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Challenge-based learning implementation in engineering education: A systematic literature review

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Abstract

Background: Challenge-based learning (CBL) is a pedagogical approach increasingly adopted in engineering education. Despite its growing practice, there is little consensus in the literature about how CBL is implemented in engineering curricula and what experiences teachers and students have in relation to it.

Purpose: To address this gap, the following research questions guided the study: How is CBL currently implemented in engineering education? What difficulties and lessons learned are associated with the implementation of CBL?

Methods: We systematically reviewed the empirical literature published between 2010 and 2021. Forty-eight empirical studies describing CBL implementation were analyzed using the curricular spider-web framework.

Results: The review shows the variation in CBL implementation at the course and project levels. CBL courses and projects shared the use of open-ended, real-world challenges as a starting point for student learning. However, they differed in the embeddedness of a challenge in specific courses and the focus of the learning, which ranged across knowledge acquisition, knowledge application, and development of transversal skills. CBL experiences also varied in terms of challenge characteristics, such as the link with global societal challenges, stakeholders' involvement, and multidisciplinarity. Similar difficulties and lessons learned were reported by teachers and students across the different examples of CBL implementation.

Conclusions: CBL as a pedagogical approach in engineering education can promote student engagement with complex societal challenges within a real-world context. However, there are limitations to the review and implications of the findings for educational research and practice.

KEYWORDS
CBL implementation, challenge, challenge-based learning, engineering education, systematic review

1 | INTRODUCTION

Global challenges of the 21st century are increasingly complex, and sociotechnical developments demand a new way of educating engineering students (Beagon et al., 2023; Byrne & Mullally, 2014; Hadgraft & Kolmos, 2020; Jonassen, 2014). Furthermore, future engineers are expected to act in complex situations and develop innovative technological and sustainable solutions (Hadgraft & Kolmos, 2020; Kamp, 2016; Redish & Smith, 2008). To achieve this, future engineers should exhibit a T-shaped profile, where the vertical bar represents depth and mastery in one or more technical fields or disciplines (Gerson & Ramond, 2007; Rogers & Freuler, 2015), while the horizontal bar represents broader professional skills to address global, societal, and multidisciplinary challenges, such as thinking critically, working collaboratively, and communicating ideas (Rijk, 2019; Tranquillo, 2017).

The demand for such "T-shaped" engineers has led engineering schools to focus on more active learning pedagogies, such as problem-based, project-based, design-based, or challenge-based learning. These pedagogies put students in the lead with regard to their learning and provide tailored coaching to foster their self-directed and collaborative learning in what are often multidisciplinary teams (Hadgraft & Kolmos, 2020; Mann et al., 2021; Prince, 2004; Prince & Felder, 2006; Ravesteijn et al., 2006). Research has suggested that active learning pedagogies positively affect student learning (Freeman et al., 2014; Hadgraft & Kolmos, 2020; Hake, 1998). Real-world challenges stimulate learning and allow students to acquire and link new knowledge with prior knowledge and apply it to new challenges, while developing important transversal skills for their professional future (Hadgraft & Kolmos, 2020; Jonassen, 2014).

Challenge-based learning (CBL) is emerging as a popular active learning pedagogy in higher education, and its use in engineering education has flourished within the last decade. Several studies have suggested that CBL has the potential to educate engineering students and prepare them for their future careers by combining knowledge acquisition and application, developing disciplinary and transdisciplinary skills, shifting the control of learning to students, and fostering active learning and motivation (Gallagher & Savage, 2020). Recently published literature on CBL has focused on describing its most prominent characteristics (Gallagher & Savage, 2020), the current state of CBL research (Leijon et al., 2022), a conceptual framework to assess variation in CBL (van den Beemt, van de Watering, & Bots, 2023), and comparing CBL and other active learning pedagogies (Sukackė et al., 2022). Although these reviews provide a useful starting point for understanding the state of the art of CBL in engineering education, no systematic review has focused on implementing CBL in practice. A CBL-focused mapping is currently lacking of essential curriculum elements of educational practice, such as the vision behind adopting CBL in a specific learning context; intended learning objectives to be addressed by CBL; teaching and learning practices, such as learning activities, materials, and resources; the role of teachers and other important actors in the learning process; and assessment practices. With an increasing number of reported CBL educational interventions, a review is needed to map current CBL practices and lessons from implementation to guide future educational developments.

This systematic review addresses this gap by exploring how CBL has been implemented in engineering curricula. We do this by reviewing CBL-relevant curriculum elements using the curricular spider web by van den Akker (2003) and assessing the reported difficulties and lessons learned related to CBL implementation.

1.1 | Background

The increased interest of practitioners and researchers in CBL has created a need for defining CBL and differentiating it from other active learning pedagogies frequently used in engineering education, such as problem- and project-based learning. In the following, we describe the origins of CBL as an educational concept and its existing definitions. Then, we discuss key similarities and differences between CBL and other active learning pedagogies.

1.1.1 | Existing definitions and conceptualizations of CBL

CBL originates from "Apple Classrooms of Tomorrow—Today," a project initiated in 2008 by Apple, Inc. that aimed to redefine the essential characteristics of the 21st-century learning environment. Apple defined CBL as follows:

> [A]n engaging multidisciplinary approach to teaching and learning that encourages students to leverage the technology they use in their daily lives to solve real-world problems. Challenge-based learning is

> collaborative and hands-on, asking students to work with peers, teachers, and experts in their communities and around the world to ask good questions, develop deeper subject area knowledge, accept and solve challenges, take action, and share their experience. (Nichols & Cator, 2008, p. 1)

Although the definition by Apple initially focused on secondary education, examples of CBL can be found on several levels, from elementary to higher education. We identified two working definitions of CBL relevant to higher education that we discuss below. First, Gallagher and Savage (2020) conducted an exploratory literature review on CBL in higher education. They provided an overview of frequently reported CBL characteristics, including using global real-world challenges as drivers for students' learning, involvement of academic and external stakeholders, and use of technology as crucial elements in the learning process. In addition, they emphasized CBL's flexible approach to teaching and learning, having disciplinary and multidisciplinary specificity, promoting collaboration among students, and fostering innovation and creativity.

Another popular definition of CBL specific to engineering education can be found in the work of Malmqvist et al. (2015). They defined CBL in engineering education as "the identification, analysis, and design of a solution to a sociotechnical problem. The learning experience is typically multidisciplinary, involves different stakeholder perspectives, and aims to find a collaboratively developed environmentally, socially and economically sustainable solution."

Finally, van den Beemt, van de Watering, and Bots (2023) suggested that existing conceptualizations of CBL vary and highlighted the need for a comprehensive framework to capture this variety within CBL implementation in higher education. Based on a literature search and reflecting on current practices in their institutions, they suggested a model in which CBL is analyzed based on its vision, teaching and learning practices, and support systems. They suggested 11 relevant indicators of CBL, at the level of vision, teaching and learning, and support practices. They also reflected on the importance of having minimum requirements for an educational intervention to be called CBL. They defined three minimum indicators for a CBL educational intervention. Those included (i) real-life and authentic challenges that (ii) stimulate students' combination of deep content understanding and a general view of engineering issues and (iii) the use of learning activities that promote a rigorous treatment of fundamental engineering knowledge and skills.

All the above definitions emphasize the importance of real-world and authentic challenges as the starting point for students' learning. The importance of students' engagement in active, collaborative, (multi)disciplinary learning to tackle those challenges is also stressed in terms of the learning process. The definition by Malmqvist et al. (2015) focused on the characteristics of the solution for the challenge, and its wider scope as including not only technical but also societal considerations. Finally, in addition to the characteristics of the challenge, van den Beemt, van de Watering, and Bots (2023) focused on the students' expected learning, with an emphasis on developing disciplinary and transversal skills.

1.1.2 | Comparison of CBL and other active learning pedagogies

Studies of CBL have suggested that a deeper theoretical grounding in educational science and learning theories could enrich the CBL literature (Leijon et al., 2022; van den Beemt, Vázquez-Villegas, et al., 2023). Given that CBL promotes real-world, active, self-directed, and collaborative learning (Sukackė et al., 2022; van den Beemt, van de Watering, & Bots, 2023; van den Beemt, Vázquez-Villegas, et al., 2023), it resonates with learning theories and active learning pedagogies, such as problem-based learning (PBL), project-based learning (PjBL), and design-based learning (DBL) in terms of learning principles (Leijon et al., 2022; Sukackė et al., 2022; van den Beemt, van de Watering, & Bots, 2023; van den Beemt, Vázquez-Villegas, et al., 2023). These pedagogies all aim to link students' academic knowledge with professional practice by introducing them to problems, tasks, or challenges relevant to their future practice (Sukackė et al., 2022). However, they also differ across critical dimensions, including the focus of learning, the type of problems/challenges used to trigger students' learning, the learning activities, the type of solution students are required to develop, and the teacher's role in the learning process.

Although an exhaustive comparison of CBL with other pedagogies is outside this review's scope, in Table 1 we briefly summarize some critical differences across CBL, PBL, PjBL, and DBL as have been reported so far in the literature (e.g., Binder et al., 2017; Guo et al., 2020; Holgaard et al., 2017; Kohn Rådberg et al., 2020; Kolmos & de Graaff, 2014; Krajcik & Shin, 2014; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Sukackė et al., 2022; van den Beemt, Vázquez-Villegas, et al., 2023).

Table 1 presents some prototypical examples of the four pedagogies as a way to highlight their fundamental differences regarding the type of challenges/problems students are presented with, the learning process, the role of the teacher, and the expected outcomes. However, it is noteworthy that in practice, similarities and boundaries among

TABLE 1 Comparison of differences between CBL and other active learning pedagogies.

	CBL	DBL	PjBL	PBL
Type of problem	CBL starts with a real-world global challenge. Challenges in CBL are interdisciplinary, requiring students to integrate knowledge and skills from multiple areas. Often, challenges are presented by external stakeholders.	DBL starts with a design challenge or problem. It is usually associated with subjects related to design (e.g., engineering, art, or architecture). DBL can be interdisciplinary. Teachers or external stakeholders can present design challenges/ problems to students.	PjBL typically starts with a driving question or a task. Projects in PjBL can be interdisciplinary, but may also focus on a specific subject or skill. Teachers usually predefine the driving question or task, which is either theoretical or based on real-world issues.	PBL starts with a specific problem. Problems in PBL are usually discipline-specific. Teachers predefine the problem, which is either fictional or based on real-world issues, but is presented to students in a structured manner.
Learning process	Students propose a solution for the global challenge by choosing the focus of the specific problem within the challenge, investigating, ideating, and implementing solutions.	Students develop a prototype or design solution by following the stages of the design process, including ideation, prototyping, and testing.	Students create a project or product to respond to the driving question or task by applying disciplinary-specific knowledge and competencies.	Students solve the problem by identifying, studying, and critically discussing the relevant literature.
Teachers' role	In CBL, the teacher acts as a facilitator, coach, or even a co-creator of the solution for the challenge.	In DBL, the teacher acts as a coach or mentor, guiding students through the design process and providing feedback.	In PjBL, the teacher acts as a facilitator or tutor, providing resources, scaffolding the learning process, and offering feedback.	In PBL, the teacher is a facilitator, guiding students as they explore and solve the problem.
Outcome	The primary outcome is a proposed actionable solution for the identified challenge, but the learning process and the knowledge and skills students gained during the process are equally important.	The primary outcome is a prototype or design solution, but the design process, including the iterations and refinements of the outcome, is crucial.	The primary outcome is a final project report, presentation, or product, but the skills and knowledge gained during the process are equally important.	The primary outcome is the knowledge acquisition and development of problem-solving and critical-thinking skills. The solution for the problem is not the focus of PBL.

these paradigms are often nuanced and less distinct. An example is Aalborg University, where elements of PBL and PjBL are combined in the engineering curriculum (Kolmos, 2012; Kolmos & de Graaff, 2014).

