Chapter 2

Problem-Based Learning and Inquiry-Based STEM Education

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Chapter Highlights

Effective STEM education requires equipping learners with the necessary skills to navigate the increasingly complex and technology-driven world. Among many promising pedagogical approaches, problem-based learning (PBL) and inquiry-based learning (IBL) stand as particularly promising due to their unique characteristics: Both approaches prioritize the learner being at the center of the learning process. Learners actively participate in the learning process by employing critical thinking skills through investigation. Consequently, both methods foster critical thinking skills, collaboration, and active participation of learners in authentic learning contexts, which are also essential skills for effective STEM education.

- Key Components of Problem-based Learning – The foundation of problem-based learning, characteristics, teacher roles and student benefits.
- Problem-based STEM Education– The intersection of problem-based learning and STEM, affordances of problem-based STEM education and different approaches for problem-based STEM teaching.
- Key Components of Inquiry-based Learning – The foundation of inquiry-based learning, characteristics.
- Inquiry-based STEM Education – The intersection of inquiry-based learning and STEM, affordances of inquiry-based STEM education and different approaches for inquiry-based STEM teaching.

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Introduction

Problem-based learning (PBL) is grounded in the principles of constructivism. (El Sayary et al., 2015; Mabley et al., 2020; Hmelo-Silver, 2004; Thibaut et al., 2018). Constructivism is predicated on the notion that learners should be encouraged to construct their own understanding and establish meaningful connections between new concepts and prior experiences. In this sense, the PBL approach aligns with constructivist learning theories (Thibaut et al., 2018; Woods-McConney et al., 2020). PBL involves students to collaborate in small groups and acquire the necessary knowledge to resolve a problem (Hmelo-Silver, 2004). Originated in medical education, PBL was pioneered in the School of Medicine at McMaster in the 1960s (de Graaff & Kolmos, 2003; Mabley et al., 2020; Servant-Miklos, 2018). Smith et al. (2022) characterized four principles of PBL as:

Problems embed in rich and relevant learning contexts;
active and strategic metacognitive reasoning;
collaboration based on intrinsic motivation;
problems embedded in real and rich contexts.

The effectiveness of PBL depends on the problems being placed in rich, relevant and authentic settings that allow students to grow in their ability to apply resources, knowledge, and skills both inside and outside of their discipline (Smith et al., 2022). Moreover, the problems need to be complex and ill-structured that are moderately scaffolded and situated in authentic contexts, as such problems both engage and challenge learners while enabling them to connect prior knowledge with cognitive development (Jonassen & Hung, 2008). In this manner, students' active involvement in the process of problem solving become central. Thus, PBL approach is accepted as student-centered pedagogy (El Sayary et al., 2015).

Recognized as a student-centered pedagogy, the effective implementation of the PBL approach in classroom contexts carries significant importance. Several models describing its application are discussed in the literature, one notable example being the seven-step model proposed by de Graaff and Kolmos (2003) (see Figure 1). This model starts with clarifying concepts being addressed during PBL process and finishes with testing and reporting the solution step.

