of this part is to investigate the scientific skills (and their scope) that the participating students put into play. On the other hand, in relation to advanced students, compare the characteristics of the sequence with their educational needs to conclude if this sequence could be an option for science work with these students.

This study aims to contribute to the advancement of knowledge in educational research within the context of secondary education by designing and developing a (TLS) focused on the scientific practice of inquiry. The central tool of this research is a weather station, which is used to promote practical and experimental learning in the classroom. The specific objectives of the research are as follows:

Develop a design-based research study (DBR): Create and evaluate a teaching–learning sequence (TLS) centered on the PBL methodology and by means of the scientific practice of inquiry and determine the validity of the sequence for classroom implementation in secondary education.

Design assessment tools: Develop specific tools to measure students' performance in scientific practice throughout the development of the TLS.

Analyze the utility of the weather station: Investigate the extent to which a weather station can serve as an effective tool for developing inquiry skills in the classroom and also to evaluate the problem-solving methodology of learning in this case.

3. Materials and Methods

3.1. Stages of Design-Based Research

Design-based research (DBR) can be defined as a research methodology where the tools available to researchers at each stage are flexible. However, a common theoretical framework is necessary for this methodology to be genuinely useful (Alghamdi & Li, 2013; Juuti & Lavonen, 2006; Reeves, 2006). Therefore, it is essential to clarify the specifics of each stage of design-based research. These stages are as follows: (a) theoretical foundations; (b) design; (c) implementation; (d) evaluation and redesign. Each of these phases is outlined below, with a focus on how they will be concretized in the context of our research.

3.1.1. Theoretical Foundations for Research

The starting point for designing a teaching–learning sequence (TLS) rests on two main ideas. First, one of the primary goals is to understand and comprehend the epistemology of science (Guisasola et al., 2008, 2021), emphasizing that students should view the production of scientific knowledge as a rational process. Second, considering DBR in its social and constructivist dimensions (Guisasola et al., 2008), learning begins with students' prior ideas and is not only focused on the individual but also supported by the entire student body, the learning environment, and the activities conducted (Leach & Scott, 2002).

3.1.2. Design Phase

Based on the theoretical foundations, the experience to be implemented in the classroom is designed. This involves defining learning objectives, identifying difficulties, addressing learning demands, and outlining the teaching strategies to be employed.

In any science teaching process, contextualization is crucial as it allows for the establishment of relationships between science and everyday life, leading to more durable learning (Caamaño, 2018; King & Ritchie, 2012). It facilitates the transfer of learned concepts to other contexts (Gilbert, 2006; King & Ritchie, 2012) and helps observe the presence of science in daily situations (Chamizo & Izquierdo, 2005), which increases interest in science (Gilbert, 2006; Sanmartí & Márquez, 2017).

Teachers must carefully choose an appropriate context to capture students' attention (Avargil et al., 2012; Romero Ariza & Quesada, 2015). This context should not only be relevant to students' lives but also serve as a source of the scientific ideas they aim to explore (Dori et al., 2018). This generates a need to know, facilitating lasting learning (Ültay & Çalik, 2012). Additionally, the design considers the "epistemological" and "learning demand" analysis tools (Guisasola et al., 2021), which aim to construct scientific knowledge in the educational context through a comprehensive study of the content to be covered. This will help define the "guiding problems" to be addressed in the TLS (Guisasola et al., 2021) and determine the sequence of activities within the TLS (CherryHolmes, 1992; Savall Alemany et al., 2016, 2019). By analyzing learning demands, the goal is to identify ontological and epistemic differences between students' ideas and the defined objectives (i.e., what is and what is thought to be) (Leach & Scott, 2002).

Finally, learning strategies are established to align with the objectives and learning difficulties. Based on these blocks, the design of activities that will form the TLS can begin.

In this research, the development of the TLS is carried out toward inquiry. Inquiry is one of the three scientific practices that students must develop to work with science in the classroom (inquiry, argue, and modeling) (Sánchez-Azqueta et al., 2019). It is a process through which students can understand the methods scientists use, evaluate the potential of observations, develop the ability to formulate investigable questions, and make hypotheses that are then tested or refuted based on collected and analyzed data (Crawford, 2007). Inquiry has an epistemic purpose, allowing students to grasp the provisional and evolving nature of science (Aguilar & Barroso, 2015; Jiménez Aleixandre, 2011; Kelly & Duschl, 2002). It is well founded that this inquiry-based approach promotes procedural learning, where both scientific skills and reasoning are addressed. By engaging students in a genuine process of scientific discovery, inquiry fosters reasoning and scientific competence. Thus, learning science is presented as a constructive process in which nothing is final and students "learn science by doing science" (Couso et al., 2020; Pedaste et al., 2015). From a pedagogical perspective, the complex scientific process is divided into smaller, logically connected units that guide students through scientific reasoning. These individual units are called inquiry phases, and their connections form an inquiry cycle. The literature describes various phases and cycles of inquiry, but we base our work on (Pedaste et al., 2015) to outline, in the Methodology Section, what these phases are, their objectives, and the actions required from students in the TLS presented in this research.

3.1.3. Implementation of the Activity

Guisasola et al. (2021) define this stage as a "teaching experiment" aimed at studying whether the design truly enhances student learning. Using the teaching–learning sequence (TLS) as a guide, it will be possible to establish improvements on the initial design (Cobb et al., 2003).

3.1.4. Retrospective Analysis: Evaluation and Redesign

Research tools are not predetermined by design-based research (DBR), so they will depend on the didactic strategies used and the aspects that need to be evaluated. However, it is advisable to use multiple evaluation designs that explicitly show the results of the TLS (Nieveen, 2009). Guisasola et al. (2021) propose evaluation instruments in two dimensions: the evaluation of the quality of the sequence and the evaluation of learning outcomes. In this work, tools were designed to assess both dimensions, allowing conclusions to be drawn about the research question posed in the introduction of this study. A summary of the stages of DBR is presented in Figure 1.

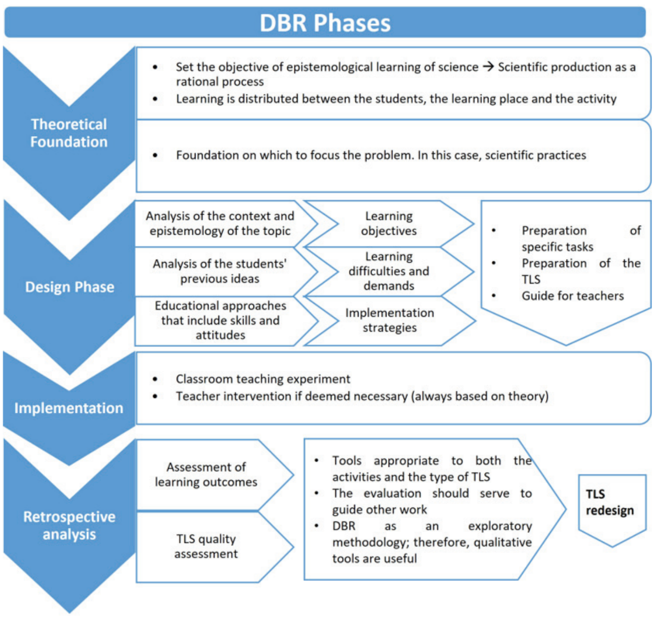


Figure 1. Summary of the stages of DBR.

3.2. Instruments

The methodology followed in this research adheres to the phases of design-based research established in the previous section, which itself serves as the theoretical foundation of the research. When working within the framework of design-based research (DBR), the design of the learning sequence (TLS) is included as a result of the research itself, thus it has been included in the Results Section.

To collect and analyze the data obtained from the development of the TLS, various instruments were used (semi-structured interviews with teachers, researchers, and students, direct observations, written student reports, questionnaires, and audio and video recordings of the sessions). However, often more than one instrument was used for the same session, which facilitates the triangulation of both methods and data (Aguilar & Barroso, 2015). We proposed evaluation instruments to both analyze the learning outcomes and the quality of the sequence.

To evaluate the learning outcomes of the TLS, evaluations were first separated for each of the two activities it comprises. As described in the Results Section, the TLS consisted of an activity where students must decide on the purchase of a weather station (activity 1) and a second activity where they must choose a location for this weather station within the educational center (activity 2). For each activity, the evaluation process followed consisted of the stages that each activity underwent during its implementation. For evaluating the development of the skills involved in each stage, as a reference we used the work of (Ferrés-Gurt et al., 2015), which synthesizes the Practical Test Assessment Inventory (PTAI) system (Tamir et al., 1982). Before deciding the reference instrument, we carried out a literature analysis to find other authors who described a similar assessment of the inquiry process (Buty et al., 2004; Lou et al., 2015). Akuma and Callaghan (2019) describe the evaluation and design of evaluation instruments as one of the most important challenges in the design of TLS. All assessment tools must be designed in the context in which they are going to be applied; therefore, for the design of ours, despite using reference works, we specifically designed a tool that would allow the assessment of the main objectives in our research.

Following their models, we divided down each activity into the stages of investigation that composed them, associating the skills involved and adapting each of the skills described by the authors to the work performed for this research. Figure 2 specifies the stages of each activity, the skill associated with the inquiry process according to the literature, and the skill addressed in our research concerning the first, for each of the two TLS activities.

The evaluation of each stage did not always correspond to a single session. This was due to two reasons: firstly, the development of the stage within the activity may not be completed in just one session; for example, measurements may be taken over several sessions. Secondly, some skills were associated with more than one session. This factor needs to be reflected in the results and for this purpose, a rubric was developed that specifies different items within each skill. To develop these items, a new variable was included: the cognitive level or depth of knowledge required for each of the proposed actions. This evaluation method is included within the PISA assessment framework (OCDE, 2016; Rosales Ortega et al., 2020) and derives from the revised Bloom's taxonomy (Krathwohl, 2002). This inclusion has been useful for establishing different levels of achievement of the objectives beyond a simple yes or no dichotomy. Additionally, to make these levels easier to analyze, they were assigned scores. These scores were used to quantify the levels of scientific competence achieved, following a tool adapted from the one proposed by (Ferrés-Gurt et al., 2015).

To make the cognitive demand level of each item more visible, a color scale was established to denote cognitive demand from lower to higher requirement. Each demand level was associated with a score. The scale used is shown in Figure 3.

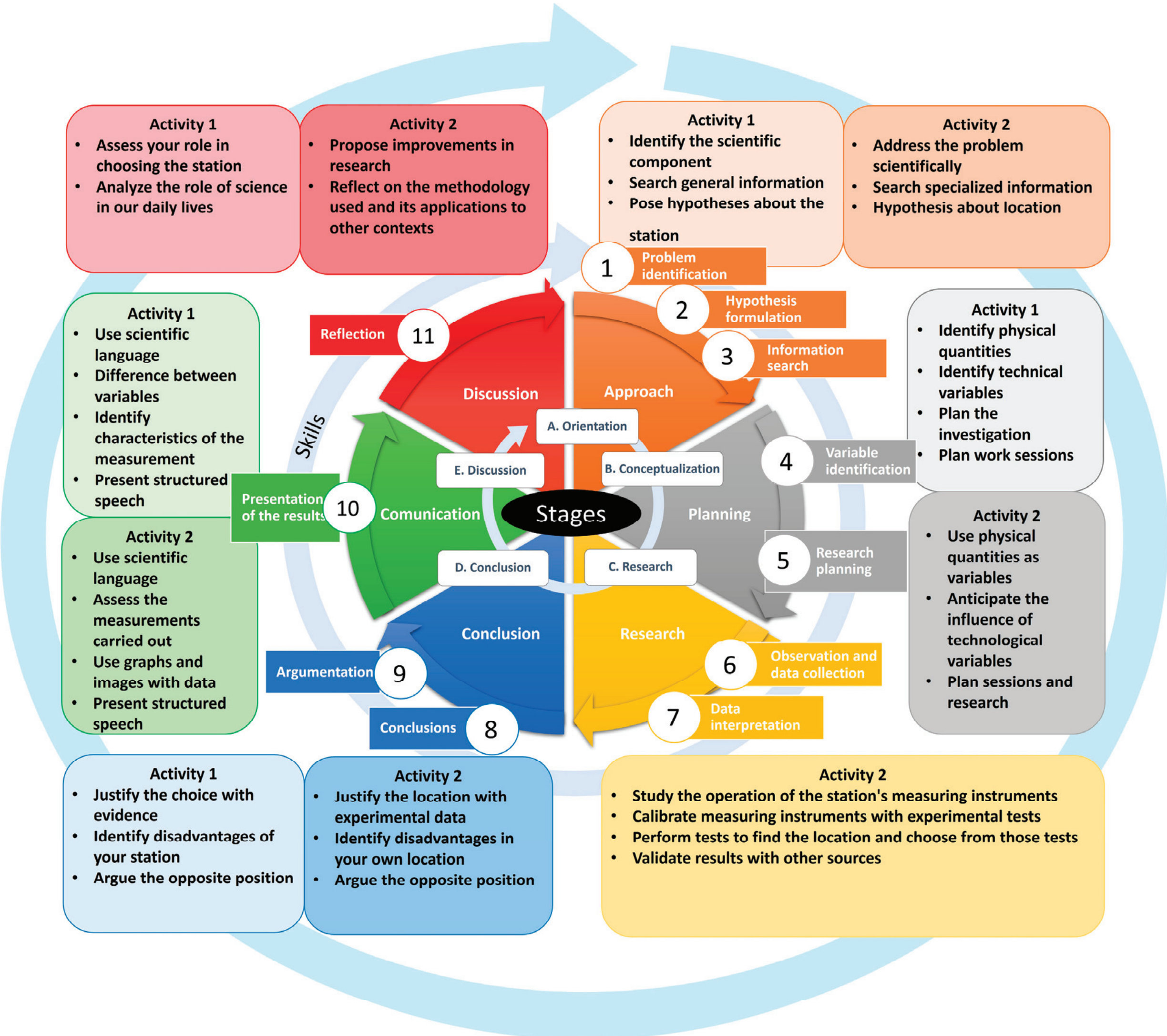


Figure 2. Adaptation of the stages of inquiry according to Pedaste et al. (2015) to this research, including the skills associated with each stage and their development in the TLS.

Figure 3. Color scale used for cognitive demand.

Keeping this scale in mind, the stages, skills, and adapted skills are detailed in Tables S1 and S2 of the Supplementary Materials, and the item and score of each item, for activity 1 and 2.

Tables 1 and 2 detail the scores for each stage and skill for activity 1 and 2. The Supplementary Materials are used as a detailed evaluation rubric for each of the skills, so that by adding the maximum possible scores to be achieved, it is established that if the student reaches that score, his or her level of inquiry is "inquirer". And thus, a scale was established based on the specialized literature (Ferrés-Gurt et al., 2015).