In terms of learning, CBL drives students' knowledge integration and application through engagement in real-world challenges that lack a predefined solution. Challenges in CBL are sociotechnical, which means that they require addressing pressing current issues (e.g., climate change and energy transitions, data privacy) which require a combination of technological innovations, policy development, and societal engagement to find effective solutions (Malmqvist et al., 2015; McGowan & Bell, 2020). Students should work toward a solution using technical knowledge from various disciplines, taking into account the complex interplay between societal, technological, and environmental factors, and must present their (proposed) solution to a panel of experts and stakeholders (Gallagher & Savage, 2020; Kohn Rådberg et al., 2020; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). The challenges presented to students in CBL differ from those of PBL where problems are often predefined and developed by the teachers as vehicles for knowledge acquisition (Gijselaers, 1996; Kolmos et al., 2019; Zin et al., 2017), and PjBL where problems are often predefined and developed by the teachers for students to learn and apply new knowledge and skills. CBL also differs from DBL in this respect, as design challenges tend to be more specific and focus on creating an artifact or product, emphasizing the function of the particular production of artifacts (Gómez Puente et al., 2011, 2013). In terms of product, in CBL, students are expected both to focus on their learning process, as in PBL, where the main focus is on reasoning and the learning process rather than the product, and to develop a concrete solution, similar to PjBL and DBL (Gallagher & Savage, 2020; Gómez Puente et al., 2011, 2013; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). Finally, teachers in CBL act as coaches and co-creators of a solution, in addition to being a tutor and facilitator of knowledge acquisition, which are the usual teacher roles in PBL, PjBL, and DBL (Gallagher & Savage, 2020; Gómez Puente et al., 2013).

1.1.3 | A working definition of CBL

CBL builds on the strengths of other active learning pedagogies and encourages students to learn autonomously and collaboratively in a contextualized way. CBL aims to develop students' disciplinary and transversal competence by having them work with challenges. What is new is the type of challenges students are invited to tackle. In CBL, challenges to be tackled by the students are societally relevant and connected with sustainable development goals (SDGs), often presented by external partners (from industry partners to local communities). Regarding the learning process, emphasis is given to the collaboration between students, teachers, and external stakeholders as the point of departure for learning and to the co-creation of a solution for the challenge. The outcome of such a co-creation process is development of a tangible solution that addresses both technical and societal considerations.

1.2 | The present study

In the last decade, there has been a significant increase in publications related to CBL in higher education and, more specifically, in engineering education (Gallagher & Savage, 2020; Leijon et al., 2022). However, although CBL is becoming more popular, and more studies are being published on its potential to enhance students' learning and experience, questions remain about the quality of implementation, as this has been observed to vary tremendously (Gallagher & Savage, 2020; van den Beemt, van de Watering, & Bots, 2023).

Current empirical work on CBL in engineering education mainly describes single learning environments or compares small-scale CBL educational interventions with traditional teaching and learning approaches (Malmqvist et al., 2015; O'Mahony et al., 2012). van den Beemt, van de Watering, and Bots (2023) discussed three relevant levels of implementation: vision, teaching and learning practices, and support systems. This provides a useful framework for identifying current CBL practices. They developed a model aiming to capture the diversity in the implementation of CBL practice in a systematic way.

This systematic review aims to provide a more holistic understanding of CBL implementation practices and lessons from implementing CBL in an engineering context and to synthesize the piecemeal evidence provided in earlier empirical studies. The theoretical framework guiding this systematic review is the curricular spider web developed by van den Akker (2003), which presents 10 essential elements to consider when designing or evaluating an educational intervention (see Figure 1). The rationale for the educational activity lies at the heart of the spider web, and is the answer to the question, "Why are students learning?" Nine spider web threads refer to the aspects of learning in a curriculum. These include the aims and objectives of a course, the content and the learning activities, the role of the teacher, the materials and resources used, the grouping of students while learning, and the location, time, and assessment of learning. The curricular spider web is a helpful framework for guiding educational innovation, curriculum, and policy development. The spider web highlights the most relevant curriculum components and emphasizes the need for interconnectedness and alignment of all elements to assure quality and maintain curriculum coherence.

This systematic review of the implementation of CBL in engineering education is timely, as CBL has gained popularity among engineering educators. Therefore, it is essential to map the current CBL practices in engineering courses or curricula in a systematic way to create an overview of CBL implementation and how educators implement different curriculum elements. In this review, we aim to map the vision behind adopting CBL, understand the characteristics and role of challenges as a way to drive student learning, map aspects of students' learning process, and map how this process is translated to the curriculum elements implemented. The significance of such an effort is twofold. On one hand, we aim to build knowledge and evidence of good practices to help future educators to design CBL environments and develop, assess, and scale up educational initiatives emphasizing various interrelated curriculum elements that need to be considered. On the other hand, we aim to provide recommendations for educational researchers for future directions for empirical research. The review is framed around two major research questions.

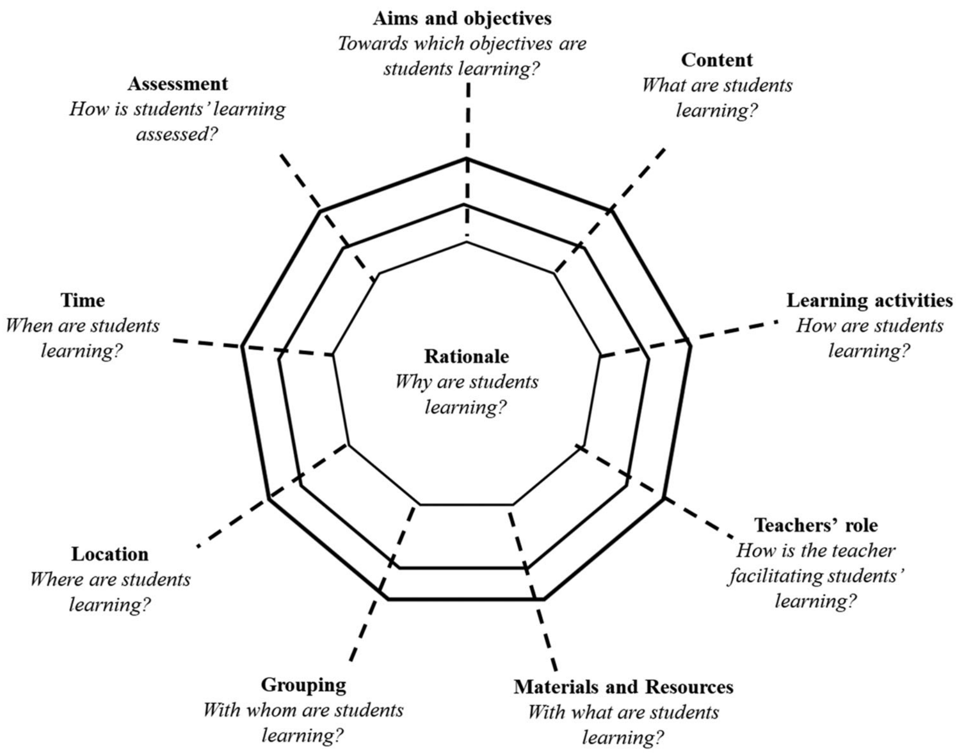

FIGURE 1 Curricular spider web. *Source*: Adapted from van den Akker (2003).

- How is CBL currently implemented in engineering education?
- What difficulties and lessons learned are associated with the implementation of CBL?

2 | METHODS

Educational research studies on CBL in engineering education were searched for and analyzed. As our focus is on the development of future engineers, we decided to narrow our search only to studies of CBL implemented in higher engineering education. We conducted a systematic search of the literature to identify the available evidence concerning CBL implementation in engineering education.

As a first step, we developed a working definition of CBL giving its key elements and used the curricular spider web framework to map aspects of its implementation. The curricular spider web includes the vision/rationale for adopting CBL as a pedagogy in a study, learning aims and objectives within the specific CBL context, the learning content, the learning activities, the role of the teacher, materials and resources used, the time and location of CBL implementation, and assessment methods. In addition to these curricular aspects of CBL implementation, there are also the difficulties and opportunities experienced by teachers and students during the implementation of a CBL intervention. In our review process, we used methodological recommendations Borrego et al. (2014) developed for a systematic literature review in engineering education. Below, we describe in detail all steps we followed, namely the development of a search strategy (Section 2.1), the development of criteria for inclusion and exclusion (Section 2.2), the process of selection of studies (Section 2.3), the analysis of individual studies (Section 2.4), and, finally, the synthesis of findings (Section 2.5).

2.1 | Development of a search strategy

Defining CBL was crucial for our systematic review. It guided our search strategy and selection criteria. The term "challenge" was chosen as central in our search, as it encompasses broader scenarios than just "problem" or "project," and it is the driving force for students' learning. This definition helped us to refine our search keywords, ensuring that the studies we found were pertinent to CBL. The definition also determined the scope of our review, directing us toward specific educational settings and age groups, notably higher engineering education. It acted as a guideline, allowing us to select studies that matched our understanding of CBL. For example, studies that highlighted real-world challenges in a team environment were prioritized. On the other hand, it also helped us to identify what CBL is not. Studies that might discuss active learning but did not fit our CBL criteria were omitted. For instance, research focusing only on textbook problems without a real-world context was excluded. Our CBL definition ensured a focused, relevant, and rigorous review process. The search terms we used included ([challenge OR "challenge based" OR "challenge-based" OR CBL] AND [learning OR education OR instruction OR pedagogy] AND [engineering]). We chose to use broad keywords to maximize the range of challenge-based studies accessed, consistent with previous reviews on the topic (Leijon et al., 2022). We chose Scopus, Web of Science, Institute of Electrical and Electronics Engineers (IEEE) Xplore, and the American Society for Engineering Education (ASEE) as research databases. We considered that if a learning challenge is central to a study, the basic search terms (challenge or "challenge based" or "challenge-based" or CBL) should be at least mentioned in the title, abstract, or keywords. However, this search setting was used only for the initial search, and it was not used to determine the suitability of a study to be included in the review. This was accomplished by reviewing the content of each article.

2.2 | Selection of criteria for inclusion and exclusion

We did the first screening by reading titles and abstracts, aiming to identify only relevant articles that met the following inclusion criteria (IC):

IC1. The article focused on the implementation of CBL in engineering education. The article described how challenge-based learning was used as an educational approach to achieve certain student-related outcomes. A description of the challenge and its characteristics was necessary to ensure that the educational approach differed from other similar approaches, such as PBL.
IC2. The article explicitly described the implementation of curriculum or course-related aspects of CBL. The article described how the challenge was implemented within a specific context (course, project, curriculum), emphasizing some spider web characteristics such as the role of the teacher, the learning activities, assessment, and so forth. Not all educational implementation aspects had to be present for an article to be included.
IC3. The article had to provide empirical findings on the evaluation of CBL.
IC4. The search period of this review was limited from January 1, 2010 to December 31, 2021.
IC5. Studies had to be peer-reviewed to be included.
IC6. The article was published in English, and the full text was available.

