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Engineering Education in K-12: Professional Development (PD), Challenges, and Opportunities

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Abstract

The current review determined the importance of professional development (PD) in K-12 engineering education. It highlighted the challenges teachers face and opportunities available for students to enhance their problem-solving and critical-thinking skills. The review used research studies on PD focusing on challenges and opportunities teachers and students face in K-12 engineering education. Data was gathered using the last ten years (2015-2024) from authentic published studies from databases (Springer, Wiley, Taylor & Francis, MDPI). This review study used keywords that include; "K-12 Engineering Education," "Professional Development in STEM," "Active Learning Strategies," "Challenges in Engineering Education," and "Opportunities in K-12 STEM". Seventeen articles were extracted from the data and included as final studies. Research results showed that successful PD programs that use project-based and gamified learning approaches deliver meaningful improvements to internal education competence and student problem-solving ability for teachers. Teachers face obstacles because of restricted resources, insufficient teacher development, and institutional obstacles. Findings showed that PD can help teachers implement innovative teaching methods for engineering education in K -12 classrooms.

Keywords: K-12 Engineering Education, Active Learning, Teaching Challenges, Training, Professional Development (PD), Project-based Learning (PBL)

Introduction

Engineering in K-12 education is important in this 21st century for students to provide them with opportunities. It involves problem-solving exercises for students, which increase their ability to solve real-world problems (1). For this purpose, professional development (PD) is important in integrating engineering to prepare students with critical thinking and problem-solving skills in K-12 education, such as project-based learning, experimental learning, collaborative learning, and gamification. Studies have determined that learning outcomes in K-12 engineering education can be achieved through educators' participation in PD activities (2). PD involves professional development to increase knowledge using active learning methods. The study by Brod (2021), defined active learning methods as actively constructing knowledge among students, particularly in science, technology, engineering, and mathematics (STEM) education. Therefore, for students in K-12 engineering education, active learning methods such as case study exercises, problem-solving exercises, simulations, and gamification potentially increase the various skills of students and provide them with opportunities to grow. Active learning has various potentialities, which include the opportunity to develop communication competencies, the ability to reflect on personal skills and lacking, and the opportunity for teachers to collaborate with students effectively and enjoy the overall learning process by increasing the motivation level of students when students feel they are achieving new opportunities and skills (3). A recent study defined factors contributing to k-12 engineering education as effective methods: collaboration and interaction with peers, field trips, and real-world focused activities.

Teachers play the most prominent role in facilitating the integration of engineering in K-12 education (4). Various studies have been presented on PD and its approaches for engineering in K-12 education, as well as opportunities for students with a growing interest in the challenges teachers face (4, 5). Limited studies combined these three aspects: PD Approaches, Challenges, and Opportunities

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in Engineering Education for K-12. It stressed the need to conduct this current review, which may improve the PD of teachers for engineering education in K-12. PD increases teachers' capacity and capabilities for motivating students and gaining opportunities. Teachers face various challenges, including a lack of training, insufficient resources, and a lack of student-centered approaches (6). This review addressed such challenges by providing suggestions aligned with previous studies' research. This allows teachers to implement efficient PD and gain opportunities for students that would help them in their personal and PD, for instance, by using a problem-solving approach to resolving real-life and industry problems.

Past studies have examined the role of PD approaches for engineering students, integration of engineering in K-12 education, and active learning approaches for K-12 engineering education but lack in manipulating PD, challenges, and opportunities (4, 6, 7). This review aims to highlight the significance of PD in developing opportunities for students and combating challenges faced by teachers in institutions for engineering education in K12.

Literature Review

The Role of PD for Engineering Education in K-12

Engineering education for K-12 students benefits significantly from the important role of PD (8). PD provides educators with important teaching techniques to successfully incorporate engineering principles across their educational material. PD is necessary to grasp engineering principles that help instructors overcome conventional educational approaches. Professional training enables teachers to execute advanced academic methods that develop students' ability to think critically while solving problems. Studies demonstrated that successful PD programs follow educational standards and create targeted instruction for K-12 educators (8, 9). Educational workshops involving teacher collaboration and practical instruction help educators discover innovative approaches to building interactive teaching methods. Educators who pursue PD opportunities establish best practices networks that become essential for coordinating engineering curricula throughout different school grades. Active teaching practices that stimulate student involvement emerge from PD participant development (10). PD gives teachers a way to address engineering education implementation obstacles as they serve multiple student performance levels and face resource restrictions. Quality professional development enables teachers to enhance their skills and produce better academic results for their students, contributing significantly to K-12 engineering education.

