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SPECIAL FOCUS PAPER

The Impact of Peer Learning on Conceptual Understanding in Online Engineering Education

Sunday Clement[1], Marcellin Yovogan[2], Purvi Pujari[3], Afsha Matloob[4] (✉)

[1]Rushford Business School, Lucerne, Switzerland

[2]Sofia University St. Kliment Ohridski, Sofia, Bulgaria

[3]Vijay Patil School of Management, D Y Patil University, Navi Mumbai, India

[4]European Global Institute of Innovation and Technology, San Ġiljan, Malta

afsha.matloob@euglobal.edu.eu

ABSTRACT

This study aims to critically explore the impact of peer learning on conceptual understanding in online engineering education. By leveraging current peer-reviewed articles, the research provides an extensive analysis of the efficacy, variations, and challenges of peer learning approaches in virtual engineering classrooms. A comprehensive systematic literature review (SLR) methodology is used in the study, adhering to PRISMA for transparent identification, screening, and assessment of suitable studies. The major databases searched for articles were PubMed, Scopus, and Google Scholar. The inclusion criteria were peer-reviewed articles published from 2015 to 2025, in the English language, and aligning with the scope of this study. The selected articles were then analyzed using a thematic analysis approach to identify patterns related to peer learning approaches like peer instruction, collaborative projects, and discussion forums, improving the conceptual gains of engineering students. Comparative findings were drawn from these parameters related to the study. Based on the extensive review and analysis of literature, a conceptual framework is presented in this paper, highlighting the relationships between peer learning approaches and their implications for online pedagogy. Recommendations focused on optimization of peer learning structures for the online environment in engineering and identifying support mechanisms for diverse learning groups. The review also identified research gaps, promoted adaptive peer learning models and longitudinal studies, and significantly contributed to the advancement of inclusive and effective online engineering education.

KEYWORDS

engineering education, peer learning, education, online education

1 INTRODUCTION

With advances in available technology in recent years, the prevalence of online engineering courses has also increased, providing learners with a flexible option and increasing the global reach of the courses. More than 1.5 billion learners have opted for online courses, and the majority of institutions globally now offer a

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variety of class formats [1]. This change in the educational landscape necessitates the examination of traditional pedagogical models and the embracing of innovative strategies to improve the conceptual understanding of students in online engineering courses. Peer learning includes different practices such as online discussion forums, collaborative projects, and peer instruction that are all of key importance in improving peer engagement, interaction, academic achievement, and critical thinking [21]. The importance of SLR is felt as academicians and researchers focus on using the research resources to design best practices in engineering education and identify research gaps. Through the review, stakeholders can dive deep into the research area and understand key trends and identify actionable findings to be used in various engineering courses in a digital environment [17]. It is relevant because of the interdisciplinary nature of engineering education, balancing concepts of technology and principles of learning. With growing research in this area, there is a wide array of information available that becomes overwhelming for stakeholders to understand and implement in practice. A major motivation for conducting the review on the impact of peer learning in online engineering education comes from the recorded changes in student interaction patterns, promoted by technology-supported learning environments, which directly affect self-regulation, knowledge retention, and collaborative outcomes [6], [8].

2 METHODOLOGY

The methodology focuses on ensuring transparency and minimizing bias in assessing the impact of peer learning on conceptual understanding in online engineering education. Following the PRISMA guidelines and structured approach, the review started with the formulation of a clear research question as stated below:

1. How do different peer learning strategies (such as peer instruction, collaborative projects, and discussion forums) influence the conceptual understanding of engineering students in online environments?
2. What are the strengths and limitations of peer learning for engineering students in virtual classrooms and the comparative understanding of peer learning in online and offline engineering courses?

After identifying the key research question, an extensive search approach was implemented, focusing on three major databases: Google Scholar, Scopus, and PubMed. The search string used for conducting the initial search is "engineering education" AND ("peer learning" OR "collaborative learning"); "online learning" AND "engineering education" AND "conceptual understanding"; and "peer learning" AND "virtual engineering". The inclusion criteria used for the article selection included:

- Peer-reviewed articles in the English language
- Published between 2015 and 2025
- Alignment with the focus on peer learning in online engineering education

Conference abstracts, non-empirical reports, and narrative reviews were excluded to maintain methodological rigor.

The initial search yielded a wide range of studies, which were then screened using title, abstract, and complete article assessment following the PRISMA chart shown in Figure 1.