Finally, by using a scoring system associated with the skills involved in each activity and stage, as well as with cognitive demand, we can establish a categorization of performance levels in inquiry practice for each stage. The performance levels on which the design for this research is based were proposed by Ferrés-Gurt et al. (2015) and were adapted for other works such as the study by (Crujeiras-Pérez & Cambeiro, 2018). The established levels were as follows: non-participant, non-scientific (or unscientific), pre-scientific, emerging inquirer, uncertain inquirer (or hesitant inquirer), and inquirer.

To clarify the assessment process, the researchers designed a specific document (acting as a rubric) that can be observed in the Supplementary Materials. Each section of the rubric is quantified with a maximum number, which corresponds to the higher level of development of this section. Based on it, the researchers just had to quantify every section with numbers (attending to the detailed description of each in the rubric). Therefore, it allowed us to quantify the cognitive demands of activity 1 and 2. And, knowing the stages (Figure 4), it was possible to classify the level of the inquiry developed in activities 1 and 2.

Table 1. Distribution of scores by stages and skill for activity 1 and maximum cognitive demand that must be achieved in each of the activities.

Activity 1: Choosing a Weather Station											
Stages	Skills		Cognitive Demand							Total	
E1: Research approach	Identification of researchable problems		0	1	2					3	28
	Hypothesis formulation		0	1	2	3	4	5		15	
	Information search		0	1	2	3	4			10	
E2: Research planning	Identification of variables	Recognize types	0	1	2	3				6	55
		Technological	0	1	2	3	4			10	
		Physics	0	1	2	3	8	5		19	
	Research planning	Long term	0	1	2	3	4			10	
		Each session	0	1	2	3	4			10	
E3: Data	Observation and data collection		0							0	0
	Interpretation of results		0							0	
E4: Conclusions	Conclusion and argument	Reference to evidence	0	1	2	3	4	5	6	21	63
		Disadvantages	0	1	2	3	4	5	6	21	
		Opposite position	0	1	2	3	4	5	6	21	
E5: Communication of results	Results presentation	Clarity	0	1						1	31
		Graphics and images	0	1	2	3	4	5		15	
		Language	0	1	2	3	4	5		15	
E6: Reflection	Reflection	Science and technology	0	1	2	3				6	12
		Self-assessment	0	1	2	3					
		Total	0	16	30	42	48	35	18	**189**	

Table 2. Distribution of scores by stages and skill for activity 2 and maximum cognitive demand that must be achieved in each of the activities.

Activity 2											
Stages	Skills		Cognitive Demand								
										Total	T
E1: Research approach	Problem identification		0	1	2					3	28
	Hypothesis formulation		0	1	2	3	4	5		15	
	Information search		0	1	2	3	4			10	
E2: Research planning	Variable identification	Recognize types	0	1	2					3	49
		Technological	0	1	4					5	
		Physics	0	1	2	6	12			21	
	Research planning	Long term	0	1	2	3	4			10	
		Each session	0	1	2	3	4			10	
E3: Data	Observation and data collection	Functioning	0	1	2	3	4	5		15	101
		Instruments	0	1	2	3	4	12	6	28	
		Location		1	2	3	4	6	6	22	
	Interpretation of results	About data		1	2	3	4	5	6	21	
		Validation	0				4	5	6	15	
E4: Conclusions	Conclusion (argumentation)	Reference to evidence	0	1	2	3	4	5	6	21	63
		Disadvantages	0	1	2	3	4	5	6	21	
		Opposite position	0	1	2	3	4	5	6	21	
E5: Communication of results	Results presentation	Clarity	0	1						1	31
		Graphics and images	0	1	2	3	4	5		15	
		Language	0	1	2	3	4	5		15	
E6: Reflection	Reflection	Science and technology	0	1	2	3				6	12
		Self-assessment	0	1	2	3				6	
		Total	0	20	40	51	68	63	42	**284**	

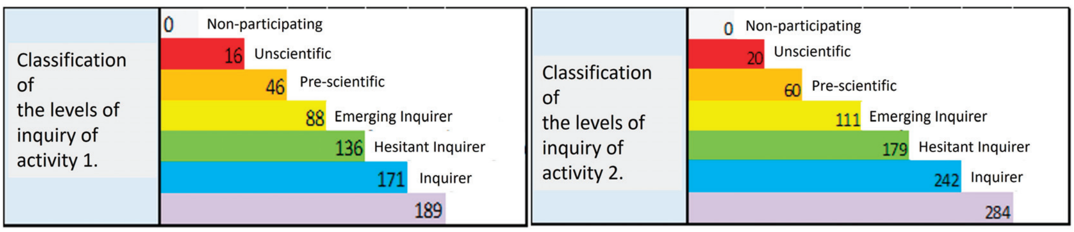


Figure 4. Score to achieve each level of inquiry for activities 1 and 2.

Figure 4 shows the scores required to achieve the defined performance levels.

3.3. Sample

The research was conducted with a group of 16 first-year high school students (8 female students) in the subject of Scientific Culture, through a situation arising from the needs of the school itself: purchasing a weather station (with a fixed budget of 250 euros) (activity 1) and finding a location to install it in the school (activity 2). Four groups of 4 students each were formed, and each group was tasked with proposing a weather station for purchase. The entire class had to decide and buy the most suitable station for the proposed needs. Subsequently, each group proposed a location, and all the groups had to choose the option they considered most appropriate according to the criteria they established.

The teaching staff acted as teacher-researchers, collecting the questions that students asked in each phase of the project and, as support, providing access to what was required. As Mosquera Bargiela et al. (2018) demonstrated, showing an attitude of support and providing resources to students so that they can answer in the school context encourages their scientific development.

The students started with a problem to solve (choose by themselves), and they had to design the procedure in order to obtain results and draw conclusions about this problem, which is a daily problem.

4. Results

The stages implemented in each activity can be seen in Figure 2. The first stage of activity 1 was dedicated to presenting the research project and identifying students' prior knowledge about the main learning outcomes involved in this TLS (see Table 3), which served as the final design of the TLS.

Table 3. Previous ideas of the students participating in the TLS.

<table>
<tr><th colspan="2">Presented Idea</th><th>Associated Data or Phrase</th></tr>
<tr><td colspan="3">Related to Scientific Practice and Inquiry</td></tr>
<tr><td colspan="2">They understand the activity as buying a weather station online and then placing it in the school</td><td>"So we looked online for a station to buy and then we put it in the school."</td></tr>
<tr><td rowspan="2">They justify the scientific component because:</td><td>It is conducted in the subject of Scientific Culture</td><td>"It's a scientific project because otherwise, we wouldn't do it in the Scientific Culture subject."</td></tr>
<tr><td>A weather station is purchased, an instrument associated with measuring atmospheric phenomena</td><td>"It's a meteorological project because it's used to measure the weather."</td></tr>
<tr><td colspan="2">They do not see the usefulness of the weather station, although they do recognize the importance of knowing the weather</td><td>"And why do we need a weather station if in the end, the mobile phone tells you the weather forecast?"</td></tr>
<tr><td colspan="3">Related to Physical and Meteorological Content Linked to the Project</td></tr>
<tr><td rowspan="4">Magnitudes</td><td rowspan="2">They do not know the meteorological magnitudes measured by a weather station.</td><td>"All weather stations will be more or less the same."</td></tr>
<tr><td>"It will measure heat, cold, wind, storms, lightning, and all that."
"Lightning cannot be predicted or measured."</td></tr>
<tr><td>The only magnitudes clearly mentioned are temperature and wind</td><td>"It won't measure heat and cold, just temperature."</td></tr>
<tr><td>The weather station is not exactly understood as a measuring instrument but rather as a weather forecasting tool</td><td>"The station will be used to know if the weather will be good or if there will be a storm."</td></tr>
<tr><td rowspan="2">Measurements</td><td>Only the thermometer and the weather vane are named as meteorological instruments. The units of measurement are known, but not the name of the instrument that measures wind speed</td><td>"Temperature is measured with a thermometer and wind with a weather vane."
"Temperature is measured in degrees or Kelvin degrees."
"Wind speed is measured in km/h."</td></tr>
<tr><td>Regarding characteristics, it is only mentioned that there should be no errors. It is not specified how or what needs to be considered for this to happen</td><td>"It is important that the station measures accurately"... "That means the station should not have measurement errors."</td></tr>
</table>

Table 3. *Cont.*

Presented Idea		**Associated Data or Phrase**
Location	Two characteristics are mentioned: there should be no obstacles that interfere with the wind; it should be placed in the sun (without justification)	"It should not be placed behind a wall, for example, because then the weather vane won't move." "And it should also be in the sun" (the reason is not provided).
Related to Technological Implications and Project Aspects		
They believe that all weather stations are the same or very similar in characteristics		"All weather stations will be more or less the same; there won't be a difference between the ones each group chooses."
They are unaware of the station's operation regarding its connection formats, parts, etc.		"But the station runs on batteries." "And we need to check it to know what it is measuring."

Below (see Figures 5 and 6), the results obtained in the practice of the inquiry are presented for each of the groups with which activity 1 and 2 of the TLS were implemented.

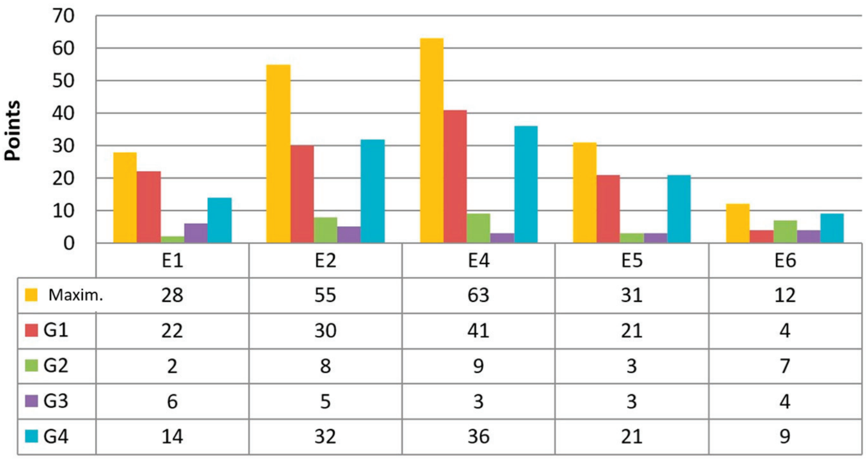


Figure 5. Scores obtained by groups and stages in activity 1.

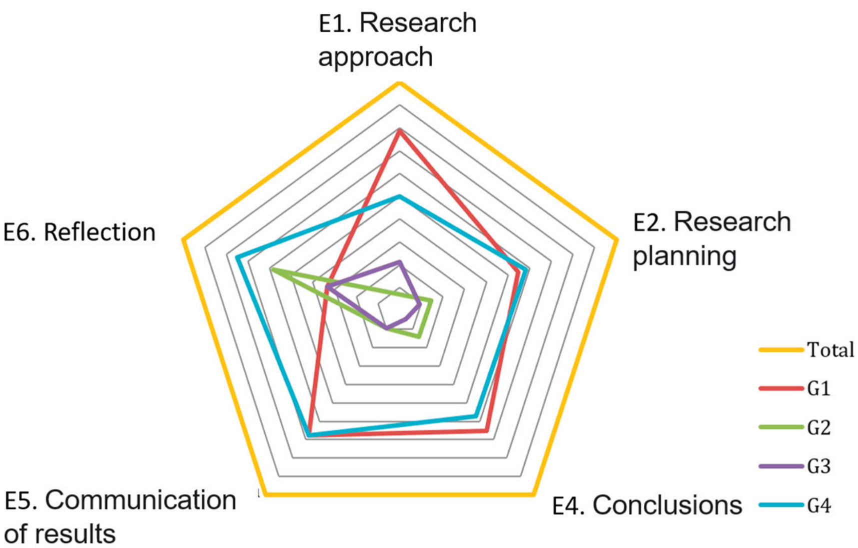


Figure 6. Proportional representation of the performance achieved by each group in activity 1 (Stage 3 has been eliminated as it is not necessary in this activity).

4.1. Activity 1: Choice of Weather Station

Stage 1: Research Proposal: Group 1 used scientific data to propose a hypothesis for choosing the station, stating that "the temperature range is between −10 °C and 50 °C, as temperatures here can range from −3 to 40 °C". On the other hand, Group 4 presented a very thorough report on their station choice. This report included the group's initial hypothesis, specifying the physical magnitudes measured by the station along with their units. However, they proposed a station with a temperature measurement range of 0 °C to 50 °C, without considering that this range was not suitable for the intended use of the station. Groups 2 and 3 demonstrated fewer skills at this stage of the activity. Group 2 did not mention specific magnitudes, ranges, or precisions, nor did they relate to the context of the location. For example, they used phrases like "Our station has components commonly found in weather stations, such as a rain gauge, a thermometer, etc." and "It has a very low error tolerance, meaning high precision". Finally, Group 3 proposed a station with temperature ranges between 30 and 80 °C, which did not meet the required criteria.

Stage 2: Research Planning: In the second stage, which involved identifying variables influencing the problem, Groups 1 and 4 again stood out. Group 4 organized their discussion by differentiating between physical and technological parameters. Group 3 received the lowest score as they met only the items with lower cognitive demand and did not plan any sessions. They identified the physical variables of temperature, pressure, wind, and precipitation, but did not refer to any measurement characteristics (e.g., units, ranges, or pressures) and did not propose additional variables such as humidity or solar radiation measurement. Group 2 performed better than Group 3 because they included these additional variables for the station.

Stage 4: Conclusions and Argumentation: Group 1 used arguments related to the physical and technological parameters of their station. Regarding technological ranges, they mentioned the allowed distance between devices (100 m), using these data as justification. They also used data related to the station's power supply. However, where this group really excelled was in using physical magnitudes as arguments. They provided data on the station's precision and ranges and related them to the population's needs. They also identified a disadvantage of their station. This factor was documented in writing and included in the debate. Their station "measures a wind speed range of 0 to 50 km/h. In the environment, winds can exceed 45 km/h, so there may be days when the maximum is surpassed". In the case of Group 2, they barely participated in the debate, presenting only the general characteristics of their station without using evidence beyond listing some features, and did not mention disadvantages or other groups, although they did listen to their peers. Group 3 also presented their station's characteristics in a generic manner and opposed the view by saying that they believe "the other stations are more or less similar to ours".

Stage 5: Communication of Results: In this stage, Groups 1 and 4 used their own photographs of the purchased station and edited them to identify each exposed part. The only difference was that Group 1 explained the functioning of most of the measurement instruments (all except the solar radiation meter). However, in this part of the activity, none of the groups referred to the measurement characteristics related to precision and range.