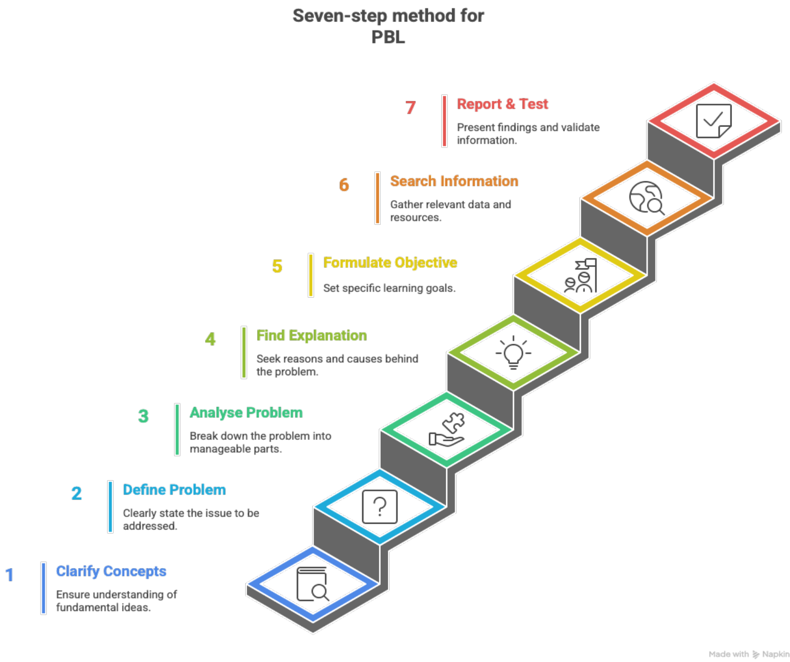

Figure 1. Seven-step model for using PBL in the classrooms (Adapted from de Graaff & Kolmos, 2003)

Teachers' role in PBL

While students actively involved in solving real world problems (Hung et al., 2008), teachers' roles are suited in being a guide and facilitator for students to develop appropriate problem-solving skills (de Graaff & Kolmos, 2003; El Sayary et al., 2015; Smith, 2022). It is important to maintain a careful balance in the level of guidance provided. While they provide required support for students to solve problems by acquiring new knowledge and skills, they also need to provide space for their student to become independent learners (Slough & Milam, 2013).

Affordances of PBL

PBL approach is implemented across diverse educational settings, ranging from primary to undergraduate education (Hung et al., 2008; El-Sayary et al., 2015; Taylor & Mifflin, 2008; Rehmat & Hartley, 2020; Yew & Goh, 2016). It has positive outcomes on developing skills including problem-solving, critical thinking, higher order thinking, collaborative learning, research and negotiation skills as well as communication and teamworking skills. In addition, the approach nurtures learners' self-confidence and motivation. Lastly, there has been significant improvements in students' performances in various tasks significantly (de Graaff & Kolmos, 2003; Hung et al., 2008; Kilroy, 2004; Warnock & Mohammadi-Aragh, 2015; Wood, 2004; Yew & Goh, 2016). Consequently, PBL is associated with three types of learning: cognitive, content and collaborative learning (de Graaff & Kolmos, 2003).

Problem-based STEM Education

PBL approach is usually associated with interdisciplinarity (Sayary, 2006). Interdisciplinarity, which entails the integration of knowledge, skills, and perspectives from two or more disciplines to generate products, account for phenomena, or address problems in ways unattainable within the boundaries of a single discipline (Boix Mansilla, 2010), the PBL approach offers a rich and meaningful context for exploring the interdisciplinary nature of STEM. By engaging learners in authentic, ill-structured problems that demand cross-disciplinary reasoning, PBL creates opportunities for students to transcend disciplinary silos, synthesize diverse forms of knowledge, and cultivate practices of inquiry that mirror those employed in real-world scientific and technological endeavors. Thus, the PBL framework highlights the potential of STEM education to advance both theoretical understandings of interdisciplinarity and its practical realization in classroom settings. Indeed, Asghar et al. (2012) identified PBL as the best strategy to teach STEM.

El Sayary et al. (2015) explained how PBL's three types of knowledge (content, collaborative and cognitive) which led to higher order thinking skills are situated in problem-based STEM education (see, Figure 2). Through problem-based STEM education, students could develop higher order thinking skills.