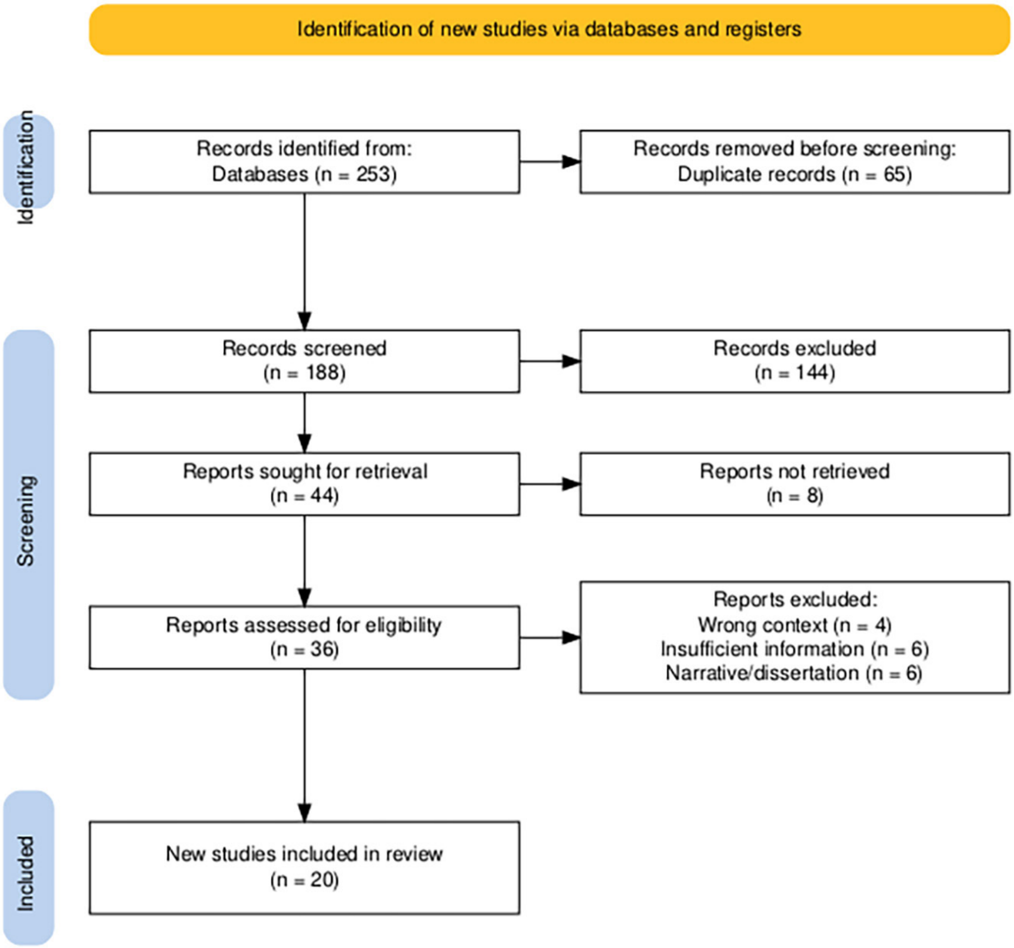

Fig. 1. PRISMA chart

The initial search on the three selected databases yielded 253 articles, from which 65 duplicates were removed. The next 188 articles were screened using their title, peer review, and relevance, from which 144 were excluded. The remaining articles were screened using the abstract, after which 44 were found suitable and were retrieved for full text retrieval. Thirty-six full-text articles retrieved were assessed for quality using the Critical Appraisal Skills Program (CASP), which focuses on study context, methodology, intervention, outcome, and relevance. Finally, 20 articles were selected for this research. The selected articles were analyzed extensively to identify key findings, patterns, and themes. The systematic processes helped in the identification of established impacts and identified research gaps on the basis of which the recommendations were prepared.

3 FINDINGS

The review of the selected article revealed crucial information, as highlighted in the summary of selected articles (refer to Table 1), including the methodology designed, key findings, and CASP appraisal.