While reading the abstracts and full texts, the research team also formulated exclusion criteria (EC). Those included the following:

EC1. Only articles in the field of higher engineering education were eligible for inclusion. Thus, studies conducted in secondary education or other higher education disciplines, such as nursing, were excluded.
EC2. The article presented a CBL implementation without an evaluation. For example, publications that only described the educational intervention without any findings, insights, or conclusions were excluded.
EC3. The authors defined the education intervention as CBL, but after reading the full text, we believed that their conceptualization was not aligned with our current conceptualizations of CBL.
EC4. CBL implementation was not the focus of the article. Studies were excluded if mentions of CBL were made but without CBL implementation being the main focus.
EC5. Editorials and reviews on CBL were excluded. Only empirical studies were the focus of this review.

The appraisal and inclusion of studies was a collaborative and iterative process, including all research team members. All inclusion and exclusion criteria were developed after several rounds of discussion about our definition of CBL and the type of studies we wanted to focus on. When the list of exclusion and inclusion criteria was finalized, the first author conducted the database search, read all abstracts, read through full texts, and created the list of articles to be included in the study.

When determining the publications to be included in our review, we paid attention to two aspects:

1. ***whether*** researchers called their educational approach "challenge-based learning" and
2. ***how*** researchers defined CBL in their articles.

We introduced this focus to limit as much as possible the occurrence of Type I error: inclusion of studies with an educational approach defined as CBL, but whose definition was not consistent with our working definition. For example, studies that did not stress the importance of real-world challenges or did not require students to work toward developing a solution or a proposal for a solution to the challenge were not included in the study.

Despite our efforts to include all studies that described and evaluated the implementation of CBL in engineering education, we may have missed studies that essentially implemented CBL but did not label their approach as such (Type II error). Still, we applied a rigorous process to identify whether the authors implemented CBL as claimed or not. Thus, we excluded several identified studies that claimed to implement CBL but the approach used did not differ from other active learning pedagogies (e.g., PBL).

2.3 | Screening phases

The first search yielded 530 articles. However, 276 articles remained to be reviewed after duplicates were removed. We downloaded and merged the abstracts of all publications into an Excel file. The first author read all the abstracts and decided whether each article should be included or eliminated. The selection process and all decisions were discussed during weekly meetings with the research team. Based on the initial screening of titles and abstracts, 210 articles were excluded for not meeting one or more of the inclusion criteria, and 66 full-text articles were assessed for eligibility. This closer analysis of each study led to the exclusion of 18 more articles and the final inclusion of 48 articles in the present review. The full-text appraisal followed a process similar to that of abstract screening. Figure 2 provides the flowchart for the selection of the studies in the review.

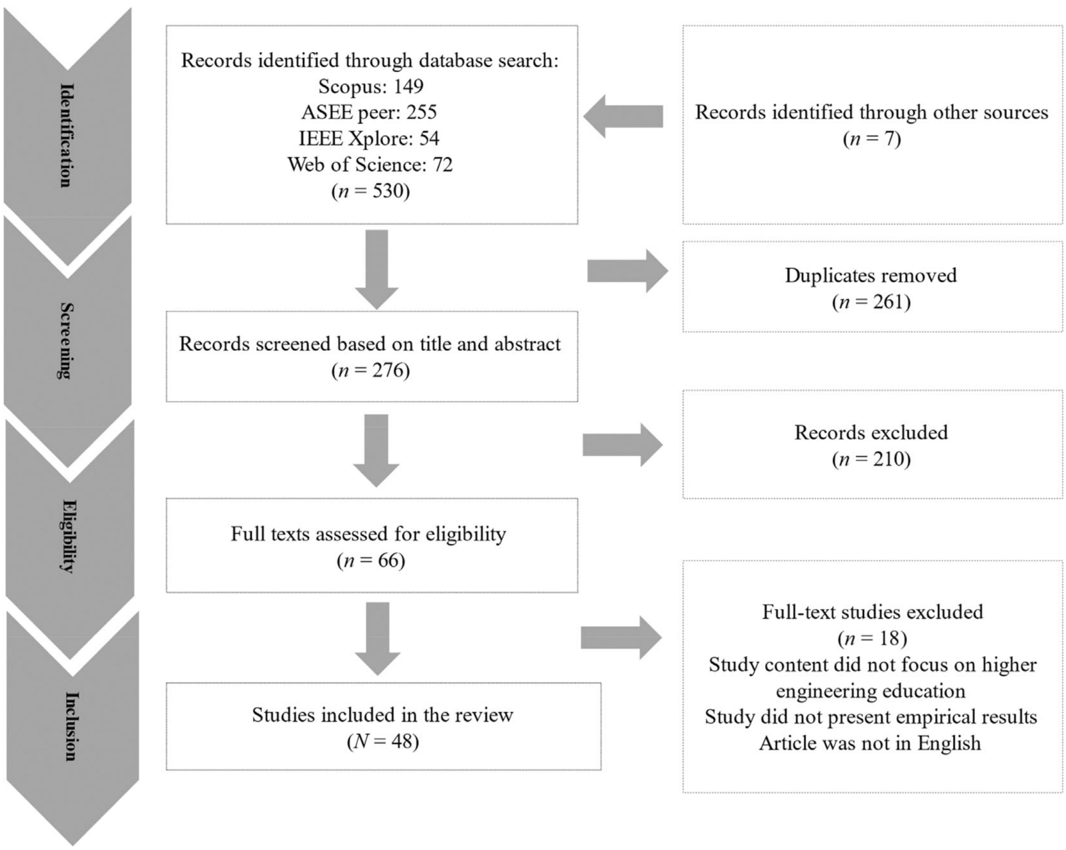

FIGURE 2 Flowchart of systematic review process.

2.4 | Data analysis

In the first step, we coded the descriptive characteristics for each study, including the type of publication, country of study, theoretical background and research methods, domain, educational level of students, and the number of students participating. To answer the first research question, we used the curricular spider web to identify the critical components of the CBL curriculum as presented in the included studies (van den Akker, 2003). A coding scheme was developed based on the 10 initial themes mentioned in the spider web framework. Appendix details the coding scheme used to assess each study. First, we looked for information to map the rationale of the use of CBL, meaning why the authors decided to adopt CBL pedagogy and the learning aims and objectives they aimed to achieve (why and what). Subsequently, we focused on the description of the implementation, seeking to map the reported curriculum elements mentioned in each study (how).

To answer the second research question, we used open coding to capture the most important challenges and lessons learned related to implementing CBL, as reported by the authors of the included studies (Thomas & Harden, 2008). Articles were read multiple times and coded by the lead researcher to ensure the validity of the data analysis. After several group discussion rounds, the initial themes and codes were adjusted and refined into the final coding scheme.

The first coder analyzed the data from all 48 articles. A second coder was involved in evaluating the applicability of the coding scheme. First, the two authors had a training session to review all codes. Then, the second coder independently coded two articles. After this, the two coders met again, went through the coding scheme, and resolved any disagreements and unclarities, finalizing the coding scheme, which involved detailed descriptions and instructions for coding. The validity of the coding scheme was addressed using a content validity check with all research team members.

For our data analysis, we used the software program ATLAS.ti 22, which makes it easier to organize the data and handle large datasets (Paulus et al., 2017). First, to calculate intercoder reliability, the two researchers randomly picked 10 (20.8%) articles and coded them using the coding scheme. Next, the files for the two coders were merged. To ensure consistency in the interpretation of the coding scheme, we used Krippendorff's α to measure intercoder reliability after the initial coding. Krippendorff's α coefficient is one of the most widely used coefficients for measuring intercoder reliability in content analysis. In our study, we used it because it was suitable for the categorical data used in the coding scheme; it adjusts for chance agreement between coders. It manages "shades of gray" in content analysis, where reviewers might partially agree with each other on a specific code (Krippendorff, 2004). According to the literature, a Krippendorff's α coefficient above .80 suggests good interrater reliability (Krippendorff, 2004). The overall Krippendorff's α coefficient was .88, suggesting very good intercoder reliability. Table 2 gives the α values for each coded theme.

2.5 | Synthesis of findings

After all curriculum components, reported difficulties, and lessons learned had been coded for every included study, we conducted a second round of analysis, where emergent themes were identified by comparing the studies. This process developed over multiple meetings, and it was iterative. All authors collaborated closely in the process by reviewing emergent themes. Again, points of debate and uncertainty were discussed until a consensus was reached. In this process, we emphasized the concept of alignment using the spider web framework and whether curriculum implementation (how) was aligned, especially with the why and what of the CBL studies.

3 | RESULTS

Below, we discuss the findings of the systematic review. First, we provide details about the included studies regarding descriptive characteristics (Section 3.1), including theoretical background (Section 3.1.1) and research aims and methodologies adopted (Section 3.1.2). Then we present the findings related to CBL implementation (Section 3.2), including CBL implementation at the course level (Section 3.2.1) and the project level (Section 3.2.2). Finally, we present the reported difficulties and lessons learned (Section 3.3) concerning the implementation of CBL.

TABLE 2 Intercoder reliability for identified themes.

	Themes	Krippendorff's α coefficient
RQ 1	Challenge characteristics	.88
	Rationale	.97
	Aims/learning objectives	.92
	Teacher role	.89
	Grouping	.89
	Learning activities	0.81
	Materials/resources	0.80
	Time	0.93
	Location	1
	Assessment deliverable	0.90
	Assessment focus	0.93
	Assessment level	1
	Assessment type	0.93
RQ 2	Teacher difficulties	0.83
	Student difficulties	0.81

3.1 | Descriptive characteristics of included studies

The studies included in the review were reported in 20 published articles in peer-reviewed journals and 28 papers in published conference proceedings on engineering education. In engineering education, top-tier published conference proceedings are considered high-status publications equal to those in highly ranked journals. Supplements 1 and 2 describe in detail the characteristics of each included study. The included studies described single implementations of CBL, with 27 studies adopting a mixed-method design, including analysis of data collected via interviews, surveys, and observations. Eleven studies were qualitative, and 10 studies adopted a quantitative design, mentioning only the results of students' self-reported questionnaires.

In terms of context, 36 studies were conducted at the bachelor's level, 9 studies were at the master's level, 1 study reported the inclusion of students from both bachelor's and master's programs, and 2 studies did not report at which specific level CBL was implemented.

3.1.1 | Theoretical frameworks used in the studies

To be able to interpret the findings of each study, we first analyzed the theoretical background used for the study, the research aims, and the methodology selected to attain those aims. Although mentions of the theoretical grounding of the research were sparse in most of the studies analyzed, we identified three frequently mentioned theoretical frameworks guiding the implementation of CBL. Those were experiential learning, active learning, and self-determination theory. Several studies mentioned experiential learning as a theoretical framework (Chanin et al., 2018; Charosky & Bragós, 2021; Jensen et al., 2018; Palma-Mendoza et al., 2019). These studies recognized the value of hands-on experiences, projects, and real-world application of knowledge in enhancing student learning, developing innovation competencies, and preparing students for future challenges. In addition, a number of studies shared the common use of active learning as a theoretical framework (Arrambide-Leal et al., 2019; Chanin et al., 2018; Cheung et al., 2011; Gaskins et al., 2015; Membrillo-Hernández et al., 2018; Membrillo-Hernández & García-García, 2020; Membrillo-Hernández, Munoz-Soto, et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Torres-Barreto et al., 2020). Active learning was used to encourage students to engage in the learning process, promoting deeper understanding and skills development. Finally, a few studies drew on theories such as self-determination theory to highlight the importance of engaging students in their learning process and motivating them to participate actively (Bombaerts, 2020; Bombaerts et al., 2021).