Stage 6: Reflection: The ability of each group to relate the results obtained to their role in the activity and the connection between the project and science and technology was evaluated. In this regard, Group 4 showed the best performance. This group described their role in the activity as "a challenge to face alone" and also related their work to that of scientists.

4.2. Activity 2: Choice of Weather Station Location

Stage 1: Research Proposal: Three of the four groups identified a scientific issue in the activity due to the data collection processes. They made statements such as "we need to take measurements and use the collected data" (Group 1); "it is necessary to collect and record data, otherwise we cannot justify anything later" (Group 2); "we need to take measurements to choose a location" (Group 3). Group 4 identified the scientific issue by relating it to the first activity of the project: "we need to use the information obtained in the first part of the project to continue with our research" (Group 4). Group 3 proposed a location where the station is exposed to both sun and shade throughout the day without providing any arguments for it. Group 1 argued before choosing the locations: "before thinking about the ideal site, we considered several factors: that there should be no buildings or obstructions; the sensors of the station should not fall under an area with sun/shade"; "the station should face north". Group 2 conducted some preliminary tests to choose the location, which allowed them to evaluate the station they had chosen for activity 1 as incorrect.

Stage 2: Research Planning: In the second stage of activity 2, Groups 1, 2, and 4 showed very similar performance. Group 3 did not achieve the same level of performance, although the difference with the other groups decreased compared to activity 1. All four groups identified the two groups of variables (physical and technological).

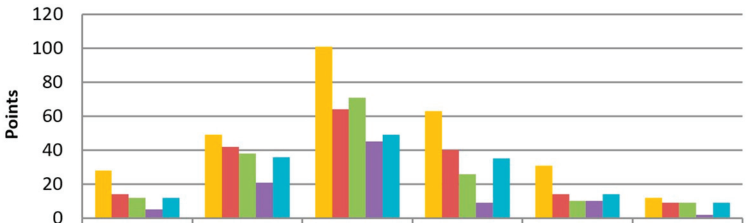
Stage 3: Observation and Data Collection: In setting up the instrument, both Group 1 and Group 2 followed similar procedures. Group 2 evaluated locations that met technical requirements ("first we tested sites where the station would function") and then took measurements ("later we will conduct tests to ensure the measurements are accurate"). Group 1 started with random connection tests and trial and error: "since it did not work in the computer room, we tried the adjacent room". Group 4 conducted a connection test to establish the maximum distance between devices "to have a range of action". Group 3 approached this part by making approximations. Group 2 analyzed the data and made decisions based on this analysis. For example, "we did tests in the courtyard and had a wind speed of 17 km/h and on the rooftop 6 km/h. We realized that the building created very strong wind currents". Upon detecting such anomalies, they decided to consult "official meteorological data sources". This group consulted data from the State Meteorological Agency. Group 1 received a similar score, as they did not manage to take systematic measurements but shared all the information they had with the other groups. Through this exchange of information, they validated their location. They also consulted meteorological data from nearby weather stations using a mobile app (Weather Underground). Group 4 identified errors in some of their tests but did not design a new experiment to address them and decided to directly "change the location because it did not measure well", attributing the issues to technological connection factors. Finally, Group 3 detected errors in their tests but did not resolve them and did not attempt to validate their data.

Stage 4: Conclusions and Argumentation: In justifying their proposed choices, Groups 1, 2, and 4 supported their decisions using the data obtained from their measurements (Groups 1 and 2) or by describing in detail the characteristics of the location for accurate measurements (Group 4).

Stage 5: Communication of Results: The highest-scoring groups distinguished in their vocabulary between magnitudes, units of measurement, and measuring instruments.

Stage 6: Reflection: Groups 1, 2, and 4 demonstrated a greater level of achievement by relating the work to their daily lives. Group 1 stated that they learned about the origin of weather maps ("now we know where the weather map data comes from"). This suggests that this group found a connection between the activity and their everyday life. Group 4 related the activity to the procedural aspects of science, stating they "felt like scientists at times and euphoric when they finally managed to connect the station". Group 2 related the activity to scientific practice, stating that "the whole activity was about constantly applying the way scientists work". Finally, Group 3 did not refer any aspects in this part of the activity.

These results are shown in Figures 7 and 8.



	E1	E2	E3	E4	E5	E6
Maxim.	28	49	101	63	31	12
G1	14	42	64	40	14	9
G2	12	38	71	26	10	9
G3	5	21	45	9	10	2
G4	12	36	49	35	14	9

Figure 7. Scores obtained by groups and stages in activity 2.

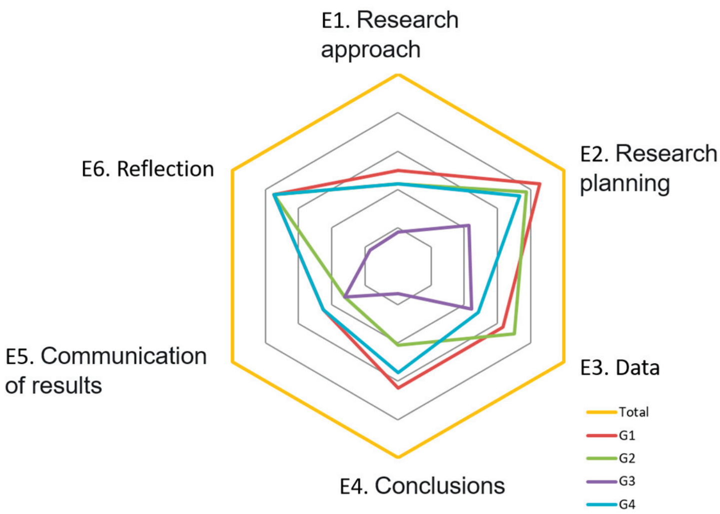


Figure 8. Proportional representation of the performance achieved by each group in activity 2.

Lastly, the results obtained for each of the groups implementing activities 1 and 2 of the TLS are presented. The data corresponds to Figure 9.

	Group 1	Group 2	Group 3	Group 4
Activity 1	118	29	21	112
	Emerging inquirer	Unscientific	Unscientific	Emerging inquirer
Activity 2	183	166	92	155
	Hesitant inquirer	Emerging inquirer	Pre-scientific	Emerging inquirer

Figure 9. Proportional representation of the performance achieved by each group in both activities attending to the colors in Figure 3.

5. Conclusions

This paper presents a design-based research study developed through the design, implementation, and evaluation of a teaching–learning sequence (TLS) based on a PBL methodology. The research methodology used (DBR) was demonstrated to be useful for both research development and teaching practice (Guisasola et al., 2021). The results from the evaluation of the quality of the TLS, i.e., the evaluation of its design and implementation using the station, address the research objectives. Specific tools were designed for this evaluation, which ultimately allowed for the establishment of the scientific level performance achieved by the students participating in the research. The adaptation of these tools may be useful for evaluating other sequences in the educational field, both for teaching and research practice.

The data obtained from the research confirms that the TLS has promoted inquiry practice among students. Firstly, the use of an inquiry-based teaching methodology has developed skills and abilities related to scientific inquiry practice (Crujeiras-Pérez & Cambeiro, 2018). The use of a weather station as a generating topic facilitated students in formulating hypotheses, identifying variables, making observations and data collection, and interpreting those data (Aguilar & Barroso, 2015), all in a context closely related to their immediate environment (Caamaño, 2018). To reach this conclusion, students' performances in different stages of the teaching sequence were analyzed. It was found that the choice of a weather station for purchase served as an introductory activity, allowing students to identify the variables involved in the problem, the characteristics of the measurements, and their relationship to the local climate. On the other hand, choosing the location for the station developed procedural practices, enabling students to create their own experimental designs for data collection and subsequent interpretation. Some difficulties among students were also identified. One difficulty is the sense of disorientation that students experience at the beginning of such activities, highlighting the crucial role of the teacher's guidance throughout the process (Sánchez-Azqueta et al., 2023), or the low performance in representing the obtained experimental data (Aguilar & Barroso, 2015). Despite these challenges, students have demonstrated performance levels that allow their classification between "pre-scientific" and "uncertain inquirer".

All students worked in an integrated manner in their groups and maintained motivation to achieve group objectives from the beginning to the end. It was observed that each of them contributed to the group based on their skills and previous experiences, respecting all opinions and ways of working.

This research work has allowed for the evaluation of the feasibility of a TLS for working on science in the classroom, offering an alternative to classical teaching and providing tools to assess the effectiveness of the TLS in developing students' scientific skills through a PBL. The PBL proposed has motivated the students and has favored the development of the scientific skills analyzed. The topic addressed in this project was a subject close to the students' everyday life and with direct applications, so they could see the usefulness of the project's development. However, one point to consider for the future is attending to the students' interest in the project topic. In this project, the topic was chosen by the teacher (the purchase and placement of the weather station), but in future projects, to better meet their needs, the topic can be chosen by the students themselves.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci15010053/s1, Table S1: Stages, skills, adaptive skills, and items established for the activity 1. Table S2: Stages, skills, adaptive skills, and items established for activity 2.

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Institutional Review Board Statement: The authors confirm all the subjects' participants in the present research have provided appropriate informed consent in verbal form. We declare that the institution (and the country) in which we developed the research does not have an ethics committee; so, to develop the research, the authors requested the explicit consent of the students and their legal tutors.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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Inquiry-Based Science Education in High Chemistry: Enhancing Oral and Written Communication Skills Through Authentic and Problem-Based Learning Activities

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Abstract: Student-centred learning requires a variety of approaches, such as inquiry-based learning and the tackling of authentic and problem-based learning activities, to make the teaching and learning process more meaningful and to encourage students to participate more actively in class. The inquiry approach enables students to investigate solutions to real problems, awakening their need to ask questions, design and conduct research, collect and analyse data, interpret results and present them in a structured way. This study investigates the influence of an inquiry-based science education (IBSE) module on the development of oral and written communication skills among 10th grade students. The study is set in a secondary school context and focuses on a problem-based learning approach centred around gases and dispersions. A total of 111 students participated in this one-group post-assessment qualitative study, where evaluation rubrics were applied to assess students' written and oral communication, focusing on correctness, clarity and mastery of scientific language. The results showed that the majority of students performed well in both written and oral tasks, demonstrating improved scientific communication skills. This suggests that IBSE, particularly in the context of secondary education, can be an effective approach to fostering students' abilities to communicate scientific concepts. The study has implications for enhancing pedagogical practices and encourages further research on the long-term effects of IBSE on student learning.

Keywords: chemistry teaching; inquiry; problematising activities; gases and dispersions

1. Introduction

Inquiry-based science education (IBSE) gained visibility in the 1990s, through the National Science Education Standards, in the United States (National Research Council, 1996). It is now considered a recommended approach for teaching science due to its potential to provide students with basic knowledge and skills and to contribute to greater motivation for learning (Crawford, 2014; Partanen, 2023; Strat et al., 2023).

Several authors (Abd-El-Khalick et al., 2004; Chang et al., 2022; Crawford, 2014; Lederman et al., 2014; Ramnarain, 2014) have stated that IBSE represents a constructivist, active, dynamic and student-centred teaching approach that focuses on students' solutions to various problems, as well as on finding answers to questions through research. In general, students solve research questions related to the world around them, collect relevant and necessary data to answer these questions, analyse the data and draw appropriate conclusions based on evidence from objective research (Abd-El-Khalick et al., 2004; Crawford, 2014; Lederman et al., 2014; Ramnarain, 2014). Not only does IBSE stimulate students' interest in science, but it also improves their understanding of scientific concepts and procedures (Chang et al., 2022; Crawford, 2014; Minner et al., 2010; Ramnarain, 2014; Van Uum et al., 2016) and is aligned with the goal of promoting students' skills in terms of creativity (Morais et al., 2019), critical thinking, problem solving and lifelong learning. In turn, these skills enable students to engage in authentic scientific practices (Boğar, 2019; Crawford & Capps, 2018; Roller et al., 2021; Šmida et al., 2023).

Guidance by a teacher is fundamental so that IBSE contributes to students' progress, as the teacher can highlight conceptual knowledge and work methods, as well as structure and focus research-based activities. In order to do this, the teacher must, for example, provide scientific content, connect activities to scientific concepts, manage how resources are used and be motivating (Strat et al., 2023). When practiced with proper guidance from the teacher, IBSE is a beneficial approach to learning science, focused on authentic and problem-based learning activities that stimulate discussion and improve oral and written communication using scientific vocabulary (Chinn & Duncan, 2021; de Jong et al., 2023; Strat et al., 2023).

2. Inquiry-Based Learning and Problem-Based Learning Activities

IBSE and PBL are often associated due to their shared emphasis on active learning, though they are sometimes viewed as distinct approaches. In our framework, PBL is seen as an integral part of IBSE, contributing to the broader inquiry-based process which involves students in problem solving and encourages critical thinking. Therefore, while PBL and IBSE have distinct methodological aspects, they can be seen as complementary approaches within the broader context of inquiry-based learning (de Jong et al., 2023; Lederman et al., 2014; Minner et al., 2010).

IBSE enables the development of authentic and problem-based learning activities (Dewi, 2023; Gomes, 2024; Joseph et al., 2022; Leite & Afonso, 2001; Leite et al., 2016; Morgado et al., 2016), starting with a question or problem that emerges from a new situation, which students try to explain based on knowledge they have acquired so far. The problem is usually discussed in groups, which allows students to exchange experiences, opinions and knowledge. Students do not arrive at their knowledge and experience without prior knowledge or without having first had contact with the topic under discussion. It is students' previous experiences that help them understand new phenomena.

After exchanging experiences, students formulate a hypothesis to solve the problem, which is a crucial stage as it determines the direction of the research. Then, students gather evidence to compare what was predicted with what actually happens. The nature of the problem influences how the information will be collected—observation, experimentation, records, identifying patterns within the data, etc.—which means there is no single or strictly defined path to a solution. If the evidence corroborates the prediction, the original ideas are accepted as valid explanations for the problem. However, if the prediction is not correct, students should not be discouraged, but rather they should formulate new hypotheses, discarding those that have been proven incorrect. By drawing conclusions and evaluating the work they have done, students have the opportunity to integrate new knowledge into their cognitive structure, something that is only possible after genuine understanding, since understanding is something that students cannot receive from others, but rather achieve through the activation of their own cognitive functions (Chin & Chia, 2006; Gholan, 2019; Latifah & Suprihatiningrum, 2024; Macedo et al., 2023; Wood & Levy, 2015; Yew & Goh, 2016).

As shown in Table 1, there are various levels of IBSE, which depend on who is responsible for formulating the problem-question and the procedure and method to be followed, as well as the interpretation of the results, with the aim of solving the problem under study.

Table 1. Levels of IBSE (Blanchard et al., 2010, p. 581).