Effective Strategies to Improve Learning Environment

Effective techniques, including project-based learning (PBL), collaborative learning, and gamification, create successful K12 engineering education standards by improving student engagement and comprehension (11). Teachers should use practical teaching methods because their classroom experience teaches them the importance of what students learn. This enables students to develop analytical abilities and maintain motivation (12). Student learning in collaborative settings transforms educational experiences by providing them with teamwork competence and chances to exchange ideas, resulting in improved communication capabilities. The educational process receives improved learning outcomes when teachers use game mechanics from gamification to establish competitive gameplay elements within school assignments (10, 13). Available research indicates that student outcomes and retention rates improve when these teaching methods are used (13, 14). Teachers who use efficient evaluation approaches to students' assessment practices, continuous feedback, and individualized learning method development produce better academic achievements of students. Teachers who develop proficiency in PD training strategies through approved methods can establish advanced teaching.

Impact of Active Learning

Learning at K-12 level with engineering, requires active learning because it cultivates essential traits such as critical thinking, creativity and problem-solving (15). Teachers need active learning to work with concrete activities that include group discussions, teamwork, and practical problems that must be resolved (15). High achievement of advanced engineering knowledge occurs through active learning methods because students better understand complex engineering concepts when engaging in this approach rather than passive learning resources. The combination of active learning practices, including project-based learning, gamification, and experimental learning, is necessary for curriculum teachers to help students transfer abstract concepts into practical conditions and grow their interest in STEM courses (16). These educational approaches enable students to build important

behavior skills, including teamwork, communication, and adaptability. The combination of peer-to-peer educational environments develops students' important interpersonal competencies, which they will need in their professional future (15, 17). Multi-directional learning helps educators monitor student participation while monitoring problem-solving methods that enable them to develop specialized instruction methods.

Challenges

Teachers face multiple challenges in implementing engineering education effectively within K-12 learning. According to studies, insufficient teacher training causes difficulties in delivering engineering concepts effectively because teachers lack confidence and experience (18, 19). Lacking engineering education expertise is common among teachers who face challenges teaching subjects without confidence (9). A scarcity of essential resources, including textbooks, laboratory equipment, and technology, restricts engineering education in schools. The continued use of old educational materials leads students to disengage because they do not understand the contemporary value of engineering. Specific standards, principles, and institutional demands imposed on teachers often lead to limited instruction that promotes test readiness instead of original educational approaches (20). The busy schedules educators are dealing with alongside heavy workloads create barriers for educators who want to exchange valuable testing approaches with each other while building united curriculum content. Schools must fund and complete PD programs to meet educator requirements and supply the resources needed to support effective engineering training programs (11). Eliminating educational obstacles enables teachers to help their students acquire the essential skills necessary to better thrive in the technology-based present.

Methodology

Search Strategy and Keywords

This review used 17 recent review articles and research publications on PD for engineering education K-12 to increase students' opportunities in the 21st century and combat teachers' challenges. The current review study focuses on PD; therefore, it examines PD strategies with existing challenges and emerging possibilities for engineering education programs at K-12 levels. Multiple electronic databases, including Google Scholar and Web of Science, were utilized comprehensively for this research.
Recent developments in the field became the focus of a literature search from articles published between 2015 and 2024. The following keywords and their combinations were utilized: The research was carried out using multiple keywords, including "K-12 Engineering Education," "Professional Development," "Professional Development in STEM," "Active Learning Strategies," "Challenges in Engineering Education," and "Opportunities in K-12 STEM."
Research strategies for this review are shown in Table 1 below. For the first strategy, 3,860 results were obtained. For the second and third research strategies, 421 and 6,550 results were obtained. After this, the search criteria were refined by setting a timeframe for 2015-2024 to narrow the most accurate and study-related results. Then, studies were selected for this review based on inclusion and exclusion criteria explained in the next section.