3.1.2 | Research aims and methodologies of the included studies

The common focus of the studies was the implementation of CBL as an educational approach in various engineering and technology-related courses and projects (e.g., Binder et al., 2017; Charosky et al., 2018; Cheung et al., 2011; Gama, Alencar, et al., 2018; Gama, Castor, et al., 2018; Portuguez Castro & Gómez Zermeño, 2020). However, the research aims of the studies differed. Some of the studies focused on comparing the effectiveness of CBL with other teaching approaches, such as case-based learning or traditional methods (Bombaerts et al., 2021; Charosky et al., 2018; Charosky & Bragós, 2021; Gama, Castor, et al., 2018). Some studies examined the impact of CBL on students' learning outcomes and competencies (Charosky & Bragós, 2021; Gudonienė et al., 2021; Martínez & Crusat, 2017; Membrillo-Hernández, Ramírez-Cadena, et al., 2019) or student engagement and motivation (Bombaerts et al., 2021; Gutiérrez-Martínez et al., 2021; Huettel et al., 2015). Many studies aimed to evaluate the effectiveness of CBL in solving real-world challenges or addressing societal issues through engineering education in multidisciplinary contexts or collaborative projects (e.g., Fidalgo-Blanco et al., 2016; Gama, Alencar, et al., 2018; Gama, Castor, et al., 2018; Hassi et al., 2016; Maya et al., 2017).

In terms of the methodologies, the majority of the studies analyzed cases of implementation of CBL in a specific course or setting. They employed mixed methods, combining quantitative and qualitative data collection and analysis techniques (e.g., Binder et al., 2017; Bombaerts et al., 2021; Chanin et al., 2018; Cirenza & Diller, 2015; Clegg & Diller, 2019; Gama, Alencar, et al., 2018; Gama, Castor, et al., 2018; Lasso-Lopez et al., 2020; Membrillo-Hernández & García-García, 2020; Membrillo-Hernández, Munoz-Soto, et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Membrillo-Hernández et al., 2018, 2021). A mixed-method approach allowed for developing a comprehensive understanding of the impact of CBL on various aspects of engineering education, as well as collecting information on students' and teachers' perceptions of the implementation. Studies such as those by Arrambide-Leal et al. (2019), Charosky and Bragós (2021), Cheung et al. (2011), Gaskins et al. (2015), Gudonienė et al. (2021), Huettel et al. (2015), and Rodríguez-Chueca et al. (2020) adopted quantitative methods, involving surveys and assessments to measure the effectiveness and outcomes of CBL in engineering education. Qualitative methods were employed in studies that focused on gathering in-depth insights and perceptions of students through interviews, reflections, and document analysis (e.g., Charosky & Bragós, 2021; da Costa et al., 2018; Pepin & Kock, 2021; Quweider & Khan, 2016; Santos et al., 2015; Torres-Barreto et al., 2020; Valencia et al., 2020). Regarding the representativeness of the student population in the included studies, most of the studies did not report whether the included sample of students was representative of the student population in their university; thus, claims about the generalizability of findings should be carefully examined.

3.2 | Forms of CBL implementation

As a common characteristic, all CBL experiences used challenges as the starting point for students' active learning. Two forms of CBL implementation were identified: at the course level ($n = 29$) and the project level ($n = 19$). We distinguished these based on whether the learning focus was on students' acquisition and application of new knowledge via real-world challenges embedded in a course (CBL courses). In CBL courses, the primary goal was to encourage students' active engagement and knowledge acquisition while tackling the challenge and developing a solution. However, it is important to note that the solution for the challenge was not the main emphasis of the CBL courses; instead, the focus was on promoting students' active learning of subject-matter knowledge.

On the other hand, the focus of CBL projects was on developing a solution. Subject-matter knowledge was presumed, and the CBL project had no link with a specific course or disciplinary content. The projects involved master's thesis projects and extracurricular projects such as hackathons. In CBL courses, the disciplinary content was learned through integrating subject-matter knowledge to develop a solution (Membrillo-Hernández, Munoz-Soto, et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Membrillo-Hernández et al., 2021; Mora-Salinas et al., 2019; Ramirez-Mendoza et al., 2018). CBL projects were not linked with a specific course or disciplinary content, and prior knowledge was assumed. Therefore, students had to focus on solution development rather than knowledge acquisition. Following the curriculum characteristics as described by van den Akker (2003), we discuss below the ***why*** (rationale), the ***what*** (aims and objectives), and the ***how*** (learning activities, assessment, information about teachers' role, grouping, location, and time) of CBL implementation at the course and project level. Table 3 summarizes key characteristics of the two forms of CBL implementation.

TABLE 3 Overview of CBL curriculum characteristics in the systematic review.

CBL curriculum themes	CBL courses ($n = 29$)	CBL projects ($n = 19$)
Rationale	• Use the CBL approach to foster active learning and motivation by presenting a real-world challenge to students • Use the CBL approach to educate T-shaped engineers, able to deal with open-ended, real-world, societal challenges, and develop disciplinary and transversal skills	• Use of CBL approach to educate T-shaped engineers, able to deal with societal challenges and develop innovative technological solutions with societal value
Aims and objectives	• Content knowledge acquisition and/or knowledge application on a specific topic • Development of transversal skills • Development of an understanding of the social value of engineering • Focus on knowledge development and the process of tackling a challenge rather than the response to the challenge itself	• Content knowledge application in a real-world, open-ended challenge that requires integration of disciplines • Development of an innovative technical solution with societal value • Integration and application of knowledge from multiple disciplines • Development of transversal skills • Development of an understanding of the social value of engineering by developing a solution with societal value • Focus on the process of tackling the challenge and the solution itself
Content	• Specific for the course—challenge developed by teachers to align with course content	• No link to a specific course content • Disciplinary content knowledge assumed or supported by modules • Students required to integrate knowledge from more disciplines to develop a solution
Learning activities	Differ per course; examples include: • Active Learning activities (ideation activities; debates) • Collaborative activities (debate exercises, ideation exercises, participation in forum discussions) • Self-regulated learning (self-study, reflections on learning process)	Differ per course; examples include: • Active learning activities: (problem-solving, ideation exercises, brainstorming activities) • Collaborative learning activities (group work, peer reviews) • Hands-on activities (design activities, prototyping) • Self-regulated learning (self-study, reflections on learning process)
Teacher's role	• Challenge developed by teacher to align with course objectives, teacher usually also acting as a lecturer • Requires teachers from more than one discipline to contribute to the development of challenges and provide module lectures to provide "just in time" support for students' learning • Teachers acting as coaches to provide scaffolding and support while students work on the challenge	• Teachers responsible for challenge development (often in collaboration with industrial or societal stakeholders) • Challenge developed by multidisciplinary groups of teachers in collaboration with societal stakeholders • Teachers acting as coaches for students as well as co-creators of challenge solutions
Materials and resources	• Modules, lectures, textbooks	• Resources to facilitate collaboration and design process (group discussions, feedback by

(Continues)

TABLE 3 (Continued)

CBL curriculum themes	CBL courses ($n = 29$)	CBL projects ($n = 19$)
	• Material and resources to facilitate just-in-time knowledge (textbooks, online material; lectures, online modules, workshops) • Resources to facilitate collaboration and design process (group discussions, feedback by peers/external stakeholder, teacher, debates) • Use of technology tools for collaboration and design process.	peers/external stakeholder, teacher, debates) • Use of technology tools for collaboration and design process
Grouping	• Individual and group work with peers from the same or a different discipline • Teachers and stakeholders possibly part of the group	• Interdisciplinary groups of students • Teachers and stakeholders possibly part of the group in co-creating the solution
Location	• Classroom/laboratories/libraries • Visits to libraries, stakeholder sites, classrooms and maker spaces; online collaboration	• Maker spaces/visits to stakeholder sites/online collaboration
Time	• Specific hours, lecture time, and self-study • Self-paced learning via modules. • Self-paced learning, but with deadlines • Project split into phases	• Differs per project • Self-paced learning, but with deadlines • Project split into phases
Assessment	• Focus on knowledge acquisition: Assessment via individual exams, final individual or group reports and presentations • Focus on knowledge application: Assessment of prototype, final report, presentations • Focus on the learning process: Assessment via reflections, portfolios • Focus on development of transversal competencies (e.g., collaboration): Self-assessment, formative assessment	• Focus on knowledge application/ performance: Assessment of prototype, solution, presentation • Focus on the learning process: Assessment via reflections, portfolios • Focus on development of transversal competencies (e.g., collaboration): Self-assessment, formative assessment

3.2.1 | CBL implementation at the course level

At the course level, the *rationale* for using CBL as a pedagogy was to overcome the shortcomings of traditional teacher-centered approaches by focusing on active learning and engagement of students with disciplinary content, using a real-world challenge as a starting point (Clegg & Diller, 2019; Gaskins et al., 2015; Huettel et al., 2015; Lovell et al., 2013). CBL courses aimed at various *learning aims and objectives*, including students' in-depth understanding of content knowledge (Clegg & Diller, 2019; Detoni et al., 2019; Gaskins et al., 2015), knowledge transfer (Clegg & Diller, 2019; Gaskins et al., 2015; Rodríguez-Chueca et al., 2020), application of knowledge (Gutiérrez-Martínez et al., 2021; Santos et al., 2015), and development of disciplinary and transferable skills (Félix-Herrán et al., 2019; Mora-Salinas et al., 2019; Membrillo-Hernández, Munoz-Soto, et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Membrillo-Hernández et al., 2018; Ramirez-Mendoza et al., 2018).

Seven CBL courses focused on content and disciplinary knowledge acquisition (Cirenza & Diller, 2015; Clegg & Diller, 2019; Fidalgo-Blanco et al., 2016; Gaskins et al., 2015; Huettel et al., 2015; Lovell et al., 2013; Quweider & Khan, 2016). The teacher developed and tailored the challenges in those courses to support students' disciplinary content learning (Clegg & Diller, 2019; Gaskins et al., 2015). On the other hand, the remaining 22 articles described the implementation of CBL courses that set as *learning objectives* students' acquisition and application of disciplinary knowledge, as well as the development of transversal skills such as ethics, problem-solving skills, leadership, communication, and collaboration skills (Cuevas-Ortuño & Huegel, 2020; Gonzalez-Hernandez et al., 2020; Ramirez-Mendoza et al., 2018). Those studies represented the largest body of articles in this review.

In terms of challenge characteristics, challenges were open-ended and real-world; in 14 cases, external industry partners and societal stakeholders were involved, increasing the complexity of the challenges (Bombaerts et al., 2021;

Membrillo-Hernández & García-García, 2020). Students had to use prior knowledge and acquire new knowledge for developing a solution for the challenge by following a process of identifying and analyzing the challenge, designing a solution, and presenting it (Gonzalez-Hernandez et al., 2020; Palma-Mendoza et al., 2019; Ramirez-Mendoza et al., 2018). To guide this process, six studies (Chanin et al., 2018; da Costa et al., 2018; Detoni et al., 2019; Palma-Mendoza et al., 2019; Portuguez Castro & Gómez Zermeño, 2020; Rodríguez-Chueca et al., 2020) used the framework developed by Apple (Nichols & Cator, 2008). According to the Apple framework, students had to define a big idea, a broad concept that they could explore in several ways. Then, following the big idea, students had to develop essential questions, define their challenge, develop guiding activities, questions, and resources, and develop, implement, and evaluate their solution. Two studies (Clegg & Diller, 2019; Cuevas-Ortuño & Huegel, 2020) adopted the STAR (software technology action reflection) Legacy Cycle methodology, which consisted of the following steps: Students had to design the challenge, generate the ideas, approach the challenges from different viewpoints, conduct research, revise, assess the skills needed for the development of the solution, and publish the solution.