Level	Type	Problem-Question	Procedure Method	Interpretation of Results/Solution
0	Confirmation	Given by the teacher	Given by the teacher	Given by the teacher
1	Structured	Given by the teacher	Given by the teacher	Open to the student
2	Guided	Given by the teacher	Open to the student	Open to the student
3	Open	Open to the student	Open to the student	Open to the student

In structured inquiry, the teacher presents the problem-question that will guide the inquiry, as well as the processes that will be implemented. In guided inquiry, the teacher presents the problem-question and the students build the process to obtain one or more potential solutions. In open inquiry, students develop their own problem-questions and procedures without knowing what results to expect before the inquiry (Abels, 2015; Anwar, 2020; Baharom et al., 2020; Blanchard et al., 2010; Fay et al., 2007; de Jong et al., 2023; Partanen, 2023; Stender et al., 2018; Vorholzer & von Aufschnaiter, 2019; Wheeler et al., 2017).

In level 0 inquiry, there are confirmation or verification activities (often not even considered inquiry (Bevins & Price, 2016)), in which the teacher provides students with the problem-question to be studied and the data collection methods. The conclusions are not immediately obvious to the students during the activities, but the teacher guides them towards the expected conclusion. The teacher helps to interpret the different data gathered by the students, so that everyone understands the importance of those results (Blanchard et al., 2010).

Open inquiry places high demands on students' experience. Thus, many teachers feel that students in the early stages of their studies are not prepared for learning through this type of inquiry. As for students, they show more positive attitudes towards guided inquiry and consider it to be the one that best contributes to their learning (Partanen, 2023; Wheeler et al., 2017).

In the classroom, these IBSE type designations may not always be clear. Teachers often need to help students formulate the problem-question, define research procedures, or interpret results. Although the initial intention is to promote student autonomy in these tasks, teachers try to provide a "foundation" as the key to helping students understand and thus improve their learning during these complex tasks. The ideal level of inquiry, and consequent type of IBSE, will vary according to the classroom setting, schooling level, students' skills, curriculum requirements and the resources available (Blanchard et al., 2010).

Several studies demonstrate the implementation of the IBSE pedagogical approach to teaching chemistry with secondary- and university-level students, who conducted laboratory activities using IBSE. These activities promoted higher levels of student engagement and more opportunities to practice logical thinking and scientific research skills, as well as a better understanding of theoretical and technical concepts (Iwasaki et al., 2023; Morais et al., 2021; Partanen, 2023; Valsecchi et al., 2024). Overall, IBSE pedagogies show a great effect on students' learning of chemistry, even for tasks that do not have a laboratory component. In addition to helping students understand the content of the curriculum, IBSE pedagogies foster the development of transversal skills, such as cooperation, time management and critical thinking (Treagust et al., 2020), as well as improving conceptual understanding (Kimberlin & Yezierski, 2016). With this pedagogical approach, students more often use metacognitive strategies associated with self-regulated learning, such as giving more correct answers and/or producing more complete scientific explanations and, through the self-assessment of their learning processes and learning outcomes, they improve their cognitive thinking (Kadioglu-Akbulut & Uzuntiryaki-Kondakci, 2021). It is also effective for acquiring skills in the scientific process (planning experiments, building data tables, designing and interpreting graphs, determining the variables under study and formulating hypotheses, as well as changing and controlling variables) (Gultepe & Kilic, 2015).

Overall, various studies (Iwasaki et al., 2023; Kimberlin & Yezierski, 2016; Morais et al., 2021; Partanen, 2023; Valsecchi et al., 2024) reinforce the idea that teachers should try to allocate enough time to guided inquiry activities so that students have the opportunity to think for themselves, get involved in creative problem solving and, during the process, make errors that they can identify and correct.

3. Inquiry-Based Learning and Oral and Written Communication Skills

Scientific writing is not limited to simply writing text, but rather involves a complex process that requires high-level cognitive, linguistic and communicative skills (Luy-Montejo, 2019). Several studies have shown that IBSE contributes to the ability to develop scientific writing skills, particularly in terms of the ability to write research abstracts and literature reviews and a greater ability to communicate conclusions in a clear and precise manner. A systematic review of 40 empirical studies, published between 2000 and 2021 (Lin et al., 2023), analysed the pedagogical practices that could help students develop scientific writing skills, associated with the ability to read, write and use texts to represent scientific concepts. The main results of the study were that IBSE could develop students' scientific thinking and scientific writing skills. When literacy development is framed within the context of IBSE, students not only learn to read and write scientific texts but also learn to conduct practical research based on scientific texts (Pearson et al., 2010; Wildan et al., 2019). Another study (Sampson & Walker, 2012) presents the implementation of a step-by-step IBSE approach that sequentially involved structured inquiry, guided inquiry and open inquiry to improve students' communication skills and scientific attitudes. The instrument used to measure communication skills involved written, verbal and social communication skills, along with indicators of scientific attitude, including curiosity, open-mindedness, objectivity, honesty in reporting the results, responsibility and mutual respect. The results of this study revealed that classes in which a step-by-step inquiry was implemented scored higher in communication skills and scientific attitudes than those in which expository approaches were implemented. Involving students in inquiry increases their ability to build knowledge and arguments, as well as strengthening their motivation for learning (Wildan et al., 2019). Another study (Sampson & Walker, 2012) analysed how the ability of university students to write scientific text changed over time as they conducted laboratory activities designed based on guided inquiry for argumentation. The reports written during each of the six laboratory activities were used to examine the changes in students' writing skills over time, showing significant improvements in their ability to write about science, as well as a greater ability to assess the quality of their peers' writing. Other studies (Jang & Hand, 2017; Lin et al., 2023) have shown that students who were trained according to an argumentation-based inquiry approach performed well in an explanatory writing task. Skills related to argumentation, explanation and reflection have also been identified as important for interpreting and writing scientific text.

Research into students' reading habits and learning interactions has shown that the fact students read and discuss contextual scientific articles, with a focus on the explanation of research procedures, contributes to the development of students' inquiry skills in formulating research questions and designing experimental procedures (Tseng et al., 2022).

Based on the above, the following research questions were formulated to guide this work:

1. How does the implementation of an inquiry module influence the development of oral and written communication skills among 10th grade students?
2. What are the specific results in terms of the clarity, correctness and mastery of scientific language following the implementation of an inquiry module?

4. Materials and Methods

This research was designed as a one-group post-assessment qualitative study, focused on understanding phenomena within the context in which they occur and with an emphasis on the description of experiences, perceptions and meanings (Creswell, 2013).

The sample for this study comprised 111 students, with an average age of 15, who, in the 2022/2023 school year, were attending the 10th grade, in a science and technology course at a secondary school in Portimão, in the south of Portugal.

The IBSE module involved students in both literature-based investigations and laboratory research, developing their scientific literacy—i.e., the ability to read, write, reason and use texts to represent scientific concepts. Students develop scientific literacy not only when they read and write scientific texts, but also when they engage in scientific investigations (Pearson et al., 2010).

In this study, students were involved in developing and justifying explanations and presenting and discussing their ideas in class, while the teacher connected prior knowledge to the new concepts being learned. The aim of the IBSE approach was to provide an environment where students performed reasoning tasks, analysed data, made inferences, constructed evidence-based arguments and interpreted scientific texts (Pearson et al., 2010).

This research context, combining literature-based research and laboratory activities, allowed students to experience scientific discovery while engaging in scientific writing (Lin et al., 2023). Both approaches are fundamental to IBSE and complement each other in science education.

In the classroom, IBSE was characterised by the discussion of investigative questions, formulation of hypotheses and critical analysis of information. Students developed skills such as scientific argumentation and problem solving. The opportunity to conduct an experimental activity to study the effect of melting sea ice and glaciers on the average sea level allowed students, in groups, to formulate hypotheses, analyse experimental results and reflect on the relationship between the activity and the concentration of CO_2 in the atmosphere. This experimental activity provided evidence to support the theoretical concepts discussed in class.

The students interacted with the inquiry module developed, as described below.

4.1. The Development and Implementation of the Inquiry Module

The inquiry module developed and implemented within the scope of this work was part of the "Gases and dispersions" subdomain of the subject *Physics and Chemistry A*, for the 10th grade, and worked on the following essential learning objectives: "Researching the composition of the Earth's troposphere, identifying polluting gases and their sources, particularly gases that cause greenhouse effects, as well as alternatives for reducing the sources of pollution, and communicating the conclusions" (DGE, 2018, p. 11). In terms of specific objectives, the aim of the module was to propose an inquiry into "The role of different gases in the Earth's atmosphere", in order to promote the selection of relevant information; problematize situations regarding the application of science and technology and their impact on society and the environment; provide opportunities to analyse texts according to different points of view; promote the analysis of concepts, facts and situations from disciplinary and interdisciplinary perspectives; and foster the development of oral and written communication skills in students.

The module focused on a guided approach, using the 7Es model (Reis & Marques, 2016) according to the plan shown in Table 2.

Table 2. The structural plan of the inquiry module.

Phase	Lesson	Activity
Engagement	1	Three questions to stimulate students' interest and involvement in the topic and identify previous conceptions. Viewing a video to familiarise students with the topics under study.
Exploration Explanation	2, 3 and 4	The search for and selection of information on the composition of the Earth's troposphere and carbon dioxide, CO_2, concluding that it is an essential and/or polluting gas. Conducting an experimental activity to study the effect that the melting of sea ice and glaciers located on the continents has on the average sea level. Sharing and discussion with the teacher.
Elaboration Exchange Empowerment	5 and 6	The search for and selection of information to construct the products that will comprise the final exhibition about a different socio-scientific problem related to the environment. Creating the written document for the interactive exhibition, aiming to share it with the educational community.
Evaluation	4 and 7	Present throughout the implementation of the module. The assessment of the oral presentation of the work—self- and hetero-assessment—and the assessment of the final product for the exhibition.

To put this into practice, students performed tasks that involved the individual search and selection of relevant information, as well as small-group work to share the knowledge acquired during the individual searches and the processing of the gathered information. The students were organised into groups of 3 or 4 and worked collaboratively to answer the problem-question posed by the teacher: "Gases in the atmosphere: essential or pollutants?".

This activity took place over seven lessons, totalling 400 min of intervention.

To help students conduct their research, it was suggested that they read textbooks/magazines/manuals made available in the classroom, as well as explore the contents of a list of links provided to them, which allowed them to analyse texts from different points of view.

Students had the opportunity to ask further questions about the context presented, to participate in group discussions and to plan and develop the inquiry.

The opportunity to conduct the experimental activity to study the effect that melting sea ice and glaciers, located on the continents, has on the average sea level allowed the students, in groups, to formulate hypotheses, analyse the experimental results and reflect on the relationship between this activity and the concentration of CO_2 in the atmosphere. The teacher's discussion with each of the work groups about the activity's results was intended as an opportunity to give students feedback on the development of their inquiry, to correct any errors and to validate the information that would be included in the written document for presentation to the community.

Formative evaluation was implemented throughout the process, allowing the teacher the possibility to regulate learning, identifying the need to review and/or reinforce certain concepts, and, for the students, the possibility to consolidate the main ideas of the research conducted, as well as to self-reflect on their progress.

After discussing the information covered in the previous phases with the teacher, and aiming to apply the scientific knowledge acquired to new and similar situations, each work group was asked to tackle a different socio-scientific problem related to the environment, such as acid rain, photochemical fog or another problem suggested by the students.

Finally, each group produced a digital and/or paper document in a format chosen by the students to orally present to the class and share with the educational community through an interactive exhibition.

This final interactive exhibition of the work produced was a way to promote active and participatory citizenship among students in the field of sustainable development and environmental education.

To sum up, the tasks proposed to the students created an opportunity for them to read and discuss scientific articles and to experience moments of interaction and learning among peers and with the teacher, as well as opportunities to develop argumentation and explanation skills, fostering their ability to interpret and write scientific texts.

4.2. Data Collection and Analysis Instruments

Evaluation rubrics were used to assess the oral presentation of the work and the written document for the interactive exhibition. The rubrics were designed mainly to support the evaluation of students' performances, allowing teachers to be more rigorous in their evaluation. The rubrics had to include a coherent and consistent set of criteria that reflected what it was expected that students would learn and/or be able to do. For each criterion, a very clear set of descriptors, as well as performance levels, had to be defined. In other words, for a given criterion, the indicators or descriptors of performance levels had to reflect fundamental guidelines so that the students can self-regulate their progress in the learning outcomes that they must achieve (Fernandes, 2021).

For this study, the rubrics developed by the researchers were an adaptation of the rubrics presented by (Reis & Marques, 2016, pp. 108, 253–255), according to the assessment criteria of the school where the study was implemented, and were contributed to by the two teachers who collaborated with this research, having created a dynamic of regular meetings to standardise and apply the assessment criteria for the students. These rubrics presented a set of criteria, as well as descriptions for each of these criteria. Thus, the oral presentation evaluation rubric was organised into three categories of criteria, as follows: (a) knowledge—scientific correctness; (b) communication—correctness of speech, clarity and objectivity, presentation of information, ability to arouse interest, audio-visual aid and use of voice; and (c) personal and interpersonal development—cooperation between group members and creativity. Similarly, the evaluation rubric regarding the product for the exhibition was organised into three categories of criteria, as follows: (a) knowledge—scientific correctness; (b) communication—message, interactivity and graphic appearance; and (c) personal and interpersonal development—activism.

In each of the categories, these criteria were organised into four levels of performance: Very Good, Good, Sufficient and Insufficient. Tables A1 and A2, included in the Appendix A, show the full versions of these rubrics.

In the case of the written document, the assessment was the same for everyone in the group. However, the oral presentation was assessed individually, depending on each student's performance.

5. Results

The main aim of this study was to analyse how the implementation of an inquiry module could contribute to the development of oral and written communication skills, including clarity, correctness and mastery of scientific language, among 10th grade students.

The analysis of students' written communication skills was mainly based on the correctness of the scientific text in the written document for the interactive exhibition, which resulted from group work. During the process of preparing the work, we also monitored the written records students created during the process, explaining the most relevant scientific information to be included in the written document, which could take the form of a poster, leaflet, infographic or news item, among others.

The work conducted by the students pertained to pollutant gases and their sources, namely gases that cause greenhouse effects, global warming, acid rain, photochemical fog and ozone depletion, in this last case referring to the role of ozone in the troposphere and stratosphere. To illustrate the students' responses and reflections throughout the investigation process, we present below selected quotes from their work.