Table 1. Summary of selected articles

Authors & Year	Methodology/Design	Key Findings	CASP Appraisal
Abirami et al. 2023	Framework proposal; empirical test	PPLP boosts problem-solving and peer learning	High
Ala et al. 2023	Qualitative case study	Peer clusters improve support and engagement	High
Amish & Jihan, 2023	Model development; qualitative	Collaborative projects improve online learning	Medium
Chiu & Hew, 2018	Quantitative analysis	Factors influencing peer learning performance	High
Dai et al. 2024	Mixed methods; analytics intervention	Forums enable adaptive help and interaction	High
Dosoftei & Alexa, 2024	Mixed-methods case study	Peer teaching enhances conceptual understanding	High
Fogg-Rogers et al. 2017	Qualitative program evaluation	Peer outreach motivates paired learning	Medium
Gong et al. 2023	Qualitative study	Peer-led learning increases engagement	Medium
Hadgraft & Kolmos, 2020	Literature review	Digital peer environments have advantages	High
Harvie et al. 2024	Experimental (online engineering)	Peer-led teams strengthen conceptual learning	High
Lang et al. 2017	Experimental outreach program	Peer learning fosters creativity, engagement	Medium
Lu et al. 2024	Mixed methods; online labs	Peer support improves lab skills, engagement	High
Neha & Kim, 2023	Survey	Well-designed forums drive peer participation	Medium
Rajarathinam, 2021	Experimental dissertation	Instructor role critical for group learning	Medium
Rasheed et al. 2021	Intervention; blended learning	Scaffolding improves peer self-regulation	High
Tomar et al. 2024	Quantitative survey	Digital assessment boosts motivation	Medium
Topping, 2023	Literature review	Flexibility/access online vs F2F immediacy	High
Tsai et al. 2023	Experimental computer ed study	Peer-facilitated programming helps learning	High
Usher & Barak, 2018	Comparative quantitative	Peer assessment is effective in both settings	High
Varatharaj, 2022	Survey; descriptive	Project collaboration develops skills	Medium

3.1 Influence of different peer learning approaches on conceptual understanding

Patterns and prevalence of peer learning approaches. In online engineering education, peer learning has emerged as an important strategy, taking different forms, including collaborative project-based learning, peer instruction framework, asynchronous discussion forums, and peer-assisted learning clusters. The diverse approach shows the efforts to address the complex and dynamic requirements of virtually connected students, maximizing engagement and conceptual understanding. In many high-quality articles, the structured peer learning model (SPLM) was highlighted as being highly effective in the context of online engineering. For instance, the scaffolding mechanism is achieved through the peer-to-peer learning process (PPLP), which improves conceptual understanding and promotes problem-solving among engineering learners in online courses [21]. The empirical research highlighted that such frameworks provide a systematic opportunity for reducing cognitive isolation and enhancing knowledge sharing in asynchronous learning. When integrated peer-assisted cultures in online engineering courses were qualitatively analyzed, it was found that peer groups significantly helped in improving emotional support, resilience, and learning outcomes [2].

Another transformative model identified in the review is the collaborative online project-based model. The qualitative model development led to increased engagement and knowledge development through solving real-world problems executed in the virtual space [3]. This key information aligns with the Fogg-Rogers et al. study that focuses on qualitative program evaluation in outreach-based paired learning. The findings of the study highlight the ripple effect of peer interaction on interest in engineering courses, students' motivation, and sustained involvement [7]. The use of collaborative learning affirms that effectively structured teamwork is the center for the development of conceptual learning and transferable skills. Asynchronous and synchronous discussion forums are identified as another important platform for peer learning, interaction, and concept clarification. When the MOOC (massive open online courses) environment was qualitatively analyzed, it was found that discussion forums were a safe space for peer interaction and learning, with their features of thread depth, response frequency, and peer moderation highlighted the relationship with performance outcome [4].

Including analytics in discussion forums promotes adaptive help-seeking behavior to ensure that peer communications are purposefully directed towards mitigating the conceptual barriers in engineering education [5]. This key information is also supported by research done by Neha and Kim, in which they highlighted that effective design and moderation of discussion forums directly influence conceptual understanding and student satisfaction [13]. The studies thus reinforce that a combination of different peer learning models, including formal frameworks and flexible discussions, has been extensively used in online engineering education over the past decade. Each of the models has different advantages and is applicable in different learning contexts, content areas, and student backgrounds.