CBL courses described various *learning activities* and *resources* to support students' learning. As knowledge acquisition was a key objective for CBL courses, lectures, modules, textbooks on foundational subjects, and disciplinary content were provided to students (Gaskins et al., 2015; Huettel et al., 2015; Lovell et al., 2013; Quweider & Khan, 2016). Furthermore, to support students in the CBL process of solution development, workshops on transversal skills such as problem solving and creative thinking, resources to facilitate collaboration and design processes such as group discussions, feedback by peers and external stakeholders, debates, and technology tools were also used (Clegg & Diller, 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019).

In CBL courses, *teachers* have various roles, including being the designers of the challenge (Clegg & Diller, 2019), developing learning modules and lectures to provide students with theoretical input to accompany students' work (Detoni et al., 2019), coaching students (Bombaerts et al., 2021; Mora-Salinas et al., 2019), providing feedback on students' deliverables such as presentations and reports, and assessing students' achievement in terms of competency development and project outcomes (Binder et al., 2017; Gaskins et al., 2015). Several studies mentioned that a multidisciplinary group of teachers collaborated in the development of the challenges and the implementation of the CBL course (da Costa et al., 2018; Félix-Herrán et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). Regarding *grouping*, all studies required students to work together as a team. The teams comprised peers from the same discipline (Félix-Herrán et al., 2019) or different disciplines (da Costa et al., 2018; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). Often, the teams were even broader, involving collaboration among students, teachers, and stakeholders (Ramirez-Mendoza et al., 2018).

The articles mentioned several *assessment* methods for the students depending on the learning objectives of each course. Below, we provide only some examples of assessment instruments used for different learning objectives. First, assessment of students' knowledge acquisition was conducted via individual exams, final individual or group reports, and presentations (Clegg & Diller, 2019; Gaskins et al., 2015; Lovell et al., 2013). Second, knowledge application was assessed via prototypes, final reports, and presentations (Membrillo-Hernández et al., 2018; Rodríguez-Chueca et al., 2020). Third, students' learning process was assessed via students' reflections and portfolios (Chanin et al., 2018; da Costa et al., 2018). Finally, transversal competencies (e.g., collaboration) were assessed using self-reported questionnaires and competence rubrics (Gutiérrez-Martínez et al., 2021; Membrillo-Hernández et al., 2019).

In terms of *time*, in CBL courses, students had both synchronous activities (e.g., lectures or workshops) and asynchronous activities (self-study of modules) encouraging self-paced learning (Gutiérrez-Martínez et al., 2021; Membrillo-Hernández & García-García, 2020). Regarding CBL courses' *location*, CBL courses that involved stakeholders mentioned the importance of students' learning outside lecture rooms and classrooms. For example, students considered visits to the stakeholders' premises and libraries, as well as working in open, collaborative spaces, very inspiring (Membrillo-Hernández & García-García, 2020).

3.2.2 | CBL implementation at the project level

CBL projects presented great variability, and three main types were identified: (i) CBL bachelor's and master's thesis projects (Kohn Rådberg et al., 2020; Maya et al., 2017; Pepin & Kock, 2021; Valencia et al., 2020); (ii) CBL projects that were part of a collaboration between different departments, faculties, or institutes and usually were intensive and lasted a couple of weeks (Charosky & Bragós, 2021; Charosky et al., 2018; Cheung et al., 2011; Hassi et al., 2016; Jensen et al., 2018; Lasso-Lopez et al., 2020; Martínez & Crusat, 2017; Torres-Barreto et al., 2020); and finally

(iii) extracurricular CBL projects such as participation in competitions and hackathons (Arrambide-Leal et al., 2019; Gama, Alencar, et al., 2018; Lara-Prieto et al., 2019; López-Fernández et al., 2020).

CBL projects *aimed* to support students in tackling open-ended and real-world engineering challenges (Charosky & Bragós, 2021; Gama, Castor, et al., 2018; Jensen et al., 2018; Lasso-Lopez et al., 2020) that had a broader focus on socio-technical challenges connected with global issues, often termed grand challenges (Kohn Rådberg et al., 2020; Maya et al., 2017; Pepin & Kock, 2021; Torres-Barreto et al., 2020). These challenges *aimed* to benefit an individual or community by promoting a collaborative and multidisciplinary approach and fostering students' awareness about the responsibility of engineers in society (Kohn Rådberg et al., 2020; Maya et al., 2017).

CBL projects that were not tied to specific courses or disciplinary content placed more emphasis on developing solutions for the challenges identified by the students. In terms of the *learning process*, students needed to identify and address gaps in their knowledge and skills (Gama, Alencar, et al., 2018; Hassi et al., 2016), integrate knowledge from multiple disciplines and independently master this content to develop a solution, and tackle challenges (Jensen et al., 2018; Kohn Rådberg et al., 2020; López-Fernández et al., 2020). The learning process was characterized by openness and iteration. As students worked on open-ended challenges, they learned to switch between divergent and convergent phases (Charosky et al., 2018; Hassi et al., 2016; Jensen et al., 2018). During divergent phases, students were expected to expand and explore their understanding of challenges, redefine them, generate ideas, and engage in explorations with users. Students also learned to select the best solution from various options, defend their choice, and communicate the results to relevant stakeholders (Charosky et al., 2018; Hassi et al., 2016). Furthermore, hands-on learning played a central role in CBL projects. Students were required to apply theoretical knowledge to real-world challenges, conduct experiments, design solutions, and reflect on their experiences (Chanin et al., 2018; Cheung et al., 2011; Lara-Prieto et al., 2019; Rodríguez-Chueca et al., 2020). They were expected to act in a self-directed and collaborative manner (López-Fernández et al., 2020).

In terms of *grouping*, the teams in CBL projects included not only students but also teachers and stakeholders (Charosky et al., 2018; Charosky et al., 2022; Gama, Alencar, et al., 2018; Gudonienė et al., 2021; Martínez & Crusat, 2017; Jensen et al., 2018; Torres-Barreto et al., 2020). Students had the freedom to decide how to assign different roles in their groups and were responsible for distributing their tasks. Multidisciplinary *groups* of students were mentioned in 12 CBL projects (Charosky & Bragós, 2021; Charosky et al., 2018, 2021; Gama, Alencar, et al., 2018; Gudonienė et al., 2021; Jensen et al., 2018; Kohn Rådberg et al., 2020; López-Fernández et al., 2020; Martínez & Crusat, 2017; Maya et al., 2017; Pepin & Kock, 2021; Torres-Barreto et al., 2020; Valencia et al., 2020).

Teachers in CBL projects were expected to fulfill the role of expert, coach, and co-learner (Charosky et al., 2018, 2021; Gama, Alencar, et al., 2018; Gudonienė et al., 2021; Jensen et al., 2018; Martínez & Crusat, 2017; Torres-Barreto et al., 2020).

Learning activities and resources involved group discussions, online modules, workshops on collaboration, and feedback sessions (López-Fernández et al., 2020; Martínez & Crusat, 2017; Torres-Barreto et al., 2020). Information and communications technology (ICT) tools and technology platforms were used to support students' collaboration and project management (Jensen et al., 2018; López-Fernández et al., 2020).

Assessment of CBL projects focused on the quality of the solutions that were developed. Students usually produced a report and a presentation to assess the solution for the challenge, where they provided argumentations for their suggested solution. This product was usually evaluated with rubrics and checklists of criteria (Charosky et al., 2018; Hassi et al., 2016; Jensen et al., 2018; Martínez & Crusat, 2017; Torres-Barreto et al., 2020).

The duration of CBL projects differed significantly. Some CBL projects had a very brief duration of a few days (López-Fernández et al., 2020; Gama, Alencar, et al., 2018) or a few weeks (Charosky & Bragós, 2021), and others lasted a semester, in the case of bachelor's and master's thesis projects (Kohn Rådberg et al., 2020; Valencia et al., 2020).

Regarding *location*, some studies stressed the importance of the physical learning environment as an aspect that facilitated learning within CBL and the use of maker spaces and innovation labs as creative and interactive locations ideal for students' collaboration (Jensen et al., 2018; Kohn Rådberg et al., 2020; Valencia et al., 2020).

3.3 | Difficulties and lessons learned related to the implementation of CBL

In addition to describing different forms of CBL implementation, we analyzed the studies for reported difficulties and lessons learned related to the implementation of CBL. These included experienced difficulties reported by teachers and students as they were captured via reflections, observations, and responses to open-ended questions reported in the included studies. The critical synthesis of those findings will serve as the basis for further development of CBL implementation. Below, we organized the difficulties and lessons learned related to CBL implementation as reported by teachers (Sections 3.3.1–3.3.4) and students (Sections 3.3.5–3.3.7).

3.3.1 | Development of complex sociotechnical challenges with the collaboration of external stakeholders

Teachers reported difficulties related to the development of challenges. For example, in the case of CBL courses, developing an open-ended and complex challenge was reported to conflict with the limitations of traditional learning environments, such as time constraints and the need to align the challenge with intended learning objectives (Bombaerts et al., 2021; Fidalgo-Blanco et al., 2016; Gaskins et al., 2015; Quweider & Khan, 2016). To achieve this, teachers had to scope the developed challenge to be manageable for the students within the time allowed for a course (Membrillo-Hernández et al., 2021).

The involvement of real-world stakeholders made the challenges relevant for students (Bombaerts et al., 2021; Membrillo-Hernández et al., 2021; Pepin & Kock, 2021). However, co-designing a challenge in collaboration with industry partners presented some difficulties for teachers, who reported struggling to align industrial partners' interests with a challenge that provides a good learning experience for students (Bombaerts et al., 2021; Membrillo-Hernández et al., 2021; Mora-Salinas et al., 2019; Ramirez-Mendoza et al., 2018; Valencia et al., 2020). In some reported cases, when stakeholders were involved, the challenges were open-ended and ill-defined to the extent that, in several cases, the teachers did not know in advance what the exact challenge or the solution was, which means that the levels of uncertainty were high not only for students but also for the teachers (Hassi et al., 2016).

Finally, time and effort spent were two important aspects influencing teachers' experiences with CBL (Bombaerts et al., 2021; Cuevas-Ortuño & Huegel, 2020; Membrillo-Hernández et al., 2021; Mora-Salinas et al., 2019; Palma-Mendoza et al., 2019). Teachers faced a heavier workload in CBL courses. For teachers, developing a challenge demands time, resources, and networking. The study by Bombaerts et al. (2021) mentioned that preparing and conducting a CBL course required approximately 60% more time than a traditional case-based approach. However, whether the time and effort remained the same throughout all future iterations of the same CBL course or project was not reported. In agreement with Bombaerts et al. (2021), Papageorgiou et al. (2021) reported the need for educators to exhibit flexibility and improvisation when designing and implementing CBL, because the necessary hours invested cannot be exactly predicted at the beginning of a CBL course or project.