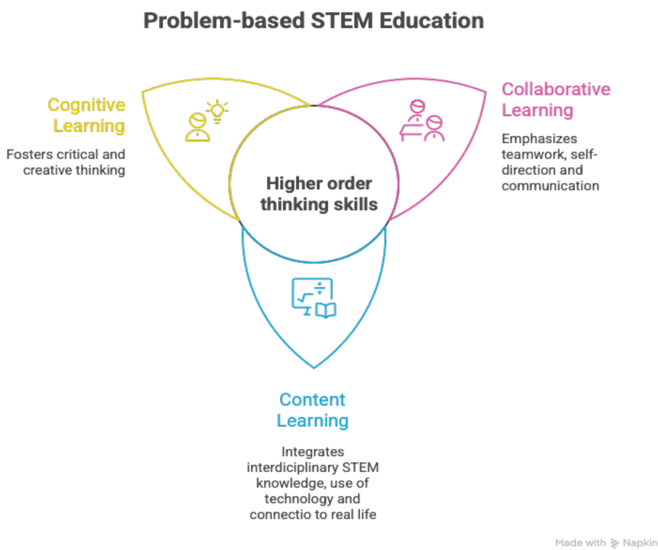

Figure 2. Problem-based STEM education (Adapted from El Sayary et al., 2015)

Affordances of problem-based STEM education

The literature increasingly documents positive outcomes associated with problem-based STEM education. Figure 2 illustrates how problem-based STEM education can be a valuable approach to enhance students' multiple skills development, including higher order thinking skills, 21st century skills (problem solving, collaboration, technology use, productivity, STEM awareness), as well as improving performances in STEM subjects and inspiring interest in STEM careers. Boosting students' motivation, engagement, enthusiasm and encouraging team work and communication were other benefits reported in the literature (Anazifa & Djukri, 2017; Beier et al., 2018; Coufal, 2022; de Graaff & Kolmos, 2003; Karamustafaoglu & Pektas, 2023; Rehmat & Hartley, 2020; Smith et al., 2022; Thibaut et al., 2018).

Approaches for problem-based STEM teaching sequences

While PBL approach is frequently adopted in educational settings, problem-based STEM applications are relatively new (Cebesoy, 2023). As there are many benefits that are associated with using problem-based STEM education, researchers used various methods to integrate PBL to STEM (e.g., Abbott, 2016; Karamustafaoglu & Pektas, 2023; Sarı et al., 2018; Rahmat & Hartley, 2020). For instance, Sari and colleagues (2018) used a five-step model to integrate PBL into STEM (Figure 3). In their model, teaching sequence started with identifying the problem to be addressed (step 1). The students, then, collected information and resources required to solve the problem (Step 2). In step 3, students formed hypothesis and suggested solutions to the problem being addressed. The students discussed possible solutions and selected the one among the suggested solutions by considering limitations and materials (step 4). In this step, they used engineering design. The last step includes student groups to present their designs and propose improvements/redesign elements for their designs.