3.2 Impact on conceptual understanding

The peer-reviewed scholarly literature agrees on a common point that structured peer learning achieves substantial growth in conceptual learning of engineering theories. The PPLP approach resulted in remarkable improvement in problem-solving along with high-order reasoning tasks among undergraduate engineering students, attributable to the scope for doubt clearing, hypothesis testing, and reasoning articulation in peer-mediated contexts [21]. A similar conclusion was made in the study conducted by Ala et al., highlighting that integrated peer learning clusters form an accountable social space in which students internalized and refined core engineering principles through reciprocal teaching and peer feedback [2].

Online discussion forums play a key role in fostering learning by encouraging dialogue, which adds structure and depth to peer conversations and enhances overall learning outcomes [4]. Students who regularly participate in meaningful peer exchanges tend to achieve higher conceptual understanding, indicating a strong link between peer-supported reflection and academic performance. Chiu and Hew state that students who posted at least five times on the discussion forums, including peer repliers, achieved a 15% higher average score on the post-course conceptual test than students with less than two peer interactions [4]. Moreover, when forum participation is supported by learning analytics, students engage in more strategic and adaptive help-seeking behaviors. This enables them to overcome complex conceptual challenges, especially during demanding tasks such as engineering design activities [5].

In experimental online settings, peer-led teams have shown significantly better results in acquiring and applying conceptual knowledge compared to non-peer courses [10]. The percentage of students taking peer-led courses increased to 75%, credited to the benefit that it provided [10]. This improvement stems from the active engagement that peer teaching demands, where learners explain, question, and provide feedback to one another, leading to deeper understanding through multiple perspectives and iteration clarification. Collaborative project-based learning further supports this approach. Activities involving synthesis, debate, and negotiation within groups help improve knowledge transfer and foster long-lasting skills relevant to engineering education [3], [20].

In a mixed-method case study, it is highlighted that peer teaching in an online setting not just increases understanding but also students' confidence in disciplinary discourse, showing that social presence mediates deeper engagement with complicated concepts [6]. In the case of project-based and outreach initiatives, the benefits observed include increased creativity, practical knowledge acquisition, and willingness to experiment [11], all of which are key to better conceptual understanding in technical fields. The collective findings are that when online peer learning is meaningfully incorporated within the curriculum and supported by suitable tools, it is a strong driver of conceptual understanding in engineering courses.

3.3 Factors influencing the effectiveness of peer learning

A key area of convergence across the review is the identification of factors that affect the success of peer learning strategies in online engineering courses.

1. Group Dynamics and Participation: The quality of interaction in a peer group is crucial [8], [20]. Group accountability, equitable distribution of tasks, and team cohesion form a strong foundation for learning benefits. Challenges such as communication hurdles, non-participation, and reduced motivation can impair individual and collective benefits of peer learning, highlighting the need for clear expectations and reflective tools.
2. Instructor Facilitation and Intervention: The instructor's role is important in facilitating, scaffolding, and intervening in peer learning practice [6], [14]. The presence of an instructor provides structure, can mitigate issues, and maintains group focus to ensure that any disengagement or misunderstanding is avoided. Active involvement of instructors helps students achieve a better level of conceptual clarity and collaborative problem-solving.

3. Self-regulation and Digital Motivation: With the design and implementation of the provision of explicit scaffolds for self-regulation, such as goal setting, progress tracing, and reflective prompts, students' persistence and independence in peer learning situations increase [15]. Digital assessment tools can work as motivators, promoting healthy competition and providing feedback for sustained engagement [16].
4. Technological Readiness and Equity: Peer learning outcomes are sensitive to digital literacy, technological infrastructure, and accessibility [9], [12]. Lack of technical skills or the digital divide can become a hurdle in active participation, thus limiting the democratizing potential of peer models if not addressed proactively.

4 STRENGTHS AND LIMITATIONS OF PEER LEARNING IN ONLINE ENGINEERING EDUCATION

4.1 Challenges and barriers

Despite major evidence supporting peer learning, there are certain persistent challenges and barriers that need to be addressed. Many studies identify the key issues, including:

1. Variability in Group Composition: It is both a potential asset and a risk. A heterogeneous workgroup has the pro of stimulating creativity and innovation, as it brings students from different cultural backgrounds, skill sets, and perspectives. But it also presents certain challenges. If not managed carefully, it can result in social isolation, uneven distribution, or conflict and adversely impact learning outcomes. Intentional group structuring is important to cultivate emotional support and resilience, along with learning benefits in peer-assisted groups [2]. In case of uneven task allocation in collaborative projects, the risks increase, thus suggesting strategic scaffolding to ensure equitable contribution of students [20].
2. Inconsistent participation: A significant barrier is inconsistent participation levels, with some students being dominant in the discourse while others stay passive, thus reducing the effectiveness of collective learning. Imbalance hinders the overall peer learning efficiency since it limits the exchange of diverse perspectives and peer feedback [8]. Monitoring and facilitating equitable participation is crucial in teams to increase conceptual understanding [14].
3. Technological barrier: The scalability and inclusivity of online peer learning are challenged by technological barriers. Unreliable internet access, inadequate digital platforms, and unfamiliarity with collaboration tools result in frustrated students and decreased participation [9], [12]. Technological literacy is a basic prerequisite for active and productive involvement in online discussion forums [13]. In comparison to physical labs, digitally literate students were interested in working in collaboration in an online space, increasing the proportion from 25% to 52%. Technological readiness and targeted support can be advantageous in improving accessibility and active participation.
4. Assessment and Feedback Constraints: Many courses lack clear mechanisms and parameters for assessment of participation quality, conceptual progress, and peer contribution, usually depending mainly on summative group grades, which undervalue students' learning efforts. Integration of formative digital assessment provides real-time motivation and promotes peer engagement [16]. Structured peer assessment is effective when the parameters are clear and consistent, and it focuses on individual accountability within the team [19].

5. Cultural and Linguistic Diversity: This poses a major challenge to equitable peer learning. Differences in cultural background, academic preparation, and language proficiency can impact the participation quality, followed by comprehension. A culturally responsive peer-teaching framework is required to overcome communication hurdles and to foster an inclusive learning space [6]. Culturally adaptive peer teams can effectively support diverse students.

The articles included in the summary table reveal that digital technologies provide unparalleled opportunities for peer connection. However, co-construction of knowledge, well-thought-out instructional design, proactive facilitation, and strong support systems are crucial for mitigating the limitations and unlocking the full potential of online peer learning in engineering education. Without these components, the promise of engaging, inclusive, and successful peer learning may be undercut by persistent social, technological, and procedural impediments.

4.2 Comparative analysis: online versus face-to-face peer learning

A recurring theme in students' analyses is the distinct learning opportunities provided by online peer interactions compared to the traditional face-to-face methods. Topping (2023) points out in a comprehensive review of existing literature shows that online peer learning offers clear advantages such as improved accessibility, flexibility, and inclusivity, but it often lacks the spontaneity and immediacy found in traditional face-to-face classrooms [17]. In-person or face-to-face model learning supports richer nonverbal communication, creates a stronger social connection, and inculcates the ability to address misunderstandings in real time. However, with thoughtful design and the use of digital tools, online environments can replicate and even exceed, sometimes through features like structured interactions, learning analytics, and scaffolded support.

In a quantitative study focused on project-based engineering courses, peer assessment was shown to be effective in both online and offline formats. However, its success was strongly influenced by factors such as clarity of roles, the use of formative feedback mechanisms, and the level of peer interaction involved [19]. Furthermore, combining distributed pair programming with peer facilitation has proven to be a highly effective method in online settings, matching the outcomes typically seen in on-campus learning while also allowing broader participation from diverse student populations [18]. Overall, the literature review highlights key differences in the strengths of each model. Online peer learning excels in openness, scalability, and adaptability, whereas face-to-face learning offers stronger peer support, deeper social cohesion, and immediate feedback. Integrating the two through hybrid models may provide a balanced and effective learning experience that captures the best of both approaches.

5 IMPLICATIONS AND RECOMMENDATIONS

The systematic review of the selected articles reveals various compelling implications for curriculum design, technology adoption, teaching, and institutional policy in online engineering education. The findings suggest that peer learning is not just auxiliary but needs to be made a core part of design and operation to achieve an impactful online engineering program. Models such as PPLP, analytics-enhanced forums, collaborative projects, and peer-assisted clusters should be formally included, ensuring students benefit from interactive structured experiences. This aligns with the findings that intentional structuring of virtual learning groups improves conceptual gains, emotional support, resilience, and motivation.