3.3.2 | Development of effective CBL assessment methods

When designing the CBL courses, choosing or developing suitable assessment methods was another challenge for teachers (Membrillo-Hernández et al., 2021; Pepin & Kock, 2021; Valencia et al., 2020). Furthermore, aligning the assessment methods with the various learning objectives was difficult in cases where challenges were open-ended, as teachers did not have an overview from the beginning as to what students were expected to learn (Hassi et al., 2016; Membrillo-Hernández et al., 2021; Valencia et al., 2020). Another difficulty related to assessment was capturing individual students' discipline-specific learning gains when students mostly worked in collaborative and often multidisciplinary groups (Valencia et al., 2020). In addition, assessment of transferable skills such as communication, teamwork, problem-solving, and self-directed learning also presented difficulties because students' development of those skills often requires a longer exposure to CBL than a single course or project, and students' development is difficult to capture after only one CBL experience (Membrillo-Hernández et al., 2021).

3.3.3 | Need for CBL training for teachers

As reported in many articles, teachers were challenged to adjust their roles from lecturers to facilitators and coaches in the CBL environment (Membrillo-Hernández et al., 2021; Pepin & Kock, 2021). Without theoretical knowledge and skills regarding CBL methods, teachers often encountered difficulties designing the course activities, facilitating students' teamwork, and balancing between helping and influencing the students' work (Pepin & Kock, 2021). Membrillo-Hernández et al. (2021) and Charosky et al. (2018) stressed the importance of training teachers in CBL before engaging in CBL-based education, while Valencia et al. (2020) mentioned the importance of teachers' assessment literacy for designing and implementing effective assessment methods that are aligned with the CBL's intended learning objectives.

3.3.4 | Need for support from departments and institutions for CBL implementation beyond the course or project level

As most studies described CBL implementation in single courses and projects at the system level, an important difficulty was the lack of support from departments or institutions to support CBL implementation beyond the course or project level (Membrillo-Hernández et al., 2021). Teachers reflected that they need more supportive materials, resources, and policies from the faculty or university to improve the effectiveness of CBL (Charosky et al., 2021; Cuevas-Ortuño & Huegel, 2020; Membrillo-Hernández et al., 2021).

3.3.5 | Students' difficulties in balancing knowledge acquisition and application

In the early years of their bachelor's studies when they had yet not built solid disciplinary knowledge, working on complex and open-ended challenges proved difficult for students (Binder et al., 2017; Membrillo-Hernández et al., 2021). That was especially true for CBL courses involving a real-world challenge with an external stakeholder (Membrillo-Hernández, Munoz-Soto, et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Membrillo-Hernández et al., 2021; Mora-Salinas et al., 2019; Palma-Mendoza et al., 2019; Ramirez-Mendoza et al., 2018). In those studies, it was commonly reported that students struggled to combine knowledge acquisition and implementation simultaneously within the timeframe of one semester.

3.3.6 | Students' difficulties in dealing with the ambiguity and uncertainty of open-ended challenges

One crucial aspect that influenced students' experience with CBL was the uncertainty that was integral to CBL (Arrambide-Leal et al., 2019; Kohn Rådberg et al., 2020). The openness and ill-defined nature of challenges combined with the student's need for self-directed learning and initiative created uncertainty and sometimes resistance (López-Fernández et al., 2020; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). Several researchers pointed out that it was challenging for students to narrow down broad challenges and translate knowledge into practical solutions (Rodríguez-Chueca et al., 2020). Within this context, students felt insecure about achieving the desired outcomes. As a result, some studies suggest introducing students first to a smaller-scale challenge as an exercise, so that they could practice the process before moving to bigger and more complex challenges (Fidalgo-Blanco et al., 2016).

As the expected outcome and the process were not known in advance, students experienced increased levels of uncertainty when navigating an open-ended challenge (Gama, Castor, et al., 2018; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). In the study by Jensen et al. (2018), students mentioned difficulties in the analysis phase of the CBL project, leading to difficulty transitioning from the divergent to convergent stages of CBL. Similar findings were reported in the studies by da Costa et al. (2018) and Detoni et al. (2019). In the study by da Costa et al. (2018), students experienced difficulties narrowing down the broad challenge and developing guiding questions, and in the study by Detoni et al. (2019), students reported difficulties in the investigation phase, mainly when conducting research necessary to analyze the challenge. Other student-reported difficulties were associated with a lack of technical knowledge (Binder et al., 2017), lack of familiarity with the CBL process (López-Fernández et al., 2020), and difficulties with self-study (Cheung et al., 2011). Students also struggled with time constraints in CBL. They reported needing more time than for traditional courses or projects (Cuevas-Ortuño & Huegel, 2020; Valencia et al., 2020). Many studies suggested that new pedagogies and CBL processes were unfamiliar to students, and more time was needed to adapt (López-Fernández et al., 2020; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). That was especially true for CBL courses, where within one semester students had to master knowledge and prepare for an exam, as well as to work on a real-world challenge and communicate their solution to the clients or external stakeholders (Detoni et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Membrillo-Hernández et al., 2021).

3.3.7 | Need to provide training in transversal skills for students

In addition, students are expected to be at the center of learning in the CBL context, which requires higher self-regulated learning skills for students and working as a member of a group which was often multidisciplinary (Pepin & Kock, 2021; Valencia et al., 2020). Students lacking intrinsic motivation or self-reflection skills often found their experience with CBL and teamwork negatively affected (Rodríguez-Chueca et al., 2020). In addition, conflicts arising from teamwork were frequently mentioned by researchers (López-Fernández et al., 2020), highlighting the importance of training students in transversal skills and group processes. López-Fernández et al. (2020) reported that a combination of students' low motivation, low technical competencies, and aversion to working autonomously could negatively influence their experience with CBL. The study by Jensen et al. (2018) focused on multidisciplinary collaboration and stressed the importance of teaching students teamwork and communication skills in order to decrease the occurrence of disciplinary egocentrism.

4 | DISCUSSION

The present review aimed to assess and synthesize evidence from empirical studies on CBL curriculum implementation in engineering education, the field in the literature where most CBL studies can be found (Gallagher & Savage, 2020; Leijon et al., 2022). This review went beyond the boundaries of previous studies—which primarily focused on describing the characteristics of CBL—by delving into the actual implementation of CBL educational interventions. The study aimed to answer two research questions about CBL curricula: "How is CBL currently implemented in engineering education?" and "What difficulties and lessons learned are associated with the implementation of CBL?" Utilizing van den Akker's (2003) curricular spider web framework, we systematically analyzed the educational components of CBL curricula across multiple studies. This analysis showcased the variety of approaches and complexities in CBL implementation. However, we also identified consistent themes that are critical in implementing CBL. In the following sections, we discuss the commonalities and differences in terms of educational components that we identified in this systematic review regarding CBL implementation in engineering education (Sections 4.1 and 4.2), the importance of balancing and aligning the complexity of challenges with other educational components (Section 4.3), the importance of scaling up implementation of CBL at the curriculum level (Section 4.4), and our own conceptualization of CBL (Section 4.5).

4.1 | Commonalities in the implementation of CBL

CBL focuses on immersing students in real-world, open-ended challenges, necessitating an interdisciplinary approach to developing solutions (Gama, Castor, et al., 2018; Gonzalez-Hernandez et al., 2020; Jensen et al., 2018). This focus on real-world challenges that was identified in this review was consistent with other definitions of CBL, underscoring the broad relevance of CBL and its emphasis on linking theory and practice (Clegg & Diller, 2019; Gallagher & Savage, 2020).

Existing conceptualizations of CBL (e.g., van den Beemt, van de Watering, & Bots, 2023) and the findings of this review agree that CBL puts students in the lead in their learning process (self-directed learning). This is achieved by providing students with the autonomy to choose the specific challenge they want to focus on and to define their learning process by conceiving and defining their learning pathway (Bombaerts et al., 2021; Detoni et al., 2019; Lara-Prieto et al., 2019; Pepin & Kock, 2019; Valencia et al., 2020). In addition, self-directed learning was promoted in CBL by encouraging students to identify and address gaps in their knowledge (Pepin & Kock, 2019). Finally, the iterative CBL learning process, characterized by divergent and convergent phases, mirrored the nature of real-world problem-solving, fostering students' need for adaptability and resilience, as students were encouraged to explore, redefine, and fine-tune their solutions (Jensen et al., 2018; Papageorgiou et al., 2021).

Another key feature of CBL identified in this review was interdisciplinary collaboration involving students, teachers, and occasionally external stakeholders (Detoni et al., 2019; Hassi et al., 2016; Maya et al., 2017; Papageorgiou et al., 2021; Ramirez-Mendoza et al., 2018; Torres-Barreto et al., 2020). These studies underscored the significance of collaboration, teamwork, and multidisciplinarity in CBL for fostering a sense of community and shared responsibility among participants. The collaborative aspect of CBL was essential for developing transversal skills such as communication, leadership, and problem-solving (Clegg & Diller, 2019; López-Fernández et al., 2020; Ramirez-Mendoza et al., 2018; Torres-Barreto et al., 2020).

Regarding interdisciplinarity, challenges often represented complex problems where more than one discipline needed to be combined or where students from more disciplines needed to collaborate (Hassi et al., 2016; Membrillo-Hernández & García-García, 2020; Membrillo-Hernández, Munoz-Soto, et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Membrillo-Hernández et al., 2021; Lasso-Lopez et al., 2020; Valencia et al., 2020).

Another commonality among all studies was reference to teachers' new and multifaceted role within CBL (Bombaerts et al., 2021; Clegg & Diller, 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Membrillo-Hernández et al., 2021). Instead of just teaching, educators took on roles as challenge designers and coaches, enriching the learning process and guiding students through the learning process, which is characterized by uncertainty (Bombaerts et al., 2021; Clegg & Diller, 2019).

Finally, CBL valued diverse learning environments, such as on-site visits and labs, promoting active learning and innovation (Membrillo-Hernández & García-García, 2020; Valencia et al., 2020).

4.2 | Differences in the implementation of CBL

Despite some common aspects in the implementation of CBL, the review suggests that the scope and nature of the challenges addressed differed in the included studies. Only a few studies made explicit the societal relevance or link to SDGs that seemed central in the definitions of CBL by Malmqvist et al. (2015) and Gallagher and Savage (2020). Some studies provided students with open-ended technical challenges (e.g., mobile app development, heat transfer, lean manufacturing Cirenza & Diller, 2015; Clegg & Diller, 2019; Cuevas-Ortuño & Huegel, 2020; da Costa et al., 2018); some focused on open-ended, real-world problems (e.g., entrepreneurship, societal challenges; Bombaerts, 2020; Portuguez Castro & Gómez Zermeño, 2020); and some included challenges that were real-world, but relevant to industrial practices rather than broader societal challenges (e.g., Membrillo-Hernández, Ramírez-Cadena, et al., 2019).

This difference in the scope of challenges could be due to the specific learning aims each CBL experience aimed for the students to achieve. For example, some studies adopted CBL aiming to foster the development of specific technical skills (e.g., software development, mobile app development; e.g., Binder et al., 2017; Santos et al., 2015); some aimed to teach specific concepts (e.g., lean manufacturing, entrepreneurship; Cuevas-Ortuño & Huegel, 2020; Portuguez Castro & Gómez Zermeño, 2020); and some prioritized the development of multidisciplinary skills, such as collaboration and problem-solving (Félix-Herrán et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). The involvement of external stakeholders was also relevant and added to the complexity of the challenges implemented. Some challenges were university-led with no external stakeholder involved (e.g., Arrambide-Leal et al., 2019; Lara-Prieto et al., 2019), while those in other studies engaged external stakeholders, including industry partners, experts, or end users who contributed to or evaluated the solution (e.g., Gonzalez-Hernandez et al., 2020; Membrillo-Hernández & García-García, 2020; López-Fernández et al., 2020). Regarding the involvement of external stakeholders, Charosky et al. (2018) discussed a tradeoff related to contact with and involvement of real stakeholders, which, on one hand, can enhance the creative part of CBL, but, on the other, may reduce the time available for design, implementation, and testing of complex solutions. The studies involving a real stakeholder agreed in finding that their involvement increased the perceived relevance of the challenge by the students, but also in noting that stakeholders need to have reasonable expectations about the expected solution within the timeframe and constraints of a CBL course or project (Membrillo-Hernández, Ramírez-Cadena, et al., 2019; Ramirez-Mendoza et al., 2018).