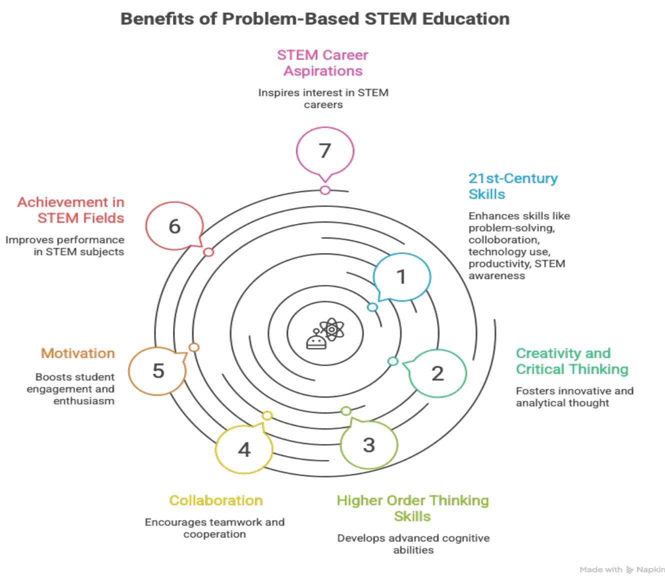

Figure 2. Benefits of Problem-based STEM education

The concept of "design" serves as a means of integrating engineering and technology with other STEM disciplines (Özkızılcık & Cebesoy, 2024). Within this framework, engineering design relies on iterative processes to address problems under specific conditions (Kelly & Sung, 2017). Similar to the teaching sequence proposed by Sari et al. (2018), Abbott (2016) incorporated engineering design into her six-step problem-based STEM teaching sequence (Figure 4). In this sequence, students were first introduced to an authentic problem—disposing of excess dyes directly into water sources. In the second step, they examined the issue from the perspective of scientists and engineers. The third step involved the use of a learning board, which included four guiding questions: (a) What do we know about the problem?, (b) What do we need to find out?, (c) How will we find our answers?, and (d) What is our action plan? The learning board was designed to foster curiosity and sustain students' interest.

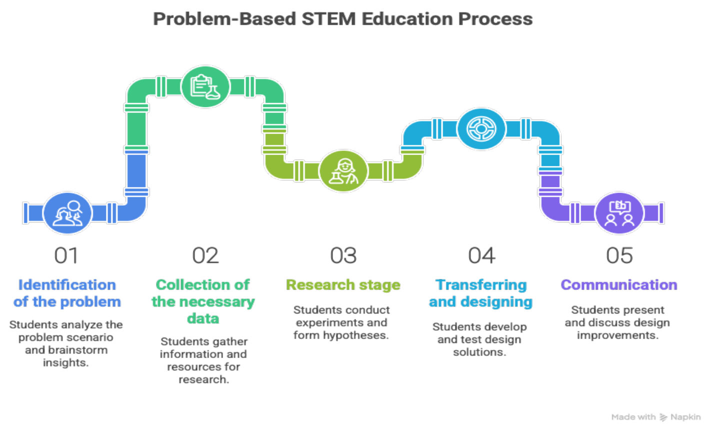

Figure 3. Five-step problem-based STEM teaching sequence (adapted from Sari et al., 2018)

In the fourth step, students conducted research using online resources and reference materials. The fifth step introduced the engineering design process (EDP) cycle (Figure 5), during which students revisited the original problem and attempted to construct a prototype solution—specifically, a filter for removing dyes. Through iterative trials, students refined their designs until they developed a functioning prototype. Finally, in the sixth step, literacy skills were integrated into the process as students documented their learning through journal writing and portfolio preparation.

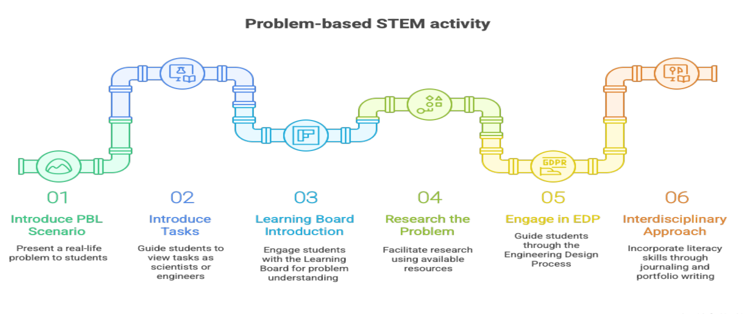

Figure 4. Six-step problem-based STEM teaching sequence (adapted by Abbott, 2016).