For curriculum designers and educators, the recommendation is to diversify the formats of peer learning. Both synchronous and asynchronous discussion forums, facilitated online labs, and project-based assignments offer opportunities for disciplinary dialogue and problem-solving. Courses should combine different approaches to maximize student engagement. Well-planned, scaffolded collaborative activities, having clear objectives, well-defined roles, milestones, and peer moderation, are strongly connected with improved student participation and achievement. The next suggestion is to have instructor intervention in peer learning. Various studies revealed that online peer groups lacking moderation face issues related to motivation, misunderstanding, and active participation, all of which result in poor conceptual learning. So, it is important to have professional development for instructors in digital facilitation, adaptive support, and feedback practice. Instructors should leverage regular check-ins, analytics for tracking engagement, and formative assessment tools to understand team dynamics and intervene when required.

Infrastructure and technology choices also need to be prioritized. Platforms should provide strong and accessible communication, resource sharing, and analytics-supported moderation. Designers should account for student diversity, support for differing levels of digital literacy, mobile-friendly tools, and reliable access, and increase participation, specifically in remote or marginalized cohorts. Inclusion of mobile learning, digital badges, and gamification functions can further incentivize engagement.

The primary drivers of peer learning success are self-regulation and motivation. Engineering programs should provide scaffolds such as goal-setting worksheets, progress trackers, and reflective journals. Gamified incentives and recognition, such as peer-nominated contributions and team awards, have been shown to improve students' motivation and persistence, especially for learners who are less intrinsically motivated [16]. The assessment practice should move beyond just superficial participation scores. Formative assessment, self-assessment mechanisms, and peer review increased transparency, recognized individual and group contributions, and achieved sustainable conceptual development. A robust assessment framework ensures equity, deeper learning, and accountability [19].

6 RECOMMENDATIONS

- Centrally incorporate peer learning formats in the online engineering curriculum.
- Invest in faculty training for digital facilitation and adaptive moderation.
- Adopt strong, inclusive technology platforms, and regularly audit and support digital access.
- Scaffold self-regulation and motivation through targeted resources, gamification, and formative feedback.
- Enhance assessment through multifaceted, transparent peer review and formative feedback systems.

By implementing these evidence-based recommendations, programs will promote not only increased conceptual mastery but also richer collaborative and lifelong learning outcomes.

7 CONCEPTUAL FRAMEWORK

Based on the various peer learning models in the review, it is identified that specific models alone fail to serve the purpose of enhancing the effectiveness and contribution of peer learning and conceptual clarity in online engineering courses. Thus, this conceptual framework combining various models is presented; however, its validity and applicability need to be checked in further research. The core of this framework includes peer instruction, collaborative projects, and discussion forums, as shown in Figure 2. The supporting mechanism includes instructor guidance, technological infrastructure, and self-regulation scaffolds. On the periphery, the expected outcomes include conceptual mastery, engagement and confidence, and equitable collaboration.

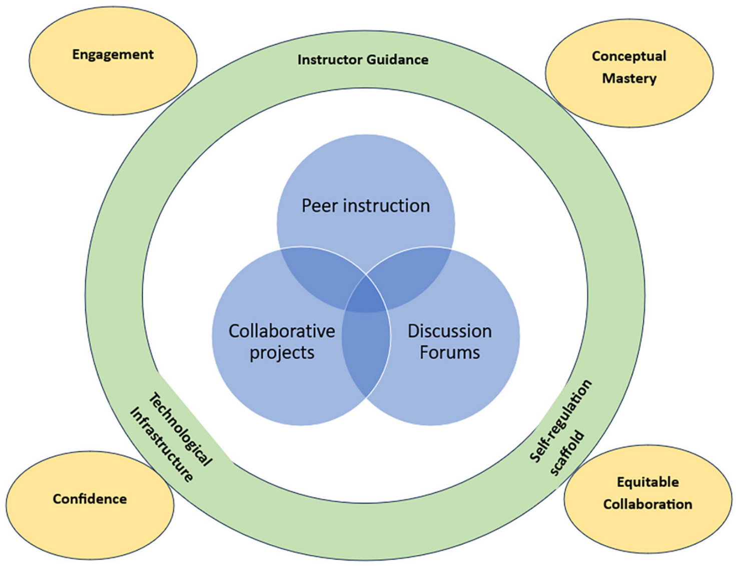

Fig. 2. Proposed conceptual framework

8 RESEARCH GAPS

Despite the rich findings, there are substantive gaps in research that need to be addressed for further improvement in the peer learning online engineering dimension:

- Longitudinal Impact: The majority of the studies focus on the examination of short-term effects of peer learning (e.g., single semester or single course). A longitudinal study tracking conceptual retention, psychosocial effects, and career readiness over the years is critically required.
- Optimal Group Formation: There is limited empirical evidence on best practices for forming peer groups that balance diversity, ability, and cohesion. Studies on rotation strategies, interventions for fragmented students, and adaptive grouping algorithms are lacking.
- Scalable Technology and Infrastructure: Technology barriers are discussed in various articles, but there is little research on how to scale peer learning in globally distributed or low-resource settings. There is a need for studies on universal design, bandwidth optimization, and mobile-first solutions.