Consequences of acid rain:

> *"In forests, the pH of the soil and the concentration of metals such as aluminium prevent vegetation from properly absorbing the water and nutrients it needs, this will damage roots, slow growth and make plants weaker and more vulnerable to diseases and pests."*

> *"The oceans could lose biodiversity and productivity. The decrease in the pH of ocean waters harms phytoplankton, a source of food for different organisms and animals, which can change trophic levels and lead to the extinction of different marine species."*

> *"Ozone is a highly unstable and very toxic gas, but it is also essential for life on Earth. It is a molecule made up of three oxygen atoms and is very reactive and oxidising. Ozone is also one of the factors responsible for the greenhouse effect and participates in the formation of smog."*

Mechanism of the greenhouse effect:

> *"Solar radiation passes through the atmosphere and part of it hits the earth's surface, heating it up. The earth's heated surface emits infrared radiation. Some of this radiation passes through the atmosphere. Another part is absorbed and retained by gases, which return most of this radiation back to the Earth's surface, thus contributing to the greenhouse effect."*

> *"Photochemical smog occurs when highly harmful gases, oxides of nitrogen or nitrogen (NO_x), are released. In the presence of light, these elements take part in photochemical reactions that generate other pollutants such as ground-level ozone (O_3), nitric acid (HNO_3) and other substances that are highly damaging to air quality. Its main appearance is its reddish or brown colour, and its daily peak concentration is usually around 10 a.m. and 12 p.m., when the light level is most intense."*

> *"Industrial smog is produced by the smoke expelled from industrial chimneys and occurs when they gather in densely populated urban areas, generating an accumulation of toxic gases in the environment. In this case, thermal inversion makes the problem even more serious, as the lack of movement of air masses causes a cloud of ash to remain under the environment."*

For their oral presentations, students mainly used PowerPoint presentations, Prezi, Canva, Google Slides or poster projections. Regarding the exhibition for the community and dissemination on the website, most of the student groups produced a poster or leaflet, such as the examples shown in Figure 1.

Figure 2 shows the results obtained by the students in the written document, prepared for exhibition to the community and dissemination on the website, and resulting from the investigative work proposed in the inquiry module, as well as the oral presentation of this work.

An analysis of the graph in Figure 2 shows that 69 students obtained a "Good" grade and 12 students obtained a "Very Good" grade in the written document for exhibition to the community and dissemination on the school website, which shows a good development of their ability to write scientific text. In these cases, the scientific correctness and graphic appearance of the documents stood out.

(**a**)

Figure 1. *Cont.*

(**b**)

Figure 1. Examples of work done by the students to be exhibited to the community and posted on the school website, resulting from the investigative work proposed in the inquiry module: (**a**) poster on the greenhouse effect; (**b**) leaflet on acid rain.

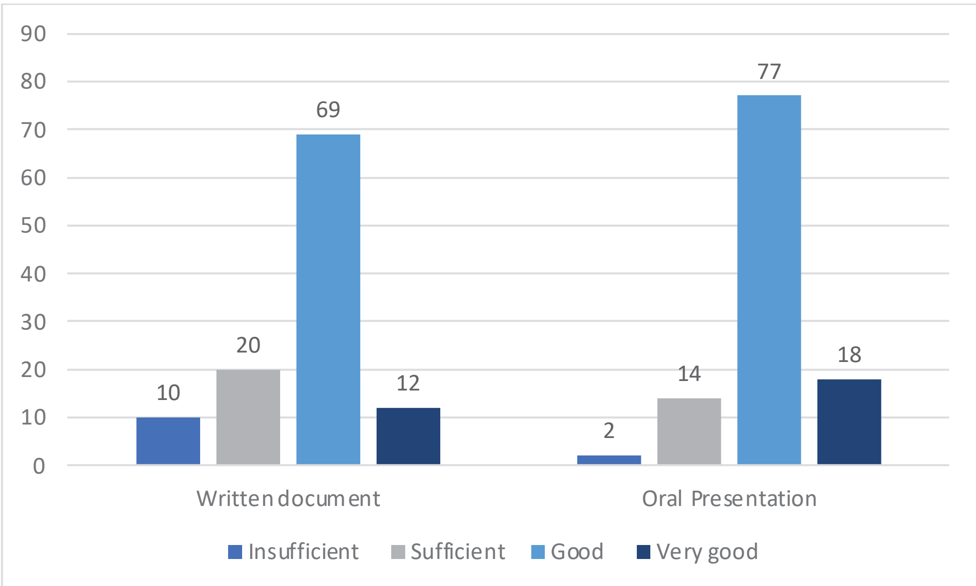

Figure 2. The overall grades obtained by the students in the written document and in the oral presentation.

Only 10 students showed insufficient development of their ability to write scientific text, specifically, with some inaccuracies in terms of concepts or information, a non-objective message, and many superfluous aspects presented.

Regarding the oral communication of the work, Figure 2 shows that 77 students obtained a "Good" grade and 18 students obtained a "Very Good" grade in their oral presentation to the class. In these cases, the presentation was indicative of an excellent grasp of concepts and information, with the students demonstrating very well-articulated speech, without any grammatical or pronunciation errors, and a correct use of scientific language.

Figure 3 shows, in more detail, the results of the criteria used in the evaluation rubrics for the written document for presentation to the community and for the oral presentation.

Analysing the results in Figure 3 answers research question 2 of this study.

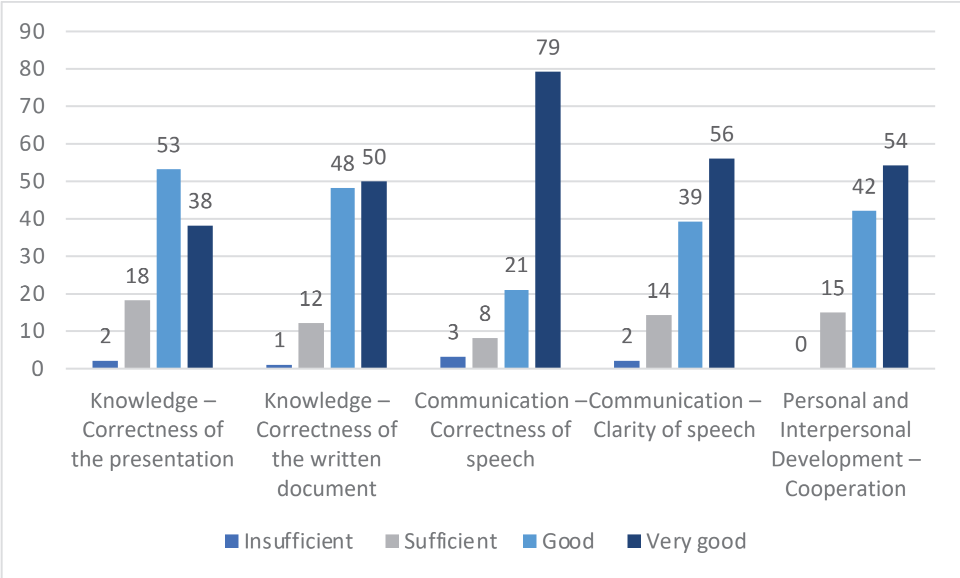

Figure 3. The grades, by category of criteria, obtained by the students for the written document and for the oral presentation.

Figure 3 shows that, in terms of knowledge, 53 students gave an oral presentation without any inaccuracies in terms of concepts or information and 38 students gave an oral presentation that showed an excellent mastery of concepts and information. Regarding the written document made to display to the community (poster, pamphlet), 50 students showed an excellent mastery of concepts and information.

In terms of communication, regarding the criterion 'correctness of speech', 79 students presented a very well-articulated speech, with no grammatical or pronunciation errors and the correct use of scientific language, and 21 students presented a reasonably well-articulated speech, with no grammatical or pronunciation errors and the correct use of scientific language. As for the clarity of speech, 56 students gave a very well-articulated speech, with no grammatical or pronunciation errors, and showed the correct use of scientific language, and 39 students gave a reasonably well-articulated speech, with no grammatical or pronunciation errors, and showed the correct use of scientific language.

In terms of personal and interpersonal development, in the cooperation sub-criterion, 54 students demonstrated excellent cooperation between the various members of their group and a logical and extremely well-organised presentation.

6. Discussion

The results show that 77 students obtained a "Good" grade and 18 students obtained a "Very Good" grade on their oral presentations, which indicates a proper use of scientific concepts and strong clarity of speech. These results suggest that the inquiry module may have fostered students' self-confidence in their oral presentation of scientific content, a valuable skill for students' complete education. However, it is important to note that due to the study's design, which only involved a single group, we cannot definitively attribute these improvements solely to the IBSE methodology. The lack of a control group limits our ability to draw conclusive comparisons.

The results on the personal and interpersonal development criterion showed that 96 students demonstrated good or very good cooperation and organisation in their group presentations, showing effective communication and cohesion which, according to the literature, are fundamental for collaborative learning (Pearson et al., 2010). This result emphasises the importance of teamwork in science education and suggests that IBSE can contribute to the development of social skills that are crucial in both academic and professional environments. However, we acknowledge that these results are based on subjective assessments and could be influenced by individual group dynamics, which were not controlled for in the study.

The results obtained in this study align with findings in the existing literature, particularly regarding the impact of IBSE on the development of scientific communication skills. As noted by previous studies, inquiry-based literacy activities facilitate both the learning of scientific content and the development of communication skills. One study highlights that "when literacy activities are driven by inquiry, students simultaneously learn how to read and write science texts and to do science" (Pearson et al., 2010, p. 459). Another review supports this, revealing that inquiry-based writing instruction "can meet the goal of developing science writers' scientific thinking and writing skills by contextualising them in scientific inquiry practices" (Lin et al., 2023, p. 253). Furthermore, research shows that "classes implementing stepwise inquiry had higher scores for communication skills and scientific attitudes than those undertaking expository approaches" (Wildan et al., 2019, p. 407), which resonates with the positive outcomes observed in our study. In particular, there was clarity, correctness and mastery of scientific language among the 10th graders, both in the writing of scientific texts and in oral communication. However, given the design of the study, we acknowledge that it is difficult to definitively conclude that these outcomes could not have been achieved through other methods of training students in writing and oral presentations. While IBSE appears to have contributed positively, we can only speculate on whether similar levels of student performance would be possible without its implementation.

According to some authors (Jang & Hand, 2017; Pearson et al., 2010; Sampson & Walker, 2012; Wildan et al., 2019), the IBSE methodology not only promotes the understanding of scientific text, but also trains students in scientific writing, allowing them to integrate scientific concepts with greater precision and clarity. In this study, most students achieved "Good" or "Very Good" grades in both written text and oral presentations, which indicates an effective development of scientific communication skills. These results suggest that practicing scientific research, associated with IBSE, can stimulate greater autonomy in students when it comes to writing scientific content and orally expressing complex concepts. However, given the one-group design, we cannot rule out the possibility that other pedagogical approaches might yield similar results in terms of scientific communication development. Further studies involving control groups and long-term follow-ups would be beneficial to explore this.

7. Conclusions

The aim of this research was to analyse the impact of implementing a research module on the development of 10th grade students' oral and written communication skills. To this end, two guiding questions were formulated:

1. How does the implementation of a research module influence the development of oral and written communication skills among Year 10 students?
2. What are the specific results in terms of the clarity, correctness and mastery of scientific language following the implementation of a research module?

Regarding the second question, the results show a positive impact on clarity, correctness and mastery of scientific language. It was observed that 100 students obtained a rating of very good or good in the correctness of their oral discourse, showing an adequate use of scientific language. In addition, 96 students presented a clear exposition in their speech, demonstrating effective and well-structured communication.

With regard to the first question, it was found that the activity contributed significantly to students' involvement in understanding scientific concepts and processes, promoting the positive development of oral and written communication skills. In terms of knowledge, 91 students gave an oral presentation without any conceptual or information inaccuracies, while 98 students demonstrated mastery of the concepts and information in the written document.

In general, the students achieved good results not only in terms of correctness, clarity and mastery of scientific language, but also in their ability to co-operate between group members, highlighting the pedagogical relevance of implementing this research module. However, we must acknowledge the limitations of our study, such as the absence of a control group and the short-term nature of the assessment, which make it difficult to attribute the observed outcomes exclusively to the IBSE approach.

Although the results are promising, we did observe some limitations. A small number of students still struggled to achieve full correctness in the use of scientific language, which indicates that additional interventions may be needed to help these students. In addition, the subjective nature of some assessments, such as the interpersonal development assessment, may have introduced bias into the results. In terms of future research, it would be interesting to explore how the effect of IBSE on oral and written scientific communication skills can be sustained over time and in different educational contexts.

Moreover, we recommend future studies compare IBSE with other teaching methods in controlled settings to provide a clearer understanding of its specific impact.

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Appendix A

Table A1. Oral presentation evaluation rubric (adapted from Reis & Marques, 2016, pp. 253–255).

Criteria		Performance Levels			
		Very Good	**Good**	**Sufficient**	**Insufficient**
Knowledge	Scientific correctness	Presentation demonstrating excellent mastery of concepts and information	Presentation without any inaccuracies in terms of concepts or information	Presentation with some inaccuracies in terms of concepts or information	Presentation with several inaccuracies in terms of concepts or information
Communication	Correctness of speech	Very well-articulated speech with no grammatical or pronunciation errors and correct use of scientific language	Reasonably well-articulated speech with no grammatical or pronunciation errors and scientific language	Grammatical errors and difficulties with pronunciation and scientific language	Speech difficulties and grammatical, pronunciation and scientific language errors
	Clarity and objectiveness	Clear, objective exposition, highlighting the key points	Clear exposition, but with some superfluous aspects	Clear exposition, but not very objective; many superfluous aspects presented	Unclear exposition, lacking in objectivity and fundamental aspects
	Presentation of information	Information presented and not read	Information presented but accompanied by reading of some notes	Most information is read rather than presented	Information is read rather than presented
	Ability to arouse interest	Well-paced, smooth and effective presentation that captures audience's attention and interest.	Presentation with some missteps but effective in capturing audience's attention and interest	Presentation with few missteps and not always effective in capturing audience's attention and interest	Presentation with missteps and that fails to capture audience's attention or interest
	Audio-visual aid	Uses high-quality audio-visual elements to support or highlight content of presentation (images, diagrams/graphs, videos)	Uses quality audio-visual elements but does not explore them properly	Uses some audio-visual elements of poor quality	Does not use any audio-visual elements to support or enhance content of presentation (images, diagrams/graphs, videos)
	Use of voice	Audible speech throughout presentation, good articulation of voice with audio-visual aid	Speech audible during most of presentation, with inflexion and expressiveness	Speech with large fluctuations in voice volume, but without expressivity	Inaudible speech with monotonous voice, lacking inflection and expressiveness

Table A1. *Cont.*

Criteria		Performance Levels			
		Very Good	**Good**	**Sufficient**	**Insufficient**
Personal and interpersonal development	Cooperation between group members	Excellent cooperation between various group members; logical and extremely well-organised presentation	Good cooperation between most of group. However, one member did not prepare presentation with others	Poor cooperation between various group members. It is clear that some of them did not prepare presentation	No cooperation between various group members; disorganised presentation
	Creativity	Extremely creative presentation both in terms of methodology and materials used	Presentation with various creative aspects in terms of methodology and materials used	Uncreative presentation in terms of methodology and materials used	Uncreative presentation in terms of both methodology and materials used

Table A2. The rubric for evaluating the final product for exhibition to the community and dissemination on the school website (adapted Reis & Marques, 2016, p. 108).