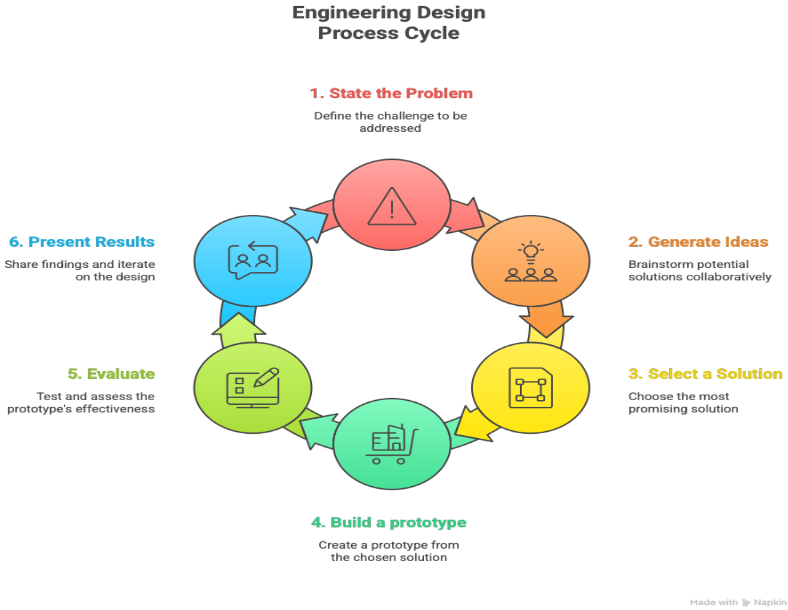

Figure 5. Engineering design cycle

Given that teachers are positioned as facilitators in PBL, this role similarly extends to problem-based STEM instruction. Consequently, scholars have emphasized the need for additional professional development to support teachers in this area (e.g., El Sayary et al., 2015). Nevertheless, studies reveal several persistent challenges, including the absence of well-defined integration models, limited teacher experience, administrative barriers, and insufficient resources (Sahito & Wassan, 2024; Smith et al., 2022). In particular, El Sayary et al. (2015) identified professional development as a critical component for ensuring effective problem-based STEM teaching practices, while Smith et al. (2022) underscored the importance of establishing a shared understanding of problem-based STEM instruction among educators. To address these challenges, 'collective sensemaking through professional dialog' among educators has been proposed (Holmlund et al., 2018, p.17). In this regard, problem-based STEM teaching practices play a crucial role in establishing a shared foundation for the effective implementation of STEM education.

Inquiry-based Learning (IBL)

Like PBL approach, inquiry-based learning is widely recognized as an innovative approach in STEM education shifting the focus from passive knowledge acquisition to active and student-centered learning. Inquiry and therefore inquiry-based learning (IBL) has been a central theme in science education (Strat et al., 2024; Zhong et al. 2022). Within the framework of PBL, students take an active role in learning by employing critical thinking skills—asking questions, planning and conducting investigations, interpreting data as evidence, constructing arguments, developing models, and communicating findings—to deepen their understanding (Anderson, 2002; Crawford, 2014).

Foundation of inquiry-based learning

IBL is rooted in Dewey's (1938) work as which established inquiry in experience (cited in Seland Strat et al., 2024). John Dewey's ideas on inquiry have influenced subsequent work, and various learning cycles such as famous 5E (Engagement, Exploration, Explanation, Elaboration, and Evaluation) adopting inquiry-based learning (IBL) have since been introduced (Oguz Unver & Arabacioglu, 2011). A classic IBL process starts with a question. Students, then, start looking for potential answers and investigate possible solutions. After creating new information chunks, students talk about their findings, experiences and reflect on new piece of information (Savery, 2006). National Research Council (NRC, 2006) identifies five essential characteristics of IBL (see, Figure 6). IBL process begins with engaging students in real-world problem. Students collect relevant data and based on evidences; they formulate hypothesis/explanations. They, then, evaluate explanations and finally, share and define their findings (NRC, 2006).