Table 1: Search Strategies (Source: Author)

S.No	Search Strategy
1.	("K-12 Engineering Education" OR "Primary Engineering Education" OR "Secondary Engineering Education")
2.	("Professional Development" OR "Professional Development" OR "Teacher Training in STEM") AND ("Active Learning" OR "Project-Based Learning" OR "Collaborative Learning" OR "Gamification")
3.	("Engineering Education Challenges" OR "Barriers to STEM Education" OR "Teacher Challenges in K-12 Engineering")

Inclusion and Exclusion Criteria

Table 2 shows the criteria for adding and omitting studies, which were used to filter the most relevant studies for the current review. The researcher also selected studies published in peer-reviewed journals.

Table 2: Inclusion and Exclusion Criteria (Source: Author)

Inclusion Criteria	Exclusion Criteria
This review included all the studies published in peer-reviewed journals in English.	All studies not published in peer-reviewed journals in English were excluded from this review.
Studies highlighting any of the defined keywords were included only.	Studies highlighting any of the defined keywords were included only.
The inclusion of papers was based on studies between 2015 and 2024.	The exclusion of papers was based on studies published prior to 2015.
Studies available in publically available full-text format were included.	Studies not available in full-text format publically were excluded.

Results

Table 3: Results

S.No	Author (s)	Title	Publisher	Research Overview
1.	(21)	Integration of engineering into K-12 education: A systematic review of teacher professional development programs	Research in Science & Technological Education	Systematically reviews professional development programs for K-12 teachers integrating engineering, identifying best practices and challenges.
2.	(22)	An introduction to the standards for preparation and professional development for teachers of engineering	Journal of Pre-College Engineering Education Research (J-PEER	Introduces standards for engineering teacher preparation and professional development, focusing on competencies and best teaching strategies.
3.	(11)	Professional development for the integration of engineering in high school STEM classrooms	Journal of Pre-College Engineering Education Research (J-PEER	Examines high school STEM teachers' professional development for engineering integration, highlighting effective training approaches and challenges.

4.	(23)	Assessing teacher education and professional development needs for implementing integrated approaches to STEM education.	International Journal of STEM Education	Investigate teachers' professional development needs for effective STEM integration, identifying training and instructional methods gaps.
5.	(24)	Continuing professional development in sustainability education for K-12 teachers: Principles, program, applications, outlook	Journal of Education for Sustainable Development	Explores continuing professional development (CPD) in sustainability education for K-12 teachers, discussing principles, program effectiveness, and future directions.
6.	(25)	The effect of teacher professional development on implementing engineering in elementary schools	Journal of Pre-College Engineering Education Research (J-PEER	Analyzes the impact of professional development programs on elementary school teachers implementing engineering concepts in classrooms.
7.	(14)	Gamified Project-Based Learning: A Systematic Review of the Research Landscape	Sustainability, 15(2), 940	This study systematically reviews the integration of gamification with project-based learning (GPBL), highlighting its impact on student engagement, motivation, and problem-solving skills in K-12 education. It identifies the key game mechanics used in educational settings and their influence on learning outcomes.
8.	(26)	Teaching Mathematics Through Project-Based Learning in K-12 Schools: A Systematic Review of Current Practices, Barriers, and Future Developments	TEM Journal, 13(3)	This study explores the application of project-based learning (PBL) in K-12 mathematics education. It examines the effectiveness of PBL in improving conceptual understanding and problem-solving abilities while addressing barriers such as resource constraints and the need for teacher training.
9.	(20)	Strategies and Skills in STEAM Education: Systematic Review of the Literature	International Conference on Information Technology & Systems (Springer Nature Switzerland)	International Conference on Information Technology & Systems (Springer Nature Switzerland) This study reviews STEAM education strategies and their effectiveness in fostering