Criteria		Performance Levels			
		Very Good	**Good**	**Sufficient**	**Insufficient**
Knowledge	Scientific correctness	Object revealing excellent grasp of concepts and information	Object without any incorrect concepts or information	Object with some inaccuracies in terms of concepts or information	Object with several inaccuracies in terms of concepts or information
Communication	Message	Clear, objective message, highlighting key aspects	Clear message, but with some superfluous aspects	Clear message, but not very objective; many superfluous aspects presented	Unclear, non-objective message, without highlighting key aspects
	Interactivity *	Object is very interactive	Object is moderately interactive	Object is scarcely interactive	Object is not interactive
	Graphic appearance	Very appealing object from a graphic point of view	Moderately appealing object from a graphic point of view	Scarcely appealing object from a graphic point of view	Not graphically appealing object
Personal and interpersonal development	Activism **	Very explicit	Moderately explicit	Scarcely explicit	Absent

* the ability to raise questions, promote individual and collective reflection, promote interaction between visitors, allow visitors to leave their mark (Reis & Marques, 2016). ** the ability of the product to raise awareness in the visitor and motivate them to action (Reis & Marques, 2016).

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Project Report

A Problem-Based Learning Electrochemistry Course for Undergraduate Students to Develop Complex Thinking

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Abstract: This paper presents a Problem-Based Learning (PBL) electrochemistry course contextualized within a real-world problem of wastewater treatment, designed to enhance students' subject matter knowledge. The sample was a group of chemistry and chemical engineering undergraduate students who were taking an electrochemical course. The research outlines various activities and analyzes five cases of team learning outcomes using Atlas.ti(TM) 22 software. The analysis identifies and describes eight categories of scientific knowledge and practices derived from student reports. The results are represented using a Sankey diagram to show the complexity of students' thinking after solving their problem. The findings indicate significant progress in students' conceptual understanding of electrochemistry, the development of complex thinking, and the recognition of its relevance in solving everyday problems.

Keywords: problem-based learning; electrochemistry; undergraduate students; scientific skills; critical thinking

1. Introduction

Electrochemistry is a versatile scientific discipline with applications in energy, technology, and environmental sustainability, contributing to a lower carbon footprint (Brett & Oliveira-Brett, 2020). Extensive research in areas such as battery technology, environmental remediation, electrosynthesis, electroanalysis, and neuroscience, to name a few, has driven innovation in this field. Consequently, it is crucial to equip students with a solid foundation in electrochemistry.

However, electrochemistry is often perceived as one of the most challenging subjects for students (Johnstone, 2010; De Jong & Treagust, 2002), with numerous documented alternative conceptions (Brandriet & Lowery, 2014; Rahayu et al., 2022; Lu et al., 2020; Sanger & Greenbowe, 1997; Sanmartín & Sanjosé, 2014; De Jong & Treagust, 2002; Taber, 2019; Barke et al., 2009; Tsaparlis, 2019; Turner et al., 2024). While many students can solve quantitative problems on exams, few can answer questions that require deeper conceptual knowledge (Sanger & Greenbowe, 1997). The challenge is that electrochemical systems are inherently complex, both spatially and dynamically, generally requiring several models to describe and understand what is happening in the electrochemical cell (Faulkner, 2014). This demands an understanding of chemical reactions, elements of electricity, mass and charge transport, elements of electrical circuits, and knowledge about the nature of electrically conductive materials (Kempler et al., 2021).

Traditional undergraduate theoretical electrochemistry courses are developed predominantly from a symbolic conceptual level. The electrochemical structuring concepts rely on the order of topics presented in the physical chemistry textbook, which emphasizes mathematical development. Specialized texts, such as Bard and Faulkner (2000), result in additional challenges for students due to their high analytical and mathematical rigor (Kempler et al., 2021). Furthermore, the use of general physical chemistry textbooks can lead to the emergence of alternative conceptions (Turner et al., 2024; Sanger & Greenbowe, 1999). For instance, the Daniell cell, presented in textbooks as the initial model, with which both language and general description of the electrochemical cell are addressed—cathode, anode, electrolyte, semi-reactions, or salt bridge—often fails to help students perceive the electrochemical cell as a system (Boulabiar et al., 2004).

Contextualization is scarce in this kind of traditional course, with few examples of real-world applications like batteries and well-known industrial electrosynthesis processes. Generally, the questions that the student answers are as follows: define, enunciate, and explain; all of which can be framed in low-level thinking requirements or declarative knowledge. Written exercises, often selected from end-of-chapter problems, can be solved using algorithmic strategies without necessarily understanding phenomenological or mathematical models. These exercises are usually disconnected, presenting a fragmented and irrelevant view of electrochemical practices. Students frequently refer to the Nernst equation as a "formula", which requires certain data that the teacher provides to solve it rather than recognizing it as a model. In general, the students have no opportunity to use it as a tool for thinking about reality, which can help them understand and solve scientific problems.

This research proposes that a theoretical electrochemistry course should not be based on textbook structure. Instead, it should be designed to produce complex scientific thinking by incorporating a guided inquiry learning orientation and experimental disciplinary practice as cognitive tools in the sense that Guile (2006) proposes: to conceive theoretical concepts as cultural tools that we apply in practice to see these tools as resources to evaluate practice critically. Also, the context and the application of knowledge in relevant practices and in learning communities based on inquiry can produce more interrelated and practical learning. Thus, students have a more significant opportunity to develop scientific thinking skills, such as inquiry, modeling, or argumentation.

This way, students are presented with an electrochemical problem that requires them to build ideas and concepts of the subject matter while developing simple, homemade, and low-cost electrochemical cells. This hands-on approach encourages them in the construction of the apparatus and the performance of the necessary experiments. They are challenged to link the macroscopic world, the construction of the cell, and the function of its elements, with the models and symbolic representations they develop to solve its functioning.

Since the course outset, all learning activities and assessments are designed around a problem to be solved, which is disciplinary centered and intended to develop students' content knowledge while orienting them to build a product: the electrochemical apparatus. That is, with a Problem-Based Learning (PBL) approach and a project orientation. The course features a flexible classroom setup, internet connection through mobile devices, and virtual space integration with the classroom platform.

Active learning environments have been shown to outperform traditional science classes. They promote improved performance, reduce failure rates, and do better at serving large groups (Freeman et al., 2014). PBL is an active, socio-constructivist learning approach based on inquiry. It integrates theory and practice and is designed based on context. The goal is to provide students with a deep and transformative learning experience that fosters scientific thinking through an authentic problem of their interest (Savery, 2006; Ramos-Mejía, 2020). This approach aims to develop critical and complex thinking, high-level cognitive skills, metacognition, collaborative work, and, in the context of scientific disciplines, an experience in which the student can build an adequate notion of the nature of science.

PBL, a student-centered approach, has been widely used in higher education, particularly in the sciences (Hung & Amida, 2020). It started in the medical training context in Canada, but now it is applied to many disciplines, including chemistry (Varadarajan & Ladage, 2024). Compared to traditional instruction, PBL has been shown to enhance students' remembering of the acquired knowledge (Dochy et al., 2003) and valuing it as powerful, specifically in enhancing learning (Dochy et al., 2005).

Problem- and project-based learning engages students in solving real-world problems and questions that are aligned with curriculum goals, fostering deeper learning and relevance (Hmelo-Silver, 2004). These problems must be significant to students but ill-defined, so they are motivated by the task. Because the challenge fulfills them, they are willing to invest themselves in the inquiry and in managing their own learning until they achieve a conceptual understanding. Such settings enable STEM students to recognize the interdisciplinary nature of complex problems, preparing them for workplace requirements through teamwork, collaboration for a common outcome, and peer critique of each other's work (Odell & Pedersen, 2020).

In chemistry education, PBL has been used successfully, for example, in sustainable development (Günter et al., 2017) and a range of transferable skills (Overton & Randles, 2015), environmental chemistry (Jansson et al., 2015), improvement in students' self-efficacy beliefs (Mataka & Kowalske, 2015), and students' critical thinking and problem-solving skills (Aidoo et al., 2016). In electrochemistry courses, Günter and Alpat (2017) found that students in PBL contexts were better at understanding the topic and its structure compared to students in traditional settings.

The student learning outcome of this course is to develop a conceptual model of the electrochemical cell, with which they can understand the basic principles of its operation and the variables that can modify its efficiency. This is referred to as "electrochemical thinking". As students build their models, they also realize that the context and purpose for which the electrochemical cell is used play an important role in understanding its design and operation. The model can then function as "a hub where heterogeneous information (scientific and empirical knowledge, relevant variables and parameters, measurement methods, pragmatic criteria concerning the solution) is collected and integrated into a coherent whole" (Boon et al., 2022, p. 15). If students are allowed to venture into designing devices and performing multiscale modeling or applying analytical thinking, this can contribute to consolidating their understanding of the basic concepts of thermodynamics, kinetics, transport, and materials science (Kempler et al., 2021), all of which are fundamental to electrochemical thinking.

Students should approach the study of building an electrochemical cell, galvanic or electrolytic, depending on their chosen problem. Figure 1 presents the problems offered to students, who must justify their choice of materials and operating details by applying electrochemical knowledge acquired in the course. As they build their devices, students develop the necessary skills to elucidate how the electrochemical device works. When theoretical predictions do not match experimental observations and data, students must be able to explain the set conditions that could be involved. Their challenge is to develop electrochemical thinking that incorporates the complexity of real systems.

The course was designed considering three skill dimensions:

1. Development of Lower-Order Thinking Skills (LOTS) through a flipped classroom approach, where students review video materials or short readings and complete a self-grading Google questionnaire. They also deliver a weekly activity that addresses various examples. Thus, as the course progresses, the focus is on using the problem selected by each team as the example with which knowledge is explored. All work is incorporated into

their final written report, ensuring that the problem is built in class rather than treated as an extra activity.

Figure 1. List of problems offered to students. They must choose one to solve in teams throughout the course.

2. Development of higher-order thinking skills (HOTS), which includes critical thinking, question formulation, problem-solving, decision-making, systemic and evaluative thinking, and transfer, according to Zoller and Nahum (2012). To solve the problem, the students' task begins with the questions they elaborate on to explore its difficulty and thus achieve the problem-solving thinking scheme: What do I know? And what do I need to know?

Students must develop the following aspects: description of materials choice and their justification based on materials' fit to function in the electrochemical cell; description of electrochemical cell configuration; description and explanation of conductivity; description and explanation of thermodynamics; kinetic description and explanation; experimental discussion and explanation regarding discrepancies with theoretical calculations; waste treatment and/or disposal; and bibliographic references.

The problem serves as an integrative activity that puts into practice the knowledge and skills obtained so far. Hence, students can develop scientific know-how in a learning community. In this electrochemistry introductory course, students recognize macroscopic phenomena instead of starting with a discussion of redox reactions at the symbolic level. Students build concepts according to the following structure: (1) recognize the macroscopic system, (2) relate with the symbolic representation, and (3) model the interface and bulk phenomena at the nanoscopic level.

Using simulators is fundamental to exploring and linking macroscopic, symbolic, and nanoscopic representations (Lee & Osmam, 2017). Students use simulators available online and develop their own using the Nernst equation for thermodynamics and the Butler–Volmer equation for a kinetic approach; they also represent double-layer electrochemical reaction phenomena through x-y diagrams and particle sketches. Simulators help students visualize the synchrony between detectable signals and nanoscopic/kinematic behaviors in electrodes (Wang & Wang, 2022).

Development of Soft Skills: collaborative work and activity planning. Students work in teams, experiencing and valuing collaboration, positive interdependence, role-based engagement, and quality criteria to reach general agreements. They engage in a "Team Contract", establishing their commitments and goals, and evaluating themselves during the activities with their own rubric.

The course identifies *scientific knowledge and practices* that students develop from the implementation of PBL as previously described:

1. Content Knowledge: Students demonstrate subject matter knowledge, ranging from definitions to the recognition of electrochemical cell elements and their functioning.

2. Modelling: Students use models to explain some issues related to electrochemistry or make graphical simulations to represent data.

3. Engineering Practice: Students design and build requested equipment related to the subject. The solution to technological problems regarding design concepts is based on functional interpretations of phenomena (Boon et al., 2020).

4. Electrochemical Thinking: There is evidence of both recognition and understanding of the interrelatedness of electrochemical processes in students' work.

5. Argumentation: Students must justify their choice of materials, show practical and professional project communication elements, and relate different kinds of knowledge that support their affirmations.

The course focuses on developing HOTS through one of the problems the students selected to show the knowledge and thinking results after solving it: **Cans out of the trash!** This problem centers on the wastewater treatment process, mainly from grey water produced in washing machines. Given the water shortage in Mexico City and other parts of the country, there are students who have suffered from this problem at home, and, therefore, it becomes relevant to show how electrochemistry can help improve wastewater quality. Electrochemistry offers different technological solutions for wastewater treatment, and electrocoagulation is one of them. This technique is mainly used in wastewater contaminated with surfactants from detergents, soaps, and organic residues such as oils or greases, which can form very stable emulsions of water–oil–surfactant systems. In sewage, the physicochemical coagulation–flocculation method is one of the most widely used within primary treatments.

The coagulants used are iron and aluminum salts, where polyvalent cations cause the destabilization of colloids' double layers. In electrocoagulation (Shahedi et al., 2020; Das et al., 2022), the coagulant is generated in situ in a proportion that can be regulated through parameters controlled by Faraday's laws in an electrolytic cell. That is, through the oxidation of an Al or Fe electrode, which functions as an anode, the polyvalent ions Al^{3+} or Fe^{2+} are generated, and the latter can be subsequently oxidized to Fe^{3+} with the action of oxygen dissolved in water. Colloids are destabilized by the interaction of charges, agglomerating and acting with insoluble basic species of metal cations formed when the pH of the system becomes alkaline; they form flocs, on which organic and inorganic substances adsorb. The floc can precipitate or be washed to the surface by hydrogen gas bubbles formed from hydrogen cation reduction at the cathode (electroflotation). Cathodically generated hydrogen is also responsible for pH increase and metal hydroxide formation, so there is no need for extra reagents to adjust the pH. Thus, the amount of reagents added is very low or non-existent, produces less sludge than normal coagulation, and organic matter is effectively removed; it has high current efficiencies, treatment is achieved in shorter times than in other methods, and in places where electricity is cheap, costs are lower than in conventional methods.