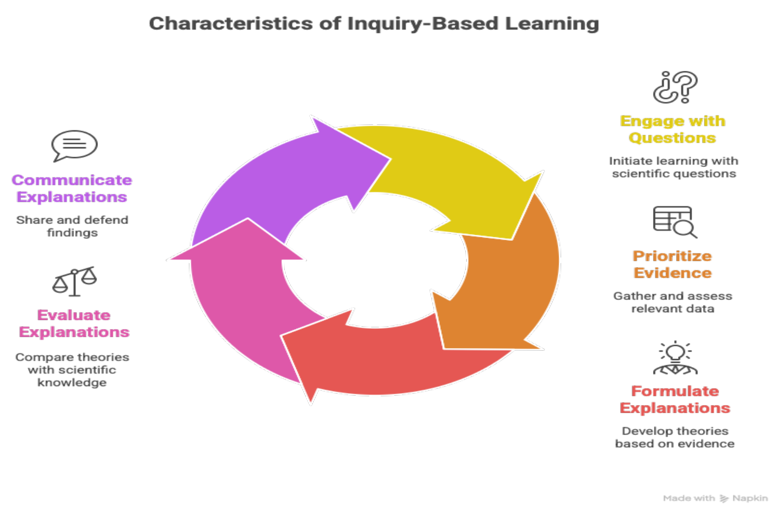

Figure 6. Five essential characteristics of IBL

Types of Inquiry

There is a wide range of inquiry-based learning activities ranging from student-directed open inquiry to teacher-directed organized and guided inquiry (NRC, 2020; Martin- Hansen, 2002):

Structured-inquiry: Students follow a predetermined process to search answers to a question that the teacher has established. Every step is structured and students get comprehensive instructions that culminate in a predetermined discovery.

Guided-inquiry: Students explore teacher-formulated questions and procedures in this type of inquiry. The questions are determined by the teacher who already know possible answers for the problem.

Coupled-inquiry: This kind of inquiry is situated between guided and open inquiry. The teacher lets the students choose an inquiry question from a database of preset queries. However, students are not involved in creating the inquiry question.

Open-inquiry: This kind of inquiry is assumed to be most sophisticated type of inquiry where students create a broad range of inquiry questions while the teacher establishes the knowledge foundation. Students use student-designed or student-selected processes to research topic-related questions during open inquiry. Every step of the open inquiry method involves the students making their own choices (Sadeh & Zion, 2012).

Inquiry-based learning in STEM education

IBL is considered a signature pedagogy of STEM learning (Crippen & Archambault, 2012). The nature, principles, and core concepts of STEM disciplines can be systematically examined and fostered through the application of inquiry-based learning in STEM education (Ješková et al., 2024; Thibaut et al., 2018; Woods-McConney et al., 2020). Inquiry-based learning in STEM is built on active, student-centered approaches in which students work in groups, conduct experiments to build knowledge, and investigate real-world issues (Ješková et al., 2024; Thibaut et al., 2018; Woods-McConney et al., 2020). In this manner, students are expected to pose questions, carry out investigations to make their own discoveries, expected to solve inquiry-based challenges, create knowledge, and collaborate and communicate with others (Zhong et al, 2022)

Affordances inquiry-based STEM education

The literature has documented numerous beneficial outcomes of inquiry-based STEM teaching for students including (a) enhanced cognitive outcomes (Donnelly et al., 2014; Li et al., 2010); (b) greater motivation (Aditomo &

Klieme, 2020; Crawford, 2014; Dilek et al., 2020; Li et al., 2010; Lord & Orkwiszewski, 2006; Sarı et al., 2020); (c) increased flexibility and creativity in addressing problem-solving tasks (Lord & Orkwiszewski, 2006; Sarı et al., 2020; Seland Strat et al., 2024); (d) the enrichment of 21st-century skills (e.g., collaboration, critical thinking, creativity, accountability, persistence, and leadership) (Ješková et al., 2024); (e) improved self-efficacy and self-confidence (Sahito & Wassan, 2024; Strat et al., 2024); (f) the facilitation of integration across disciplines (Rúa Martínez et al., 2024) the development of science process skills (Dilek et al., 2020; Sarı et al., 2020); (g) enhanced awareness of STEM disciplines (Karamustafaoğlu & Pektaş, 2024; Li et al., 2010; Sarı et al., 2020;) and (h) demonstrated higher preferences for future STEM careers (Wang et al., 2021).

Teacher roles

Teachers act as guides and experts who support inquiry through scaffolding, formative assessment, and creating/structuring inquiry-rich learning environments (Nadelson et al., 2013; Roehrig & Luft, 2004). Teacher training is essential for effective inquiry-based STEM. Systematic reviews highlight the need for explicit teacher preparation and ongoing support (Seland Strat et al., 2024; Rúa Martínez et al., 2024).