				interdisciplinary learning. It highlights the role of collaborative and interactive teaching methods in enhancing student engagement and comprehension in engineering and science-related fields.
10.	(27)	Innovations in Teaching: A Review of Contemporary Methods.	Journal of Engineering Scientific Research and Applications, 1(2), 95-111	This study examines innovative teaching strategies in mathematical education, including student-centered learning approaches such as PBL and gamification. It discusses the importance of analytical skill development and adaptive teaching methods for improved student outcomes.
11.	(12)	Trends in Digital Game-Based Learning in the Mobile Era: A Systematic Review of Journal Publications from 2007 to 2016	International Journal of Mobile Learning and Organisation, 13(1), 68-90	This systematic review analyzes the evolution of digital game-based learning (DGBL) in mobile education. It identifies key trends, educational benefits, and challenges of using mobile game-based strategies to enhance student motivation and knowledge retention.
12.	(28)	Integrating Project-Based and Skills-Based Learning for Enhanced Student Engagement and Success: Transforming Higher Education	Adaptive Learning Technologies for Higher Education (IGI Global)	This study explores the integration of PBL with skills-based learning to enhance student engagement and academic success. It highlights the need for curriculum adaptations and professional development to maximize the effectiveness of these learning strategies.
13.	(15)	How can we make active learning work in K–12 Education? Considering prerequisites for a successful construction of understanding	Psytechnological Science in the Public Interest	This paper examines the essential conditions for active learning in K–12 education, emphasizing the need for teacher preparation, student engagement strategies, and well-structured instructional design.
14.	(17)	Integrating science and engineering practices: outcomes from a collaborative professional development	International Journal of STEM Education	Investigates the impact of professional development programs on integrating science and engineering practices in K -12 education, highlighting teacher

				skill enhancement and student engagement improvements.
15.	(16)	A systematic review of K–12 education responses to emergency remote teaching during the COVID-19 pandemic	International Review of Education	Analyzes how K-12 schools adapted to emergency remote teaching during the COVID-19 pandemic, focusing on technological barriers, resource limitations, and the effectiveness of online learning strategies.
16.	(18)	Identifying the leadership challenges of K-12 public schools during COVID-19 disruption: A systematic literature review	Frontiers in Psychology	Reviews leadership challenges in K-12 education during the pandemic, including administrative burdens, staff burnout, and the need for adaptive teaching methodologies.
17.	(29)	The key characteristics of project-based learning: how teachers implement projects in K-12 science education	Disciplinary and Interdisciplinary Science Education Research	Investigate how teachers implement project-based learning (PBL) in K-12 science education, highlighting key characteristics such as real-world applications, student collaboration, and hands-on problem-solving.

Discussion

PD Increases Teachers' Capacity

Educational professionals require PD to obtain specialized skills that enable them to implement engineering education within K -12 learning environments. Specific research investigations have studied how professional development programs influence teaching abilities, educational techniques, and learning achievements in STEM and sustainability subjects. In a systematic study by Mesutoglu and Baran (2021), programs focused on K-12 engineering integration. The researchers demonstrated that successful teacher development should be an ongoing process that meets specific educational requirements to help educators properly teach engineering topics. Educators experience growing confidence in classroom implementation of engineering principles after participating in properly structured training programs that simultaneously build innovative teaching methods.

Reimers, Farmer, and Klein-Gardner (2015) study proposed the guiding principles for teacher training and continued development for engineering education. The study is based on a review with an emphasis on the PD of teachers in a professional manner. The authors highlighted the need to prevent unprepared educators from teaching engineering design processes, problem-solving capabilities, and student-focused instructional approaches. Effective programs enable teachers to teach engineering subjects and develop critical thinking with collaborative abilities in their students. Thus, it supports PD.

The quantitative study by Singer, Ross, and Jackson-Lee (2016), defined the effective PD approaches that aim to merge engineering with high school STEM content. Through workshops, peer support, and

mentoring, teachers gain better capabilities to teach engineering. According to research findings, active learning, real-world applications, and interdisciplinary teaching methods in PD programs lead students to become more engaged. The research conducted by Shernoff et al. (2017) addressed the need for teachers to train properly. This study distributed open-ended questionnaires to K-12 teachers to determine their challenges and opportunities in providing engineering or STEM education. The study defined that educational staff lacks proper interdisciplinary instruction training because they require additional opportunities to understand inquiry-based learning methods and collaborative teaching strategies for PD. According to the work of Redman, Wiek, and Redman (2018), PD expanded into sustainability education. According to their research, continuous development is vital in teaching sustainability principles within educational programs. The authors emphasize that sustainable CPD programs must consider practical aspects, reflective professional activities, and sustainability-focused foundations.

According to Porter et al. (2019), programs significantly influence how schools implement engineering education at the elementary level. Training programs that give teachers structured engineering experience and applied learning reduce their doubts when teaching these concepts. The research underlines the need for educators to receive unique PD training that matches their educational stage. This will enable them to establish engineering education at initial grade levels successfully.