Regarding implementing CBL, differences were also found regarding the link with disciplinary content, the timeframe, and learning processes. Although CBL courses were generally tied to specific disciplinary content, projects offered a broader exploration of knowledge, not restricted to a particular course or discipline (López-Fernández et al., 2020). CBL courses typically had a structured timeframe, often spanning a semester, and provided a systematic learning approach (Clegg & Diller, 2019). Projects, however, varied significantly in duration, ranging from a few days to a semester, especially for thesis projects, allowing for flexibility (López-Fernández et al., 2020; Valencia et al., 2020).

The learning process in both courses and projects was iterative, and continuous feedback was reported as enhancing the CBL process (Charosky et al., 2022; Cheung et al., 2011; Cirenza & Diller, 2015; Clegg & Diller, 2019; da Costa et al., 2018; Gama, Castor, et al., 2018). However, CBL courses were usually more structured, guided by frameworks such as Apple or STAR, while CBL projects adopted a more open and iterative process, encouraging creativity and adaptability (Cuevas-Ortuño & Huegel, 2020; Portuguez Castro & Gómez Zermeño, 2020). CBL courses used more traditional learning resources such as textbooks and lectures to support students' knowledge acquisition, whereas projects prioritized hands-on activities and real-world engagement (Jensen et al., 2018; Martínez & Crusat, 2017).

Finally, our review suggests that assessment in CBL is an important but underexplored topic. Assessment methods varied and aimed to measure students' subject-matter knowledge acquisition and their application and development of competencies (Rodríguez-Chueca et al., 2020; Torres-Barreto et al., 2020).

4.3 | Balancing complexity in CBL implementation

Aligning the complexity of the challenge with other curricular elements, such as learning time or resources, proved to be a difficulty reported by educators. Educators struggled to align intricate real-world challenges with learning objectives within traditional learning environments (Bombaerts et al., 2021; Membrillo-Hernández et al., 2021; Ramirez-Mendoza et al., 2018). The involvement of external stakeholders enhanced relevance, but also increased uncertainty for teachers, who did not know in advance what a possible solution could be (Bombaerts et al., 2021; Hassi et al., 2016). The same was also true for students. Students, especially in the early academic stages, found balancing knowledge acquisition and application difficult, especially when working with real-world challenges (Binder et al., 2017; Membrillo-Hernández et al., 2021). The ambiguity of the challenge led to difficulties in refining challenges and applying theoretical knowledge (Arrambide-Leal et al., 2019; Rodríguez-Chueca et al., 2020) within the given timeframe. Our review suggests that misalignment between the complexity of the challenge and students' ability or the learning objectives can lead to disengagement or frustration (Gonzalez-Hernandez et al., 2020; Palma-Mendoza et al., 2019; Valencia et al., 2020). The above leads to the conclusion that a real-world, open-ended challenge is a driver for students' learning, but careful balance is required to ensure alignment with learning objectives and other curriculum elements, such as the available time and resources, and that the complexity must not deter students or diminish their ability to engage effectively (Gutiérrez-Martínez et al., 2021; Santos et al., 2015; Valencia et al., 2020).

4.4 | Going beyond the course and project level: Scaling CBL up at the curriculum level

The review suggests that CBL implementation is limited to bottom-up, small-scale educational interventions focusing on the course or project level. We did not find published literature on how CBL can be implemented at the curriculum level. Membrillo-Hernández et al. (2021) discussed Tecnológico de Monterrey's efforts to adopt CBL within their engineering curriculum broadly and highlighted the critical components of their CBL model, called Tech21. However, our analysis of all related studies did not reveal how the challenges were interconnected, to what extent they built on each other, and whether they gradually increased in complexity or need for self-direction. Given the promising benefits of engaging students in this type of learning, it is essential that the CBL initiatives extend beyond the course or project level and become integrated into students' education at the curriculum level. CBL implementation at the course level can benefit students' learning and development of professional skills. However, if CBL is not integrated into engineering education at the curriculum level and students are presented with CBL only once, its effectiveness might be reduced. Students can be expected to develop a process of solving open-ended challenges autonomously and collaboratively only when exposed to various examples of CBL (Arman, 2018; Du et al., 2019). For CBL implementation to extend beyond the course level into the curriculum level, support from the faculty, department, or institution is needed (Chen et al., 2021; Malmqvist et al., 2015; Membrillo-Hernández et al., 2021).

Designing an effective CBL curriculum presents several challenges, as multiple interconnected aspects need to be considered, such as how to design learning objectives and principles and what proportion of the overall engineering curriculum should be taught using CBL (Chen et al., 2021). CBL curriculum designers would benefit from consulting pedagogical theories and the CBL knowledge base to design a professional curriculum that combines learning theories and professional standards (Helker et al., 2024). In order to design a structured CBL practice, educational researchers, engineering staff, and university managers need to set their horizon beyond single engineering courses, and to identify sustainable learning objectives for students' longitudinal development in CBL (Doulougeri, van den Beemt, van de Watering, & Bots, 2023).

4.5 | Conceptualizing CBL

In conclusion, we provide our conceptualization of challenge-based learning, based on the knowledge we acquired through carrying out this review.

CBL is an educational approach in which students engage with real-world and multidisciplinary sociotechnical challenges that are ill-structured and open-ended, lacking a single "right" solution. These challenges are ideally presented by societal or industry stakeholders and require the proposal or development of a solution. Acquisition, integration, transfer, and application of knowledge from various disciplines, along with transversal skills such as critical thinking and problem-solving, are needed to develop the solution. The learning process in CBL is active, self-directed, and collaborative, encouraging students to become comfortable with uncertainty. When designing and implementing a CBL experience, educators should put particular emphasis on the alignment between the rationale of adopting CBL (why), the intended learning objectives for students (what), and the educational components (how), including the role of the stakeholders involved, the complexity of the challenge, the role of teachers, and assessment methods.

4.6 | Strengths and limitations

In the present study, we followed a systematic approach to identify all literature to date about CBL curriculum implementation in higher engineering education. It is possible that relevant papers in journals not indexed in the databases we searched were not identified. In addition, there is the possibility that other CBL-like initiatives that did not include the term "challenge" in their descriptions were not identified in our literature search. Our analysis is based on the content described in the empirical studies included for analysis. We may have missed studies that essentially implemented CBL but did not label it this way (Type II error). We used keywords typically associated with the concept of CBL, but excluded potentially similar constructs (e.g., active learning), which is a typical tradeoff for a systematic review; future research should further investigate connections between CBL and other constructs.

As CBL is an emerging model in engineering education, we decided to include all studies we identified as meeting our working definition and inclusion criteria. In following a qualitative review approach, our goal was to collect a large sample of CBL educational interventions to provide a more comprehensive understanding of how CBL curriculum elements have been implemented. This choice led us to focus on articles published in peer-reviewed journals and conference proceedings. The included studies varied in methodological approaches and reporting of findings. This variability was reflected in different research designs, implementations of CBL experiences, and data-reporting practices, and poses limitations to the interpretation of findings across the set of studies. Although we evaluated the quality of the collected papers, we did not exclude any based on these evaluations. That choice, which aligns with this study's qualitative and holistic aim, contrasts with other approaches (e.g., meta-analysis) in which papers are typically included only if they meet specific quality criteria (Grant & Booth, 2009). Finally, our working definition of CBL guided the inclusion of studies. We included studies where the authors claimed they implemented CBL (potential Type I error). However, we applied a rigorous process to identify whether the authors implemented CBL as claimed. Thus, we excluded several identified studies that claimed to use CBL, but the approach adopted did not differ from other active learning pedagogies (e.g., PBL). Additionally, to mitigate this limitation, our research team engaged in discussions with the main coder who conducted the search and analysis and provided support by doing random cross-checks and resolving disagreements with additional discussions.

Despite these limitations, the present review shows the current state of evidence for using CBL in engineering education, while suggesting additional research with robust study designs to understand the impact of such a pedagogy on students' learning. Even though this systematic review focuses on engineering education, the review is also relevant for other disciplines that want to use CBL. For example, the curricular spider web provides a comprehensive framework for mapping and guiding the design of a CBL course or project.

4.7 | Recommendations for practice at the course and project level

Based on our systematic review, below we discuss recommendations for educators regarding CBL implementation. Successful CBL implementation entails designing open-ended, real-world challenges linked with grand societal challenges that stimulate students to learn disciplinary content and develop transversal skills in a self-directed and collaborative way (Gama, Alencar, et al., 2018; Hassi et al., 2016; Jensen et al., 2018; Lasso-Lopez et al., 2020; Papageorgiou et al., 2021). Implementation of CBL should consider the alignment between course objectives, teaching and learning methods, and assessment, as suggested by frameworks such as the curricular spider web. In addition, we discuss the importance of training teachers and going beyond course- or project-specific CBL implementation to broad curriculum implementation.

4.7.1 | Development/design of challenges

Our results suggest that CBL courses and projects use a real-world challenge as the central vehicle for instruction in CBL classrooms (Mora-Salinas et al., 2019; Rodríguez-Chueca et al., 2020; Valencia et al., 2020). The difficulty of designing open-ended and complex, yet manageable, challenges within course constraints showcases the intricate balance required in CBL design. Educators need to strike a balance that stimulates students' interest, creativity, and problem-solving without overwhelming them. Although collaboration with industry partners and other stakeholders can enhance the real-world relevance of challenges, it also introduces complexities. Aligning educational objectives with industrial interests can be challenging but essential for ensuring that students derive valuable learning experiences. It is recommended that educators allocate enough time for the development of challenges and collaborate with various experts, such as educators from different disciplines and educational researchers (Félix-Herrán et al., 2019; Kohn Rådberg et al., 2020; Membrillo-Hernández et al., 2021). When developing a CBL course or project, educators should define learning goals at various levels, including disciplinary and transversal competencies, individual or group objectives, and expected learning outcomes (Membrillo-Hernández et al., 2021; Valencia et al., 2020). In addition, educators should agree beforehand on the relevant knowledge, skills, and attitudes engineering students should develop by participating in a specific CBL course or project (Valencia et al., 2020). Finally, it is important to involve external stakeholders early in the discussion and make sure that their expectations about intended objectives and outcomes align with the course or project objectives to ensure meaningful, real-world challenges for students (Bombaerts et al., 2021; Membrillo-Hernández et al., 2021; Mora-Salinas et al., 2019; Ramirez-Mendoza et al., 2018; Valencia et al., 2020).

4.7.2 | Development of appropriate assessment methods

Assessment of students' learning was highlighted as a CBL aspect that needs further attention from educators (Membrillo-Hernández et al., 2021; Pepin & Kock, 2021; Valencia et al., 2020). Achieving alignment between learning goals and assessment methods presents significant challenges, especially when students from different disciplines collaborate (Valencia et al., 2020). In addition, the learning process in CBL is considered as important as the final product or solution development, emphasizing individual and group learning (da Costa et al., 2018; Membrillo-Hernández et al., 2021). Thus, a combination of assessments focusing on the individual and the group, process, and products should be adopted to enhance the validity of the assessment of learning outcomes (Gallagher & Savage, 2020; van den Beemt, van de Watering, & Bots, 2023).

