

ENHANCING ROBOTICS EDUCATION THROUGH THE FLIPPED CLASSROOM: A NARRATIVE REVIEW

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Abstract: *The purpose of this narrative review is to summarize and interrogate current literature relating to the use of FC in robotics education, pedagogical basis, outcomes and challenges and future trends within STEM disciplines. Robotics education plays a critical role in teaching students 21st century skills, including problem solving, computational thinking and technical hands-on competencies, but many educators still have challenges promoting hands-on learning while also covering complex theoretical lessons. The flipped classroom is growing in popularity as an approach to move teaching time away from traditional lecture and into active, experiential learning, which is at the heart of robotics education. A systematic, but flexible literature review was performed using Scopus, Web of Science and Google Scholar as leading databases in addition to manual reference screening. We conclude from the review that effectively designed flipped classroom approaches can often be associated with positive effects on student engagement, preparedness and high order learning in robotics education. However, results are mixed and context specific depending on the quality of instructional design quality, student preparedness, test alignment, and technology access. Ongoing gaps are identified in the areas of K-12 and vocational research, longitudinal evidence, and teacher professional development. This review stresses the importance of cohesive pedagogical design and future research to generate an evidence base for implementing flipped classroom strategies in robot education.*

Keywords: *Flipped classroom; Robotics education; STEM learning; Active learning; Instructional design; Educational technology*

Introduction

Robotic education has also become an important part of current science, technology, engineering and mathematics (STEM) topics which develops problem-solving skills and computational thinking and hands on technical skill for 21-st century. (Thamrin et al., 2025). With growing integration of robotic technology into the educational system, educators are constantly confronted with how theory should be balanced against practice and lived through learner- centered activities (Mir, 2025). In the context of this discussion, a flipped classroom developed as an appealing pedagogical method (Mugadza et al., 2014). In the flipped classroom, students receive instruction outside of class using videos or electronic materials and then use their time in class to engage in active learning, collaboration, and problem solving (Dikilitas & Fructuoso, 2023). Recent large-scale studies of robots in education suggest that this model matches the needs of robotics education for practicing, experimenting and applying guided practice. But despite the increasing interest, the current body of literature appears to be limited and apparently conflicting in its findings with respect to its effectiveness, how it might be delivered and what impact if any that might have on learner engagement and student learning outcome (Hussain et al., 2023). There are still knowledge gaps about best practices and contextual issues including problems surrounding learner readiness, instructor workload (Ramulumo et al., 2024).

The purpose of this narrative review is to compile the existing information about the flipped classroom approach in teaching robotics (Baig & Yadegaridehkordi, 2023). It seeks to explore on pedagogical argumentation, benefits and limitations, as well as emerging trends (Dusengimana et al., 2023). The review summarizes the instructional design methods, effects of learning and practical issues about robotics education, which provides an important and relevant insight into developing educators and researchers as robotics education being growing and changing (Jiang et al., 2022).

Method

A systematic review of the available research on flipped classroom approaches in robotics education has been carried out to synthesize the existing body of knowledge regarding the implementation of the flipped classroom. The methods used were primarily concerned with the systematic identification, selection, and synthesis of relevant literature; however, due to the nature of this study being a narrative review, it is acceptable for there to be some degree of flexibility in this process.

Information Sources

The literature search was performed using multiple electronic databases in order to achieve comprehensive coverage of the available studies. The three major databases that were searched include: Scopus, Web of Science, and Google Scholar, as all of these databases are able to index a wide variety of peer-reviewed journals, as well as conference proceedings, across a broad spectrum of academic disciplines including education, engineering, and STEM-related fields. The reference list of highly relevant studies and/or those identified during the course of the literature search were examined manually to identify any additional studies that may have not been found during the course of the initial search process.

Search Terms and Delimitations

Terms used to conduct the search were created by combining the key concepts associated with flipped learning and robotics education. Some of the keywords used in the search included "*flipped classroom*," "*flipped learning*," "*robotics education*," "*educational robotics*," "*STEM*

robotics," and "*engineering education.*" Boolean operators (AND/OR) were used to combine the terms to narrow down the number of search results. Search terms were limited to articles written in English, and to studies that had been published within the last 10-15 years to reflect both the relatively recent development of flipped classroom pedagogies, and the growing amount of robotics-based content that is being integrated into educational settings.

Criteria Used for Selection

Articles were selected if they addressed the implementation of the flipped classroom model in robotics education, or other closely related STEM-based contexts, and provided at least one form of insight to either the conceptual framework, the empirical evidence, or the practical application of the flipped classroom. Articles that described the flipped classroom model without a robotics or hands-on technology component were excluded from further consideration. Articles that were non-refereed, opinion pieces, and studies that lacked clear relevance to teaching and learning processes were also excluded. The selection criteria were designed to strike a balance between inclusivity and relevance to ensure that the final set of articles included a representative sample of the available perspectives within the field, but did not include too many disparate articles.