Impact of Effective Strategies to Grow Opportunities

Creative educational methods in K-12 engineering education allow teachers to prepare students and themselves to integrate effective engineering in K-12 education. This strategy leads to major enhancements in student involvement and academic achievement. According to research studies, integrating PBL, collaborative learning, and gamification methods inside classrooms are good teaching methods that unlock the essential skills of students and teachers in education and their professional careers. Huang, Li, and Shang (2023) analyzed how gamified PBL improves students' motivation and engagement. Students learn problem-solving abilities through interactive and motivating experiences when PBL and game mechanics are combined into their educational content. This method strengthens students' thinking ability and academic achievements, mainly in demanding subjects, including engineering and mathematics. The trend of digital game-based learning (DGBL) is expanding, as defined in the study by Chang and Hwang (2019) because mobile and digital platforms generate an immersive educational experience that proves effective.

Nguyen et al. (2024) defined PBL approaches in education to address conceptual learning and practical application competency. The study shows that students who learn through PBL classrooms achieve superior retention rates and problem-solving skills than students who learn through standard educational methods. Their assessment acknowledges that trained educators and necessary resources represent major obstacles. According to Vaithianathan et al. (2024), the combined approach of PBL with skills-based learning grants valuable academic preparation for future education. A systematic study by Segarra-Morales and Juca-Aulestia (2024), proposed incorporating STEAM educational approaches that unify engineering with mathematics and technology for interdisciplinary teaching. The research selected 48 articles on interactive methods and teamwork, which produce more profound abilities to understand material while achieving desired skills. The research by Vijayaprabha, Vasuki, and Kumar (2015) examined unique teaching approaches in mathematics education, which teaches students how to think analytically and critically through self-directed learning. Teachers should adopt PBL, gamification, and collaborative learning approaches as effective approaches, and they should receive training to provide students with expanded educational prospects and develop pivotal skills for academic and profession-based achievement.

Recommendations for Overcoming Challenges

Improving K-12 engineering education demands professional development, which also includes using appropriate resource spending and changes in educational programs for students' improvement in K-12 education. Teacher training and professional development programs to combat teacher expertise shortfall and confidence gaps are predominant for achieving excellence in engineering education. According to Brand (2020), PD programs that merge science and engineering practices make teachers better at instruction and improve their conceptual understanding. Active learning strategies must be implemented by educators with existing training (15). Every school must organize continuous professional development programs in engineering education that help teachers gain skills to communicate complicated concepts effectively.

The authors Al Mazrooei et al. (2022) demonstrated that learning methods that enhance technology can help address resource limitations and boost student active participation in programs. The study used a review method and selected 51 studies. The review indicated the challenges teachers face in K-12 education and how to overcome those challenges. It defined the importance of emergency remote training, which requires teachers to develop their competencies and knowledge to implement online tools for students' online learning during COVID-19. Institutions must address their organizational limitations and workload requirements to implement modern educational techniques effectively. Parveen et al. (2022) state that excessive administrative workload and standardized evaluation standards prevent teachers from teaching through practical and discovery-based methods. A flexible learning environment develops by lowering standardized test obligations and teaching engineering concepts across multiple subjects. A quantitative study conducted by Markula and Aksela (2022) defined scientific practices in classrooms as being able to help teachers improve engineering education in K-12. The study used a mixed-method approach and analyzed the responses of (n=12) schools to determine aspects that can help teachers in their professional development. It includes technological tools, collaboration, and research to gain knowledge continuously.

Limitations and Future Implications

The current review is limited to data collection, collected through public databases and available articles; therefore, a review is conducted. It is also restricted to articles between the years 2015-2024. Therefore, future quantitative or mixed methods research should focus on filling the gap of limiting selected year studies using questionnaires or interview approaches. This would help gain a deep understanding and review of teachers and students for effective PD and of teachers and strategies for improving engineering standards in education for K-12. Furthermore, studies on AI-driven PD solutions and insights on emerging trends like online teaching PD are required to fulfill online education demands for K-12 with engineering knowledge.

Conclusion

The review presented information about the vital role of PD in advancing K-12 engineering education. Educational professionals need structured PD programs to acquire the ability to incorporate engineering fundamentals into their instruction approach. To achieve maximum effectiveness in PD programs, the persistent barriers caused by inadequate training, resource limitations, and technological constraints must be properly resolved. The current review recognized new educational possibilities in digital tools and artificial intelligence systems, which help train teachers more efficiently. It would help students gain problem-solving and critical thinking skills so they could make decisions on their own in both their personal and professional lives.

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