4.7.3 | Scaffolding students' self-directed learning

Students reported difficulties in acting autonomously during CBL, dealing with uncertainty and the open-ended aspect of challenges, and self-regulating their learning (Bombaerts et al., 2021; Lara-Prieto et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). Despite the emphasis on self-directedness, our study suggests that students did not always welcome the autonomy provided in CBL (López-Fernández et al., 2020). Thus, we recommend that before immersing students in full-fledged CBL projects, institutions or educators could consider introducing them to smaller, more manageable challenges. Introducing smaller challenges first can serve as a warm-up, familiarizing students with the CBL approach (Fidalgo-Blanco et al., 2016). Given the autonomy expected from students, the role of teachers was also different compared to traditional teaching approaches. The teacher was viewed as a coach, rather than an expert, who guided students through the learning process (Membrillo-Hernández, Munoz-Soto, et al., 2019; Membrillo-Hernández, Ramírez-Cadena, et al., 2019). Thus, we suggest that self-regulated learning should be supported by coaching and scaffolding from teachers and adjusted to the students' current level of skill and understanding (Doulougeri, van den Beemt, et al., 2022; Doulougeri, Vermunt, et al., 2022).

4.7.4 | Supporting students in the collaborative co-creation process

All studies in our review suggested that students in CBL learn while being part of a group, indicating that collaborative learning is a central feature of CBL. However, when some students had not had prior experiences with collaborative and open-ended courses, this adversely affected the CBL experience and teamwork (López-Fernández et al., 2020; Pepin & Kock, 2021; Rodríguez-Chueca et al., 2020). Thus, the review highlights the importance of fostering collaborative skills (Clegg & Diller, 2019; Martínez & Crusat, 2017). CBL studies described multidisciplinary or interdisciplinary collaboration that extended beyond the group of students and involved collaboration with teachers and often with external stakeholders (Bombaerts et al., 2021; Hassi et al., 2016; Jensen et al., 2018). Through collaboration, students learned to explore challenges from different perspectives via continuing discussion and integration of multiple perspectives and expertise (Jensen et al., 2018). However, our findings suggested that the collaborative process is easier said than done in CBL, with difficulties reported by students in collaborating and communicating with peers and stakeholders (Jensen et al., 2018; López-Fernández et al., 2020). It is necessary to establish processes by which students can check up on their collaboration throughout CBL. To facilitate collaboration during CBL, educators should consider carefully how to organize the course/project to facilitate formative interactions between all parties involved. In addition, to accompany CBL courses, institutions should offer workshops or modules focused on transversal skills such as collaboration, self-regulated learning, and conflict resolution to equip students with the requisite skills to excel in CBL contexts (López-Fernández et al., 2020).

4.7.5 | Professional development of teachers

Teachers faced challenges in adjusting their roles from being traditional lecturers to acting as facilitators and coaches in the CBL environment. Without adequate knowledge and skills regarding CBL methods, teachers often found it difficult to design course activities, facilitate student teamwork, and balance assisting and influencing students' work. The review highlights that not only do students need to shift toward active and self-directed learning, but teachers need to redefine their role, as coaches, co-learners, and co-creators of solutions (Membrillo-Hernández et al., 2021; Pepin & Kock, 2021). Therefore, to improve CBL implementation and effectiveness, it is important to provide CBL pedagogical training to enable engineering staff to develop CBL pedagogical knowledge and coaching skills and invest additional time in designing a CBL course or project (Pepin & Kock, 2021). Institutions should offer comprehensive training programs for educators, equipping them with the skills, methodologies, and best practices specific to CBL (Membrillo-Hernández et al., 2021).

4.8 | Recommendations for future research

Using the curricular spider web framework developed by van den Akker (2003), we could map the components of the CBL curriculum in each study. That allowed us to integrate the results of our analysis, better evaluate the information, and identify the most important characteristics of CBL. However, the careful analysis of the included studies revealed several limitations and issues that require further investigation.

4.8.1 | Developing rigorous CBL educational research

The current landscape of research on CBL in engineering education, as observed in this review, brings to light a pressing concern. Many investigations of CBL practices, while promising, remain confined to small-scale, bottom-up case studies that often need more robust theoretical grounding (Leijon et al., 2022; van den Beemt, van de Watering, & Bots, 2023). To truly harness the potential of CBL, educational practices must be informed by rigorous research (Leijon et al., 2022). We can ensure that CBL experiences are effective and theoretically sound by bridging the gap between research and practice.

Researchers and practitioners should develop CBL experiences and articulate the principles underpinning the effects of those interventions in terms of theories of students' learning processes and gains (Doulougeri, van Beemt, et al., 2022). We recommend collaborating with an interdisciplinary team of policymakers, teachers, and researchers to develop sound educational research that accompanies the implementation of CBL educational innovations. Sound research fulfills a double objective: on one hand, it will lead to good educational practices, and on the other, it will lead to the advancement of our knowledge and theory about which aspects of CBL work and why (Vermunt, 2021). Hence, intensifying the educational research on CBL is not just helpful but is crucial for the evolution and success of CBL as an innovative pedagogy.

Considering this, CBL implementation should be accompanied by rigorous educational research and documentation of the research methods used (Leijon et al., 2022). For example, many studies did not explicitly clarify whether their student samples were truly representative of their respective university populations. Accurate documentation of the study population is paramount for ensuring the representativeness and validity of research findings. For transparency and rigorous scientific inquiry, future studies must provide precise details about their study populations (Pawley, 2017).

4.8.2 | Research on the process/mechanisms of CBL

There needs to be more evidence about how CBL processes influence student learning. Most of these studies measured student learning in a course in general, rather than focusing on the effects of various educational components and learning activities on learning. This is especially problematic for studies combining two or more active learning activities, because it is difficult to assess each activity's unique contribution and effectiveness if they are not studied separately (Prince & Felder, 2006). Thus, the CBL research community needs to assess which CBL processes and mechanisms are effective and supportive of students' learning outcomes. To achieve this, practitioners should emphasize systematic documentation and analysis, and reflection on the design, development, evaluation, and implementation of CBL. Researchers should report clearly the research methods and analyses and use validated instruments to capture the effects of CBL and compare it with other approaches. In this way, educational policymakers can make evidence-informed decisions based on research about CBL practices. Experimental studies may be needed as well to achieve this.

4.8.3 | Research on students' learning gains

In terms of learning outcomes or learning gains, despite the overall positive outcomes associated with adopting CBL on student learning and competence development, it is important to look critically at the methodologies reported by the authors for answering their research objectives and questions. In most studies, the measurement methods relied on students' perceptions of their learning through self-reports or analysis of student deliverables and grades. This can be problematic, because students' opinions of the course or any aspect of it can impact their estimates of their learning (Prince & Felder, 2006). The development of a number of competencies was investigated by using self-perceptions. The results showed that few CBL interventions applied control group designs. However, when no control groups are used, researchers may reach varying conclusions regarding whether the influence of an educational aspect is significant. In addition, many studies only measured the learning and competence of students after adopting CBL, without establishing a baseline. Pre and post tests could provide interesting insight into the development of or changes in student learning, but according to the findings of this review they were rarely used. Currently, a limited set of studies have compared CBL with other methodologies such lecture-based or project-based instruction (Berland et al., 2013). There is no supporting evidence as to whether CBL leads to better knowledge acquisition and application. Longitudinal studies are also essential to explore the cumulative benefit of CBL education rather than the short-term learning gains of a specific CBL course or project (Berland et al., 2013; Herzog et al., 2022).

4.8.4 | Research on teachers' professional development

The role of teachers is central to CBL (Membrillo-Hernández et al., 2021; Pepin & Kock, 2021). Assisting educators in developing suitable learning materials for CBL offers only one necessary element in promoting reform. Professional development at a broader level is a critical component in scaling up CBL across the curriculum (Doulougeri et al., 2021). Future research should explore what competencies and skills teachers should have to meet the demands of their roles as tutors, coaches, and facilitators. This research will provide more information about the support teachers need to develop a CBL curriculum (cf. Stevens et al., 2024).

5 | CONCLUSION

This systematic literature review expands our knowledge about CBL by describing its implementation in engineering education—the field of higher education where most CBL studies can be found. Two forms of CBL implementation, namely CBL courses and projects, were identified and analyzed using the curricular spider web framework of van den Akker (2003). Our review provides new insights into different aspects of CBL implementation, such as the different learning objectives, the role of teachers, assessment methods, and learning activities and resources reported in empirical studies. We also provide insights into teachers' and students' experiences during CBL implementation.

Compared to other active learning pedagogies, CBL centers learning around open-ended, sociotechnical challenges instead of purely technical challenges. The challenges used in CBL are connected with global societal challenges and often involve an external stakeholder in the educational activities. Furthermore, learning in CBL is self-directed and collaborative. CBL fosters knowledge acquisition and application and the development of transversal skills as students work toward developing a solution.

The findings indicated increasing adoption of CBL in various disciplines in engineering education. However, evaluations of those CBL educational interventions have mostly been limited to quantitative data drawn from course assessments and surveys, and only rarely included qualitative research to understand phenomena in depth and within specific contexts. By synthesizing the existing research on CBL, this study provides recommendations for researchers, practitioners, and policymakers to develop research-based action plans to develop and evaluate CBL interventions at the course and curriculum levels.

In practice, educators should focus in the future on designing open-ended, real-world challenges well aligned with desired learning outcomes. Teaching and learning practices, such as coaching and scaffolding, must be designed to foster students' autonomy. Finally, appropriate assessment methods for students' individual and group learning should focus on the CBL learning process and the quality of the solutions and products delivered. Educators should allow enough time before beginning a CBL course or project to train teachers, stakeholders, and students in the CBL process.

To advance our knowledge about CBL, sound research needs to accompany educational practice. More research into the processes and mechanisms of CBL is needed. For example, more research is needed on how CBL stimulates self-directed learning, collaborative learning, disciplinary knowledge acquisition, and the application and development of transversal skills. In addition, more research is needed about the professional development of teachers and the competencies and skills teachers should have to meet the demands of their roles in CBL. We recommend that future empirical studies go beyond a case study design and incorporate multiple methods and sources of data to explore the impact of CBL beyond its context-specific implementation. This means that future inquiries would benefit from other pedagogical research methods. Longitudinal research on the long-term impact of CBL can provide a broader understanding of students' learning. As we illustrated, adoption of CBL in universities carries institutional implications for their vision and mission. It also shapes how the university engages with ecosystem partners and, in the end, contributes to the university's reflection on its role in society.

In conclusion, CBL is a powerful pedagogy for educating future engineers. In CBL, learning occurs within a real-world context, inviting students to tackle open-ended societal challenges. However, research needs to be ongoing to ensure the continued improvement and effectiveness of CBL implementation.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX

CODING SCHEME FOR ANALYSIS OF INDIVIDUAL STUDIES

Descriptive characteristics of each study	To answer RQ 1: Coding of implementation CBL	To answer RQ 2: Coding of CBL implementation difficulties
• Type of publication	• Challenge characteristics	• Teachers' experienced difficulties
• Country	• Rationale	• Students' experienced difficulties
• Type of study	• Aims/ learning objectives	
• Methods used	• Teacher role	
• Field of engineering	• Grouping	
• Duration of CBL experience	• Learning activities	
• Number of participants	• Materials/resources	
	• Time	
	• Location	
	• Assessment	