Approaches for inquiry-based STEM education

Literature illustrates different teaching approaches that could be used for inquiry-based STEM education. These approaches are presented in Figure 7. IBL, PBL, and project-based learning (PjBL) share common characteristics, including their student-centered orientation and emphasis on active learner participation. Accordingly, various instructional models can be employed to support the integration of STEM. One such model is Bybee et al.'s (2006) 5E framework—engage, explore, explain, elaborate, and evaluate—which has been adapted for STEM education (Bybee, 2014). While this model begins with an engaging, essential problem, problem-based STEM activities extend the approach by involving students in solving authentic, real-world problems. When the process additionally entails constructing tangible solutions, such as prototypes or products developed through systematic investigations, it constitutes a specific form of project-based STEM activity. Another possibility involves technology-supported inquiry, which leverages advanced tools such as simulations, animations, and virtual or augmented reality environments.

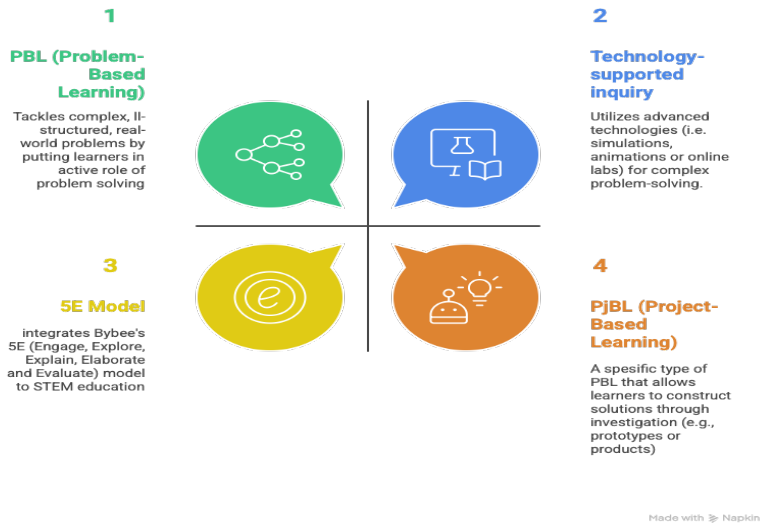

Figure 7. Different approaches for inquiry-based STEM education

To better illustrate how IBL adapted into STEM teaching, Sarı and his colleagues (2020) used a five-step inquiry-based STEM teaching strategy to teach simulation-based physics concepts (see, Figure 8). The adapted Lim (2004)'s five-step inquiry-based learning cycle into an engineering design-based STEM activity using simulations. The first step involved identifying the problem by considering the limitations and constraints. They collected necessary information to solve the problem in planning stage. In third stage, they established hypothesis, designed virtual experiments to test their hypothesis. In construct stage, students chose one of the most suitable solutions, tested, evaluated and developed a prototype. In last stage (reflect), they evaluated their engineering design products and search ways for improvement. In another model, Barry (2014) and Chang and Yang (2014) adopted 5E model into a 6E model for inquiry-based STEM teaching. Their model included (1) engaging, (2) exploring, (3) explaining, (4) engineering (elaborating), (5) enriching, and (6) evaluating steps.