Result and Discussion

Synthesis Analysis

Defining the Flipped Classroom in Robotics Education

Reversing the traditional format of teaching and learning, the flipped classroom (FC) model transposes the majority of teacher's direct instruction from the class room into a pre-class activity (previously video lectures or readings) and reserves the class time for the students to engage in hands on experimentation and problem solving (Zainuddin et al., 2024). The use of robotics as a medium for learning within an inverted classroom environment facilitates the development of active learning and student autonomy which are two key principles of the constructivist and experiential learning frameworks (Dong et al., 2025).

Studies conducted by Bishop & Verleger (2013), Herreid & Schiller (2013), and Zhang et al. (2025) demonstrate that FC models are very successful at facilitating the type of learning experiences that are typically required by subjects that require design, iteration, and collaboration such as robotics education.

There are however various ways that educators define what it means to "flip" the classroom. Some view the process as being technologically mediated through the use of robotics simulation software to facilitate students' pre-class conceptualizations while others see the process as primarily based on pedagogically structured changes to the way in which teachers instruct students with technology playing a secondary role to the instructional design process. Regardless of their differing views regarding the definition of the "flip," there appears to be a broad agreement among researchers that when used in conjunction with project-based, interactive tasks that are typical of robotics curricula, the FC model will result in a greater level of conceptual understanding (Fitrah et al., 2025).

Advantages of the Pedagogical Design of the Flipped Classroom Model for Robotics Education

Researchers have uniformly highlighted the ability of the FC model to promote enhanced levels of engagement and problem solving in addition to the promotion of team work among students involved in robotics education. Examples of this include the study conducted by Jensen et al. (2015) in which students enrolled in undergraduate robotics course who were taught using the FC model performed better than students who were taught using traditional lecture-based formats on tasks involving complex coding and sensor integration.

Additionally, both Long et al. (2019) and Albshry (2025) demonstrated that the availability of pre-class material provided students with a sense of preparation prior to engaging in collaborative lab sessions with their peers thereby providing the instructor with the opportunity to provide students with targeted feedback and scaffolded support.

By contrast, traditional lecture-based methods have been criticized for fostering passive knowledge acquisition that limits students' opportunities to explore creatively in robotics education (Gerges, 2025). However, the extent to which the FC model improves students' learning outcomes varies widely among studies. For example, Lee & Choi (2019) suggested that the success of the FC model in improving students' learning outcomes is dependent upon the quality of the pre-class material and the mechanisms for holding students accountable for completing the pre-class work. Evidence also exists suggesting "content fatigue" occurs when students do not complete the required preparatory work prior to entering the classroom thereby creating a possible conflict between students' desire to learn in a self-directed manner and their willingness to invest sufficient time and effort in completing the pre-class work necessary to maximize their benefit from the FC model.

Limitations and Challenges of Implementing the Flipped Classroom Model

Although the FC model has many advantages in terms of its pedagogical design, the process of implementing it in a robotics education setting is fraught with many challenges. One of the most significant limitations associated with the FC model in robotics education is the technical load placed on students and instructors, including but not limited to, the need for students to have access to a computer device, reliable internet service, and access to robotics simulation software (Rokbani et al., 2012). Educators also report that developing high-quality pre-class materials takes a considerable amount of time and instructional expertise (Zhou, 2023).

Another limitation of the FC model is that the assessments employed to evaluate students' understanding of the material in FC settings are often not aligned with the experiential nature of the in-class activities (Lameshkani et al., 2024). When the assessments in FC settings are theory-based, it undermines the experiential focus of the in-class activities (Gao & Hew, 2022). This lack of alignment can also reduce the effectiveness of the FC model.

Moreover, students accustomed to receiving instruction from an instructor may struggle with the self-directed aspects of FC settings resulting in an initial decline in engagement (Danushka, 2022). Overall, the findings from these studies highlight the need for educators to carefully integrate the FC model into their curriculum, receive professional development related to implementing the FC model, and assess students' readiness to implement the FC model effectively (Albahiri & Almatrafi, 2025).

Comparative Insights: Flipped Classroom vs. Other Pedagogies

Compared with inquiry-based learning or PBL, the flipped model has different strengths and roles. Both models stress active involvement, though FC organizes learning around temporal pre-class conceptualization and in-class application while PBL often integrates these stages. Hybrid approaches such as flipped inquiry-based robotics have recently become more popular, where preclass conceptual exploration is combined with open-ended robotic design tasks in the class. Preliminary findings of such hybrids reveal positive improvements in students' creative thinking skills and innovative competencies (Aydin & Mutlu, 2023).