Although electrocoagulation is very complex, it is a simple wastewater treatment option, but it represents a comprehension challenge due to all physicochemical phenomena occurring. However, extensive research has been performed on surface phenomena, electrolysis, methods of chemical determination, and water treatment quality monitoring. It also involves approaching the environmental standards field, not as recipes to be followed but as methods with reproducible protocols established by professionals in the discipline. Wastewater treatment by electrocoagulation allows the incorporation of conceptual and procedural content that is significant for the student and has important motivational content. The result is predetermined and implies a deductive approach to the object of study; that is, the problem posed is a well-documented system, solved for the teacher but still unknown to the students, which makes it a project with an open answer for them, but a controlled environment for the teacher.

This problem imposes several elements that contribute to the contextualization of electrochemical practice increasing its complexity, unlike an example of electrochemical cells in ideal conditions. In this sense, in addition to the scientific knowledge and practices described above, the following categories are added:

1. Transversal Knowledge: There is evidence that students incorporate information from other disciplines to describe complex electrochemical processes.
2. Sustainability: Students demonstrate an understanding of environmental issues and sustainable practices.
3. Context: Students develop projects using everyday materials, ensuring practical applicability in real-world settings.

2. Methodology

Electrochemistry is a mandatory theoretical course for the Chemistry and Chemical Engineering bachelor of the UNAM School of Chemistry. The cohort is 250 students and does not have an associated laboratory. Electrochemistry is taught in the second year when students have taken the conceptual elements necessary to complete this course successfully.

The study was conducted during the first school period of 2024, with one class of 50 students using the PBL approach by the instructor, who is also one of this paper's authors. Students were divided into teams of 3 or 4 members, each selecting a problem of their liking from the list provided (see Figure 1). They worked on their chosen problem theoretically and experimentally throughout the school period, presenting their solutions in a final report. This report had the following structure: introduction, objectives, justification of the chosen problem, materials selection explanation, construction process of the electrochemical cell that would solve the problematic situation, a theoretical discussion that provided a basis for the experiment, discussion, and conclusions.

Student assessments were designed considering the three skills dimensions: LOTS, HOTS, and soft skills. All students passed the course. This study focuses on analyzing whether students developed electrochemical knowledge and electrochemical thinking in the context of complex thinking, by inspecting the reports of five teams that chose wastewater treatment problems. The teams considered are Aquacan, Aluminiums, Electrovives, Electrocoagulation, and Electrolytes.

The reports written by the students were assessed using the qualitative analysis program ATLAS.ti(R). This program allows for faster coding and more efficient results. Each report was analyzed using the categories indicated for *scientific knowledge and scientific practices and* elements related to *sustainability* and the environment listed and described above. Table 1 shows quotes from every category of scientific knowledge and scientific practices as they appear in the students' documents.

Table 1. Categories and codes used for the analysis, as well as quotes from students.[1]

Category	Code	Quotes
Knowledge of the discipline (Electrochemical knowledge)	CKnw	"...to prepare the electrolyte solution. A typical concentration can be around 0.1 M to 0.5 M. The main half-reactions are as follows: oxidation: $Al \rightarrow Al^{3+} + 3e$ Reduction: $2H_2O + 2e \rightarrow H^+ + 2OH^-$ Global reaction: $2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2(g)$"
Transversal knowledge	TransKnw	"biological treatment, it should be taken into account that the effluent is not suitable for consumption due to some bacteria, viruses or pathogens that were not eliminated in the previous process..."
Modeling	Mod	In this case, students represent their electrochemical cell using graphs, equations, and interphase sub-micro representations (see Figure 2)
Argumentation	Arg	"Water is a substance with a high dielectric constant, which allows the dissociation of inorganic salts and allows the solutions to conduct electricity; in this case, the use of water should ideally be drinkable, but because other electrolytes are also available, this can increase the probability of finding the desired final product"
Context	Ctx	"Given the high amounts of water used only in domestic activities, like washing clothes, dishes, or hands, the concern arises that, in most cases, this water has only one use and is then disposed of into the drainage system or even the ground on the street"
Electrochemical thinking	EchThink	"The conductivity of an electrochemical cell is crucial for its efficient operation, especially in processes such as electrocoagulation. Understanding the difference between electrode as an electronic conductor and electrolyte as an ionic conductor is critical to optimizing cell performance"
Engineering Practice	EngP	"Although the concept may sound simple, its execution requires careful design and rigorous testing to ensure its efficacy and safety"
Sustainability	Sust	"The problems of water stress, water pollution, poor waste management, and the lack of awareness about the consumption of single-use objects that we discard by turning valuable materials into garbage are urgent global challenges".

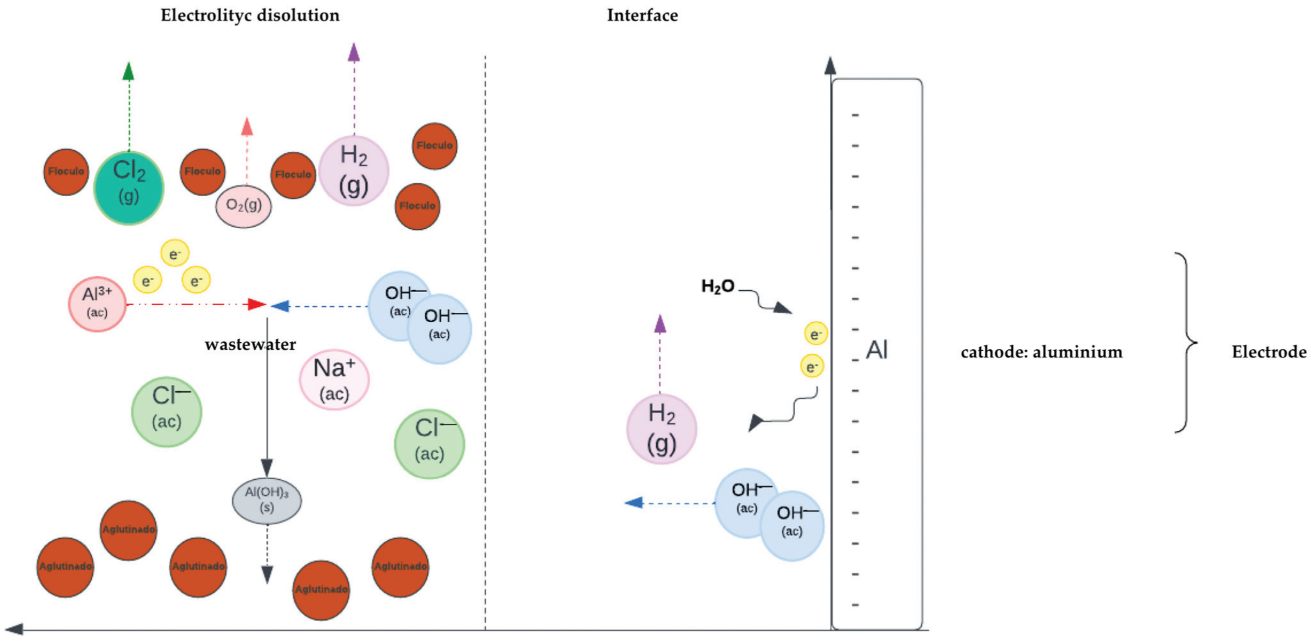

Figure 2. Students' representation of molecules and ions at the bulk and cathode interface shows hydrogen evolution on Al(s) in an alkaline environment. It uses particulate representations, arrows to show interactions and movement, and double-layer x-y graphic model representation.

3. Analysis of Results

The analysis using Atlas.ti(R) revealed the frequency of different codes and their co-occurrences, providing insights into the relationships between categories described in Table 1. Word Clouds diagrams elicit the language the students know and use, while Sankey exhibits conceptual relations that could gather complex thinking.

The Word Cloud in Figure 3 illustrates the most frequent terms used by students, after leaving only those words directly related to the problem and content knowledge. It shows the students' language in all five teams on their final report. Subject matter language can be recognized, as well as elements associated with the different categories of analysis. The most frequent words show a complete picture of the electrochemical discussion in the specific context of wastewater treatment using aluminum electrodes.

Atlas.ti(R) allows us to identify the occurrence of the different codes analyzed and bring forth the relationships that happen between them, that is, the co-occurrences. For this reason, the most frequent codes will be reviewed for the whole group and for three specific teams: Aquacan, Aluminiums, and Electrocoagulation.

Figure 4 shows the general case of occurrences. All teams exhibit the presence of all codes; however, some developed more robust knowledge than others. The sizes of color bars indicate the occurrence for every code; for example, the "Aluminiums" and "Aquacan" teams obtained more robust knowledge than "Electrovives" and "Electrolytes". This is also related to the reports presented; some were longer and argumentative, while others just showed the content knowledge and some elements of argumentation and transversal knowledge.

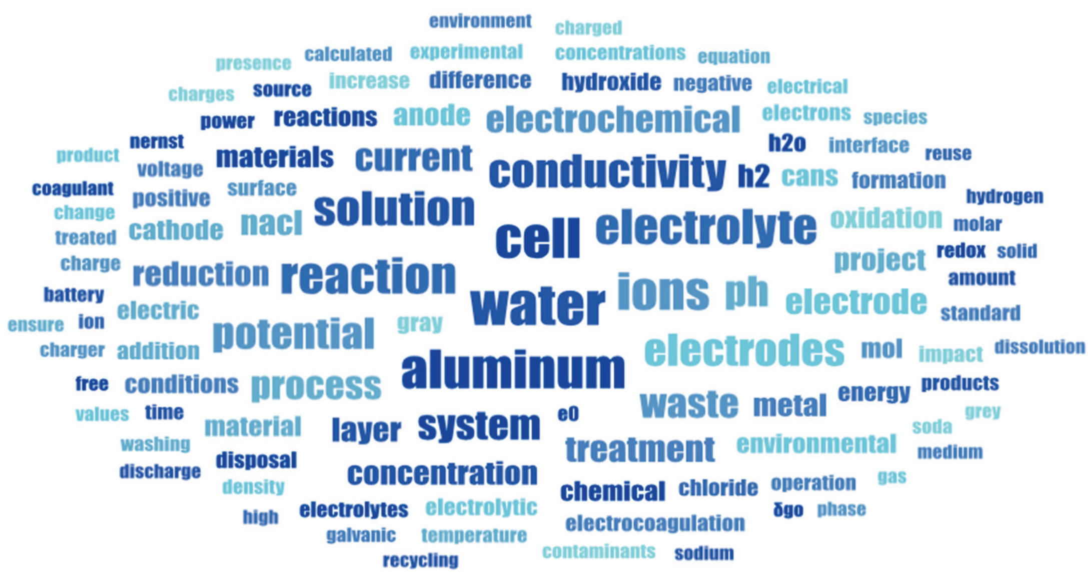

Figure 3. Word Cloud outcome of the language used on the report of selected teams.

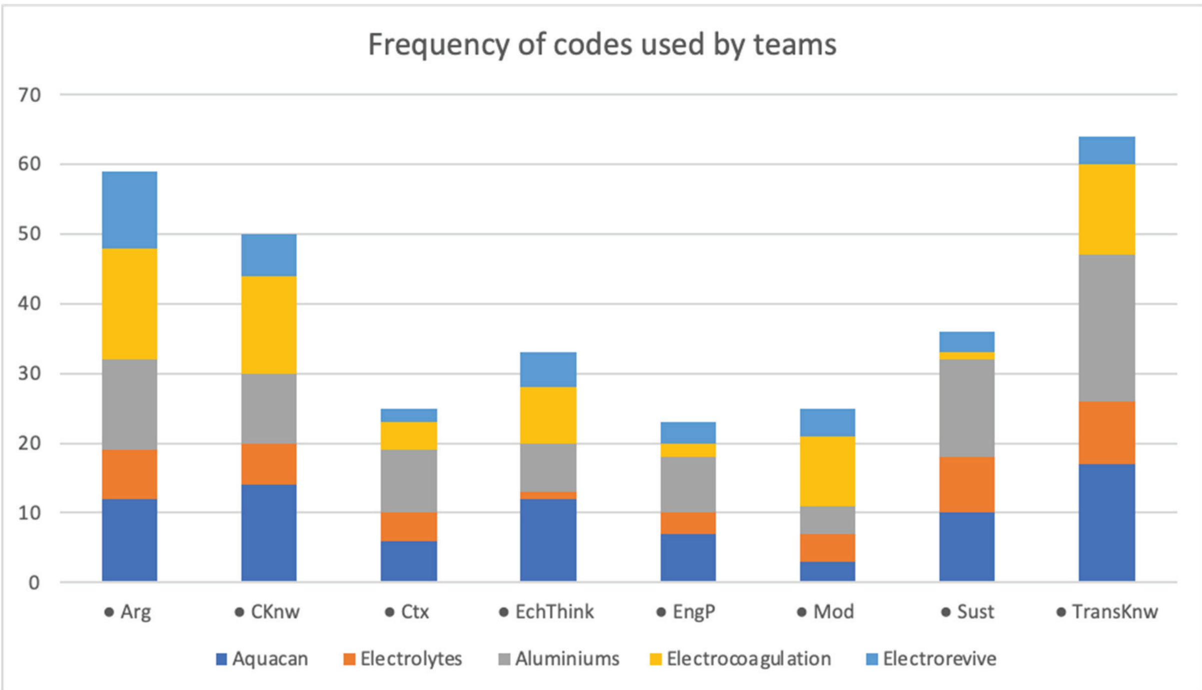

Figure 4. Bar diagrams of codes for every team. Codes are the following: Arg (argumentation), CKnw (electrochemical knowledge), Ctx (context), EcThink (electrochemical thinking), EngP (engineering practices), Mod (models), Sust (sustainability), TransKnow (transversal know).

Moreover, three code categories appear more frequently: transversal knowledge (TransKnow), scientific argumentation practice (Arg), and content knowledge or electrochemical knowledge (CKnow). To a greater or lesser extent, all five teams show a high occurrence of these codes. This frequency is expected since students must use content knowledge to address their problems. Also, they must be able to justify and/or argue in such terms the relevance of the proposed solution; however, it is interesting that transversal knowledge appears the most. This category involves the knowledge students acquire in previous courses and in the inquiry phase, which allows them to strengthen their learning and use it practically in this subject.

PBL proposals highlight the relevance of knowledge thinking and application in disciplinary contexts. As students' views become more complex, they need knowledge from other courses (TransKnow) for better contextualization. As a result, they develop a thought of electrochemistry inquiry much more like electrochemistry professional thinking. In contrast, traditional electrochemistry courses taught at the university are focused on subject matter knowledge only, with large amounts of mathematical foundation but without necessarily developing chemical and electrochemical thinking. Therefore, for these types of courses, this study would expect codes mainly related to content knowledge, without a clear context or a relationship of transversal knowledge.