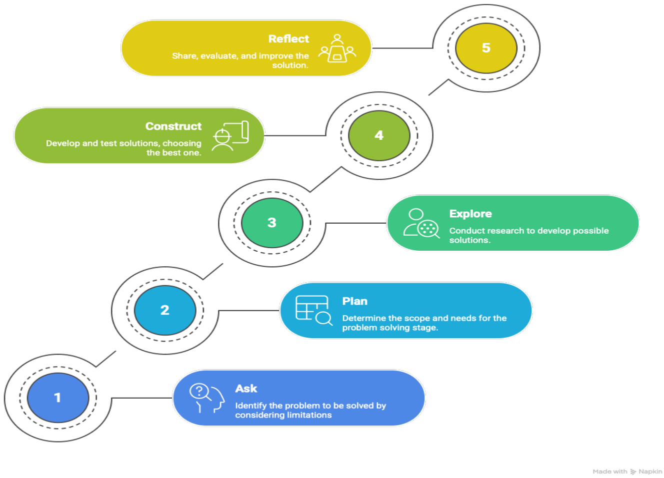

Figure 8. Steps of inquiry-based STEM teaching (adapted from Sarı et al., 2020)

Conclusion

Both problem-based learning (PBL) and inquiry-based learning (IBL) are student-centered approaches that emphasize learners' active engagement in the learning process. In this regard, both approaches can be considered as rooted in constructivist theory which emphasizes the co-construction of meaning through experience and reflection. Since STEM education also prioritizes students' active role in constructing knowledge, PBL and IBL offer a meaningful pedagogical context for teaching STEM. The literature reviewed in this chapter provides valuable insights into how problem-based and inquiry-based STEM teaching methods foster students' learning, motivation, and skills such as critical thinking, creative thinking, and problem solving. Moreover, these approaches have been shown to positively influence students' career aspirations toward STEM fields. This is particularly significant given that numerous national policy documents highlight both the shortage of professionals in STEM disciplines and the declining interest among students in pursuing STEM-related careers.

This chapter also underscores the importance of integrating complementary approaches—such as the 5E instructional model, project-based learning, or the engineering design process (EDP)—into problem-based and inquiry-based STEM education. Such integrations can strengthen the effectiveness of these methods by enhancing learning outcomes. Enriching problem-based and inquiry-based STEM practices with additional frameworks may support the development of more meaningful and structured learning environments for students. In this sense, instructional steps should be clearly articulated and provide sufficient guidance for teachers who intend to implement these integrated models.

The nature of engineering and design processes likewise offers students an authentic context for understanding how engineers work and how products or technologies are created through the engineering design process. Integrating such approaches enables students to experience the practices of engineering and to connect abstract concepts with real-world applications.

Equally important is the role of teachers as facilitators and mentors in problem-based and inquiry-based STEM teaching. Teachers' guidance is essential for navigating the complexities of these pedagogical approaches. However, existing research documents several challenges, including teachers' limited preparation for effectively enacting these roles. Therefore, it is crucial to provide ongoing professional development opportunities to enhance teachers' knowledge, skills, and competencies. Furthermore, teacher education programs should be designed to better prepare future teachers to confidently and effectively implement problem-based and inquiry-based STEM methodologies.

Recommendations

Problem-based and inquiry-based STEM education approaches require careful instructional design and curriculum-level support to realize their full potential. From a constructivist perspective, students must be provided with opportunities to activate and connect their prior knowledge to new conceptual understandings, while also engaging in authentic practices that reflect the epistemic and methodological work of scientists and engineers. Both approaches inherently foster such epistemic agency by situating learners in contexts where knowledge is co-constructed through inquiry, problem solving, and reflection. When STEM curricula systematically embed these pedagogical orientations, students are more likely to experience cognitive, motivational, and aspirational benefits.

However, the effectiveness of these approaches depends heavily on teachers' capacity to scaffold learning, orchestrate inquiry processes, and mediate the complexities of open-ended problem solving. This underscores the need for robust teacher preparation and sustained professional development. Professional learning opportunities should not only provide teachers with practical strategies but also cultivate their pedagogical content knowledge, design thinking, and capacity for reflective practice. Furthermore, the implementation of problem-based and inquiry-based STEM teaching should be conceived as an iterative process, informed by continuous monitoring, feedback, and refinement. Such an approach ensures not only fidelity of implementation but also adaptability to diverse classroom contexts, thereby strengthening the sustainability and scalability of these innovative pedagogies.

Acknowledgements

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