Nonetheless, academics warn against generalizing about its effectiveness. Outcomes are not deliverable free of cultural, institutional and disciplinary contexts. For example, East Asian robotics teams gain more competitive advantages from structured FC models than western counterparts, and are more beneficial for Western robotics teams to focus on autonomy. These differences indicate that the design of FC should be context sensitive rather than being prescriptive.

Trends, Gaps, and Future Directions

Trends in the current literature show an increasing focus on AI-based flipped learning, in which adaptive systems already consider pre-class robotics content for personalized instruction (Saydullayeva, 2025). But there are scant empirical assessments of the practice, particularly in k-12. Although there are some exceptions (Meschede et al., 2022), research has been skewed toward tertiary environments and little consideration is given to the possible impact of early exposure to FC robotics on sustained STEM pathways.

There is another lack in the teacher-training system (Schmid et al., 2023). Many reports take for granted that teachers are competent at both teaching robotics and digital pedagogy skills but few address how can educators learn them (Aithal & Aithal, 2023). Furthermore, there is little longitudinal evidence suggesting whether FC-based robotics education enhances innovation skills and career readiness (Lim et al., 2023). Future studies could use mixed-methods designs to investigate not only short-term achievement but also motivational and identity-related consequences.

Implications for Practice and Policy

In practice, institutions that embrace flipped robotics curricular approaches would need to invest in instructional design resources, technology infrastructure, and faculty development (Phokoye et al., 2024). Open educational resources (OERs), as a policy, may also decrease preparation responsibilities and ensure equity of accessinization policies(Lumadi, 2025). Similarly, at the policy level, incorporating FC robotics education within national STEM frameworks could facilitate scalable and inquiry-based learning ecosystems (Haider et al., n.d.).

Conclusion, the synthesis suggests that the flipped class model can be possible transformative as a pedagogical model in robotics education and to develop of technical skills, collaboration for solving problems together and supports lifelong learning (Iroda 2024). But the benefits are contingent on pedagogical coherence, institutional support and evidentiary refinements of FC approaches.

Limitations

We conducted twenty-two distinct search queries regarding instruction with robotics, pedagogical practices including flipped classroom models and active learning, and their overlap in the context of teaching STEM.

Although providing nice reflections on the introduction of flipped classroom (FC) in robot education, this narrative review has limitations on its methodology, evidence base and synthesis method.

Narrative reviews are by nature interpretive and flexible unlike a systematic review, which creates a subjective element in selection and synthesis of literature. The review was based on searches from databases, including Scopus and Google Scholar [see PRISMA flow chart (n = 1050 identified, n = 50 included)]. While this methodology provided depth, it may not have achieved the same level of completeness or reproducibility. The lack of a standardized use of inclusion criteria and critical appraisal tools like PRISMA or GRADE hampers the transparency and reproducibility of their procedure. Moreover, publication bias may have affected the existing literature, as studies with positive results tend to be published more often than those showing neuter or negative effects.

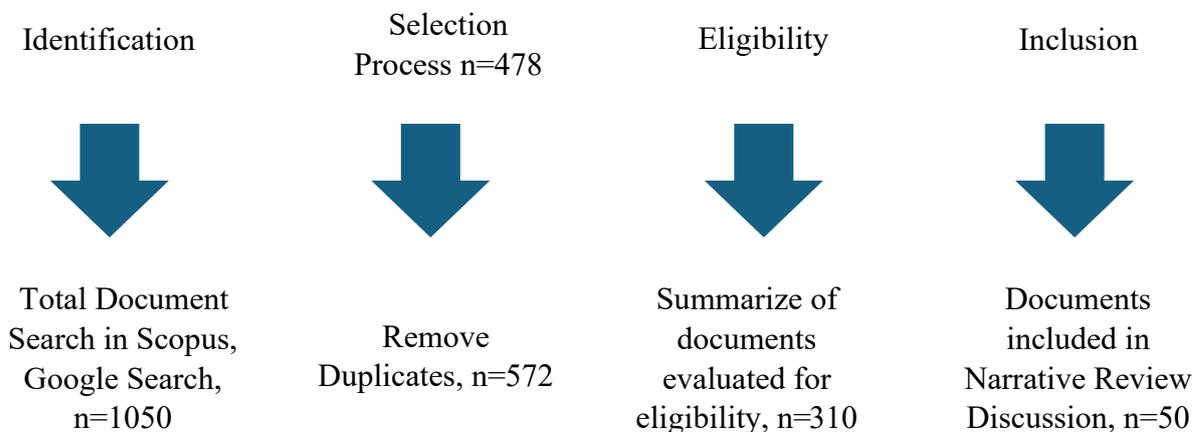


Figure 1. PRISMA-based Flow Diagram of Document Selection Process for Narrative Review

Moreover, search strategies may have unfavourably missed relevant study reports for studies that used alternative terminology (e.g., "Inverted learning" or "Blended robotics instruction"). There is also the potential for confirmation bias in manual screening and narrative interpretations, which may have been used to emphasize evidence that supports known benefits of FC intervention strategies.