- Instructor Engagement: The study on comparative research on the types, formats, and timing of instructor intervention is insufficient, particularly in multicultural and asynchronous cohorts.
- Assessment and Feedback: The recent studies focus on participation or summative project outcomes and not the quality of formative conceptual growth of individual contributions. Development and validation of multidimensional, scalable peer assessment tools are still needed.
- Inclusivity and Equity: Studies acknowledge motivational, cultural, and linguistic differences but rarely investigate tailored scaffolds for marginalized students, culturally relevant peer models, or flexible accommodations.

Addressing these gaps will allow online engineering education to unlock the full potential of peer learning approaches, fostering conceptual mastery and equitable opportunity across diverse student populations.

9 CONCLUSION

This systematic review of literature includes peer-reviewed articles, providing extensive and compelling evidence highlighting the potential of peer learning in online engineering courses. Across different research methodologies, content focus, and geographic locations, the findings of the studies converge on a consistent theme that when peer learning is carefully designed, scaffolded, and actively facilitated, it significantly improves student engagement, conceptual understanding, and skill development in engineering students in a digital learning space.

Structured peer instruction frameworks such as the PPLP, along with integrated peer-assisted learning clusters, promote interactive knowledge sharing and remove the issue of cognitive isolation in virtual space. Collaborative project teams are capable of cultivating real-world problem-solving skills through the synthesis of ideas and sustained peer negotiation. SLR revealed that paired peer learning improves motivation and discipline-specific interest among students.

Furthermore, analytics-driven discussion platforms and peer-facilitated labs function as important venues supporting adaptive help-seeking and reflective dialogue. When paired with targeted scaffolding and deliberate instructor support, these tools create opportunities for equitable participation, accountability, and deeper learning, effectively addressing many of the technological and social challenges common in remote asynchronous education.

The motivation and benefits of peer learning are further increased by supporting learners through technology access, self-regulation scaffolds, digital literacy development, and formative assessment. The role of the instructor's presence in moderating group dynamics and guiding conceptual understanding has emerged as a crucial factor across various studies. It reinforces the importance of educator training and adaptive pedagogical approaches.

Despite the various benefits, there are persistent challenges that need attention and significant research focus. Issues related to heterogeneous group composition, uneven student participation, technological differences, and assessment limitations restrict the full realization of the potential of peer learning. Another major issue is related to equity gaps for marginalized and culturally diverse students. This challenge necessitates the development of responsible frameworks and differentiated scaffolds to achieve inclusive learning. The literature also reveals the need for longitudinal studies to explore the sustained conceptual effects and career readiness linked with peer learning. Furthermore, another promising research direction is the exploration of scalable technological solutions and validated multidimensional assessments. To conclude, this review affirms peer learning as the core pedagogical lever for improving conceptual mastery along with collaborative competencies in online engineering courses. By intentionally incorporating diverse, inclusive, and scaffolded peer learning opportunities, supported by strong technology and assessments, educators can significantly improve the outcomes for all students. The extensive recommendations, proposed conceptual framework, and research gaps presented in this paper provided a strong foundation to guide practitioners and researchers towards effective, equitable, and future-oriented engineering pedagogy, empowering students to grow in an increasingly interconnected virtual space.

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11 AUTHORS

Sunday Clement is Doctoral of Business Administration, Research Scholar with Rushford Business School, Switzerland (E-mail: clement.smativa@gmail.com).

Marcellin Yovogan is with the Faculty of Economics and Business Administration, Sofia University St. Kliment Ohridski, Sofia, Bulgaria (E-mail: myovogan@feb.uni-sofia.bg).

Purvi Pujari is with the Vijay Patil School of Management, D Y Patil University, Navi Mumbai, India (E-mail: purvi.pujari@dypatil.edu).

Afsha Matloob is with the European Global Institute of Innovation and Technology, San Ġiljan, Malta (E-mail: afsha.matloob@euglobal.edu.eu).