On the other hand, from the perspective of problem-solving within a context, students must use elements, such as those described in Table 1, as ways to integrate them to formulate better arguments. Complex thinking means applying all the elements of scientific thinking within a context and with elements related to the environmental problem trying to be solved. Likewise, it requires using argumentation in a way there is evidence of critical thinking, question formulation, problem-solving, decision-making, systemic and evaluative thinking, and transfer, as Zoller and Nahum (2012) indicate as HOTS.

Sustainability and electrochemical thinking were the second most common codes. Since the problem posed is for wastewater treatment, sustainability is expected to appear frequently in student discourse. Nevertheless, some teams were better at this issue than others, highlighting that their work not only integrates sustainability but also elements of the environment. However, students do not necessarily consider this; there is not much evidence of this code in some cases.

Electrochemical thinking (ElechThink) shows how students understand and use electrochemical cells, an essential and necessary content of this course. This code is particularly relevant for the study as it shows that students are getting a real, complex understanding of the subject and how this can help solve different environmental and energetic issues.

It is also interesting to note that engineering practice (EngP) is an element that, in many cases, is taken for granted. Teachers do not explain to students how to build apparatuses or equipment, but it is mandatory in this course, the first author posits. This code appears less in some teams, suggesting how difficult it could be for students.

Another element that can be analyzed is how codes are interrelated; this phenomenon is called co-occurrence. To perform this, the Sankey diagrams represent two general ideas: the frequency of each code (occurrence), indicated by the thickness of the flow lines, and how these codes relate to each other (co—occurrences). Figure 5 shows the Sankey diagram for the co-occurrences of the "Aluminiums" team. This type of diagram represents the complexity of thinking the students acquire. In this case, as in all teams, the most recurrent codes were argumentation (Arg) and transversal knowledge (TransKnw), so it was of interest to know which other codes were related to these.

A direct relationship of co-occurrence between argumentative practice and transversal knowledge is evident. Students justify and/or argue whenever they use transversal knowledge. However, a closer look reveals relationships that go through other codes, for example, Arg—EngP—Sust—TransKnow; this means that students used these four codes interrelated simultaneously for insights. It is the same case for Arg—CKnow—EchThink—Sust—TransKnow. It is possible to observe the complexity of the thinking structure that students are building, which, the authors believe, is directly related to implementing this PBL approach in the electrochemistry course.

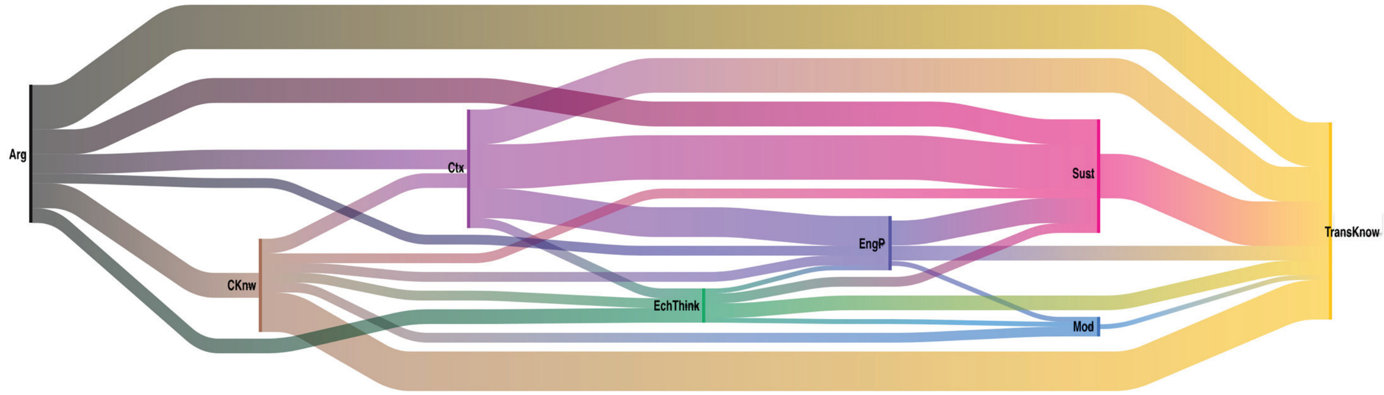

Figure 5. Co-occurrence diagram for the Aluminums team. The colors represent the different codes: black (argumentation), yellow (transversal knowledge), pink (sustainability), brown (content knowledge), light blue (modeling), dark blue (engineering practice), green (electrochemical thinking), and purple (context).

Figure 6 shows a diagram of co-occurrences for the Aquacan team, which differs significantly from the Aluminiums. For Aquacan, codes such as electrochemical thinking and modeling have a higher frequency than sustainability. However, both argumentation and transversal knowledge are the most frequent. In this case, it is possible to visualize relationships between Arg—EchThink—TransKnw, but there is also a complex relationship between CKnw—Mod—TransKnw. Another noticeable aspect is the more significant occurrence of model code, presenting relationships mainly with subject matter knowledge, as well as electrochemical thinking and transversal knowledge.

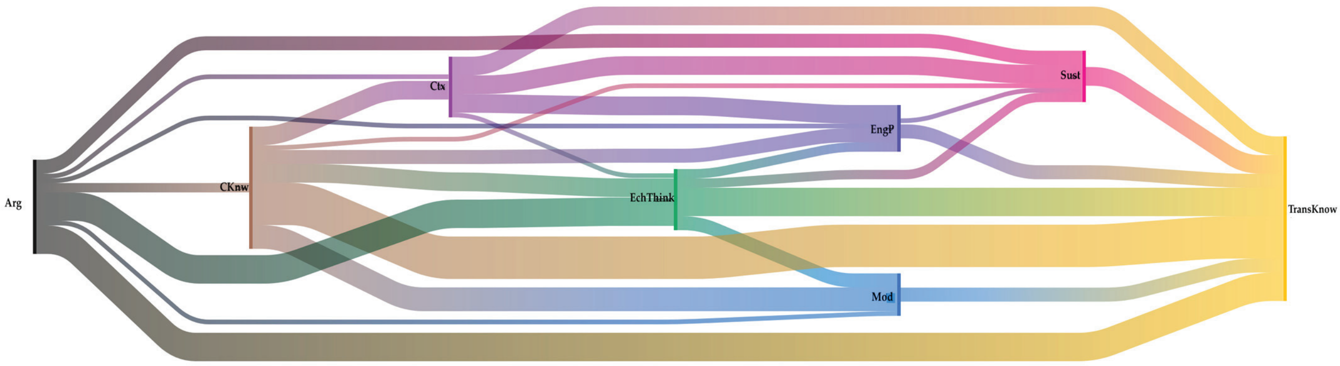

Figure 6. Sankey diagram over co-occurrences of the Aquacan team. We can see how students' thinking is complex but different from the Aluminiums team. The colors represent the various codes: black (argumentation), yellow (TransKnow. transversal knowledge), pink (sustainability), brown (content knowledge), light blue (modeling), dark blue (engineering practice), green (electrochemical thinking), and purple (context).

The fact that electrochemical thinking becomes relevant to the findings is essential to this work. It could mean that students are integrating the whole content knowledge into more complex possibilities, such as solving problematic situations and recognizing that electrochemistry is not just a subject to be memorized but to be understood. For the Aquacan team, as well as for the Electrocoagulation team (see Figure 7), electrochemical thinking appears frequently linked with other knowledge and practices. This is evidence of students explaining how they constructed their apparatus (EngP), how it worked, and how it was related to their theoretical calculations (CKnw), while at the same time, they applied a scientific perspective using modeling (Mod) and transversal knowledge (TransKnow) to support their electrochemical knowledge (CKnow) arguments (Arg). All of this is justified around context (Ctx) and with a sustainability perspective (Sust).

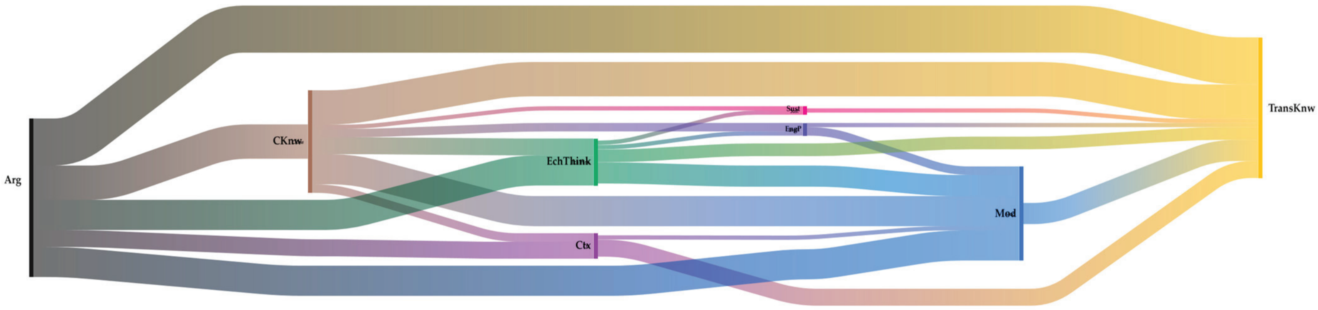

Figure 7. Sankey diagram over co-occurrences of the Electrocoagulation team.

Students achieved a model that acted as a “hub” for incorporating scientific and empirical knowledge and pragmatic criteria concerning the solution, integrating everything into a coherent whole. They posed questions and solved a problem using critical scientific thinking. Also, they made decisions while evaluating their empirical results and justified them using systemic thinking because they not only considered content-electrochemical knowledge but also incorporated context, transversal knowledge, and sustainability. Thus, students attained electrochemical thinking (EchThink) using HOTS. In other words, they achieved complex scientific thinking.

Figure 7 shows the co-occurrence diagram for the Electrocoagulation team. An important feature is the significant presence of model code, which is more frequently related to argumentation and knowledge of the discipline. Still, there is also a complex interrelatedness between Arg—Cknw—EchThink—Mod—TransKnw. In this case, codes related to context and sustainability appear with minimal occurrence, indicating that although students could develop some complex thinking, they only prioritized those elements related to scientific thinking. Unlike the other teams, where the context and sustainability look more robust, this team approaches the problem’s solution from a more superficial perspective.

The colors represent the different codes: black (argumentation), yellow (transversal knowledge), pink (sustainability), brown (content knowledge), light blue (modeling), dark blue (engineering practice), green (electrochemical thinking), and purple (context).

The findings show evidence that implementing PBL courses in undergrad studies could help students develop content knowledge and, at the same time, some scientific skills. Both let students develop different levels of critical thinking focused on the subject matter, electrochemistry, but in a contextualized way.

In the literature, the studies related to electrochemistry teaching using the PBL approach assess how much content is learned by students after being taught through this approach. One example is Acar and Tarhan (2007); these authors analyze how much students in 11th grade improve their understanding of some concepts related to electrochemistry. They found that students remediate common misconceptions when implementing a cooperative learning group approach. Another study by Günter and Alpat (2017) shows the results of executing the PBL approach in an analytical chemistry course while teaching electrochemistry. The authors identified that students understood subject matter knowledge better if they felt more motivated.

Tsaparlis (2019) also conducted a review of the electrochemistry teaching–learning process where he shows some of the few papers about electrochemistry PBL; and only one of them presents an undergrad strategy, albeit Tsaparlis (2019) mentioned that one of these papers did not show evidence of research results. Comparing these papers with this one, the authors could say that one significant difference is that the present research study assesses if students develop complex thinking when they must solve an electrochemical problem. The researchers considered that it is essential for students to improve their electrochemical understanding; however, they must provide more information about knowledge and skills related to scientific thinking and engineering practices, which is related to higher-order thinking skills.

4. Student Perceptions

It is challenging for teachers at the university level to get involved in courses with these characteristics. Students mainly focus on more traditional learning and achieving content knowledge. Therefore, knowing the students' opinions at the end of the course became a priority for this study. In the comments, students highlight various aspects of the PBL approach, such as teamwork and the perspective of the context as the center of problem-solving. It is possible to distinguish that they perceive the development of elements of complexity in the structuring of the resolution of their problem. In addition, students recognize the importance of electrochemistry in an everyday context and not just seeing it as another subject. Below are two comments from students who belong to the studied teams:

Student 1. Aluminiums team: "Working on a team project to study an electrocoagulation cell intended for greywater treatment using aluminum electrodes has been a deeply enriching and challenging experience. In particular, the fact that the aluminum used was recovered from recycled cans added an extra layer of interest and sustainability to our project. This approach allowed us to apply theoretical principles of electrochemistry and contribute to the reuse of materials and the promotion of eco-friendly practices. One of the most significant learnings was understanding the complexity and variables involved in the electrocoagulation process. Each step required meticulous planning and in-depth knowledge of electrochemical phenomena, from preparing and treating recycled aluminum to optimizing the cell's operating conditions. We learned how to evaluate and adjust parameters such as current density, water pH, and electrolyte concentration to maximize contaminant removal efficiency".

Student 2. Electrovives team: "We address a crucial problem by seeking to revitalize wastewater through electrocoagulation. This innovative technique offers a practical solution for wastewater treatment and highlights the importance of sustainability and water conservation. It is a good proposal for students to apply the concepts seen in the course as if we were in the lab, in addition to the fact that to carry out the project, we acquire greater knowledge. These projects offer a tangible perspective on how electrochemistry has useful applications for solving real-life problems, which are significant topics today".

5. Limitations of Study

This study is limited to grouping students' work. However, the authors consider it possible to collect individual data and compare whether this complex thinking is also developed in each student.

6. Conclusions

This research study presents the implementation of an electrochemistry course contextualized in a problematic situation, electrocoagulation, which may allow students to develop complex thinking about disciplinary content. Such implementation requires that students build their electrochemical knowledge from the base of transversal knowledge that has to do with scientific practices other than electrochemistry, such as characterization methods and sustainability, as well as the context in which this problem is intended to be solved.

To analyze the results of the implementation, the scientific knowledge and practices that involved solving the problem were codified, recognizing the following: content (electrochemical) knowledge, transversal knowledge, electrochemical thinking, sustainability, context, model, and argumentation. The learning outcomes of five teams of students taking electrocoagulation as their problem were analyzed using the Atlas.ti(R) software. Significant advances were found in the students' electrochemical conceptual understanding, complex way of thinking involving HOTS, and recognition of its relevance in solving real-world problems. This way of analysis recognizes how students think and, simultaneously, how they understand electrochemical knowledge from context and an environmental point of view.

In summary, this study demonstrates that a Problem-Based Learning approach in electrochemistry education can significantly enhance students' conceptual understanding, complex thinking, and scientific skills. By contextualizing learning within real-world problems, students develop a deeper appreciation for the relevance of electrochemistry in addressing everyday challenges. The integration of theoretical knowledge, practical experimentation, and collaborative work prepares students for the interdisciplinary and complex nature of scientific inquiry in the modern world.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

Notes

1 In column three are shown students' answers; the authors decided not to change or correct them.

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