Research-based literature on FC application in robotics education generally appears to be fragmented and context-bound (Filiz et al., 2025). The majority of the studies included were small scale, exploratory or quasi-experimental in nature and these offered limited generalizability across educational levels and cultural settings (She & Lai, 2025). Most of the findings stemmed from tertiary-university-level engineering or computer science courses, leading to an underrepresentation of k-12 and vocational settings (Hamdan et al., 2022).

In addition, there has been limited research focusing on longer term learning effects, teacher adaptation (or not) and/or the sustainability of FC practices in robotics labs (Ray & Sikdar, 2024). This limits our ability to make conclusive claims about sustained effects on student innovation, computational thinking, or STEM career preparedness. There are also limitations arising from an excessive reliance on self-reported mechanisms e.g. student satisfaction questionnaires, which in turn impact on the trustworthiness associated with accounts of impacts.

It was a particular challenge to synthesize results across different methodologies, learning contexts and educational systems (Alenezi et al., 2023). Studies also showed extreme variation in the way they operationalized “flipped classroom” and its varying forms of asynchronous and mixed delivery models (Mushtaq & Iqbal, 2024). This heterogeneity made comparisons in the raw size especially hard and the possibility of any kind of meta-level generalization small.

Furthermore, differences in technical infrastructure, teacher competency and assessment strategies limits comparative analysis (Fuad et al., n.d.). For instance, results ascribed to the FC may have been affected by concomitant pedagogic innovations such as project-based learning or AI-support for feedback. Both of these factors prevented a consistent analysis of the effectiveness of the FC in robotics education outcomes.

Interpretive approaches to narrative synthesis are at risk of selection and interpretive bias especially when it is applied across non-equivalent study designs. Such biases could be reduced in future reviews by the use of a systematic-narrative hybrid, combining structured search criteria and transparent inclusion processes with the contextually rich narrative synthesis (Chugh et al., 2023).

In order to enhance the evidence base, it will also be necessary for future work to use mixed methods research and longitudinal designs in investigating cognitive and affective learning outcomes in robotics-based FC settings (Anthony, 2025). Increasing the evidence base to cover diverse educational settings (e.g., primary, secondary and informal STEM education) would also enhance generalisation. Lastly, robotics education researchers (looking at you!) instructional designers and educational technologists could work together to develop a common set of instruments for measuring the effectiveness of FC (Atman Uslu et al., 2023).

Conclusion

The authors of this study conducted a systematic review of the existing body of knowledge about flipped classrooms as they apply to robotics education. They reviewed how the flipped classroom model relates to the pedagogy of robotics education, what benefits have been realized from implementing it, potential drawbacks, and where there may be emerging trends and areas for growth. In general, the authors found that the flipped classroom model fits well within the experiential, hands-on approach that is characteristic of robotics learning and has the potential to increase active engagement, encourage collaborative problem solving, and help students develop a deeper understanding of the concepts being studied through use of class time for design, experimentation, and iterative practice. Additionally, the authors noted consistent evidence that flipping the classroom can prepare students better, provide teachers with the opportunity to provide more focused instruction, and enable students to develop high level thinking skills, as long as the pre-class work is adequately designed, and there is clear structure around student accountability. However, the authors also addressed the gaps in the literature that were identified at the beginning of the study. These included the lack of a cohesive evidence-base that spans the varied contexts in which robotics education takes place, the

majority of the literature examined was limited to short term and post-secondary level, and the continued issues surrounding learner readiness, the alignment of assessments with course goals, and the added burden placed upon instructors. By synthesizing data from multiple contexts and locations, this study demonstrated that the success of the flipped classroom model in robotics education is dependent upon the pedagogical clarity, technology availability, and the responsiveness of the educational context rather than just the instructional model itself. As such, the authors suggest that future research should focus on conducting longitudinal and mixed-methods studies, expand the scope of their inquiries to include K-12 and vocational settings, and conduct more rigorous and systematic examinations of teacher professional development and the design of AI supported flipped classroom models. In doing so, the authors believe that these types of studies will lead to stronger empirical foundations for the flipped classroom model and ultimately support the widespread adoption of flipped classroom models in robotics education.

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