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How Microelectronics and Microcontrollers are Integrated into First-year and Sophomores Engineering Programs.

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How Microelectronics and Microcontrollers are Integrated into First-Year and Sophomore Engineering Programs: A Systematized Review.

ABSTRACT

In this complete, evidence-based paper, we conducted a systemized literature review to examine the ongoing efforts to introduce microcontrollers and microelectronics to undergraduate engineering students. The preceding few years have witnessed undergraduate engineering programs undertaking substantial initiatives to integrate microelectronics and microcontrollers into first-year engineering courses. All engineering systems, regardless of specialty, incorporate microelectronics and microcontrollers, necessitating the development of competencies surrounding these technologies among all engineering students. Therefore, the need to teach about microelectronics and semiconductors extends beyond electrical and computer engineering to all engineering disciplines. In addition, there is pedagogical value in integrating microcontrollers and microelectronics into first-year and sophomore undergraduate engineering programs to enhance student engagement through grounded, active learning. Three scholarly databases (Compendex, Scopus, and Inspec) provided the data for this analysis. We identified articles that discuss how academic institutions have incorporated microelectronics and microcontrollers into first-year and sophomore curricula. Additionally, we identified the assessment methods and metrics these efforts have utilized to measure the efficacy of the curricular efforts, such as learning, motivation, and retention. The search process resulted in two hundred and sixty-nine (269) papers. Thirty-two (32) provided applicable data regarding the instruction of microelectronics and microcontrollers in first-year and sophomore undergraduate engineering curricula. The results suggest specific ways that microelectronics and microcontrollers enhance the educational experience of first-year and sophomore engineering students.

Introduction

The rapid advancement of microelectronics and semiconductor technology has significantly impacted the engineering profession. In response, engineering education has seen a rapid spread in the integration of microelectronics into engineering courses, especially for introducing undergraduates to foundational concepts in microelectronics and microcontrollers, technologies which are critical for fields like robotics, automation, and data processing (Lewis et al., 2020). Although once limited to electrical engineering, microelectronics and microcontrollers have become relevant in diverse engineering fields, such as mechanical, biomedical, and civil engineering, making early exposure valuable for all engineering students. This shift is also important for meeting the workforce needs of the growing domestic semiconductor production (PricewaterhouseCoopers, n.d.: Rep. Ryan, 2022).

In response, institutions have integrated microelectronics and microcontrollers into first-year and sophomore curricula beyond electrical engineering courses (e.g., Turner et al., 2024). The aim of this integration is often focused on building students' practical problem-solving and teamwork skills through collaborative learning (Humbi et al., 2024; Nedic et al., 2009; Allam et al., 2006), as well as to ground foundational engineering skills like coding, data analytics, and engineering design in active learning hands-on activities and projects. Research has linked hands-on learning using microcontrollers with improved retention, motivation, and persistence (Mascaro et al., 2011; Robinson et al., 2020).

Without early exposure, students often miss developing crucial skills and interests, potentially impacting the future supply of skilled professionals in these areas (Bonnaud, 2019). As Mascaro et al. (2011) suggest, practical projects allow students to apply theoretical principles in real-world contexts, reinforcing learning and interest from the outset. However, questions remain about the most effective ways to integrate these devices into undergraduate curricula, particularly during the critical first two years of study. A systematic literature review (SLR) is necessary to address this question.

SLRs are crucial in engineering education, consolidating findings, and identifying trends that guide future practices. They provide comprehensive analyses to support educators in adopting evidence-based methods (Borrego et al., 2014). However, many studies lack theoretical frameworks, impacting the transferability of their findings (Karabulut-Ilgu et al., 2017). Systematic review methods, commonly used in fields like medicine, boost credibility when applied in engineering education (Froyd et al., 2015). As engineering education advances, systematic reviews remain pivotal for fostering innovation and aligning education with industry demands (Henri et al., 2017; Adesope, 2021).

In the field of engineering education, the rationale for systematic reviews stems from the need to organize and synthesize diverse findings across the field. As engineering education has grown in complexity, SLRs provide a way to aggregate evidence, identify knowledge gaps, and support evidence-based practices (Borrego et al., 2014; Qin, 2019). Systematic reviews advance engineering education by promoting effective teaching strategies and shaping future research (Froyd et al., 2015). In addition, systematic reviews can enhance the rigor and quality of research by adapting methodologies from fields like education and psychology. This is especially needed for new pedagogical approaches, such as gamification, which require careful validation (Karabulut-Ilgu et al., 2017; Rodrigues, 2020; Bodnar et al., 2015).

Recent calls to increase the microelectronics workforce necessitate a systematic assessment of integrating microelectronics and microcontrollers into engineering programs. We need to assess the teaching strategies and approaches taken by different engineering disciplines in this integration. This research employs a systematized literature review methodology to examine various approaches to incorporating microelectronics and microcontrollers into engineering curricula. The goal of this review is to identify the various methods and detail how these efforts have measured their impact on student learning, motivation, and retention (Zhu & Trowbridge, 2023; Davishahl, 2024). By synthesizing findings from previous studies, we aim to provide a comprehensive, evidence-based report on the role of microelectronics and microcontrollers in early-stage engineering education curricula and suggest best practices to enhance student's educational experiences. Addressing this knowledge gap, this study explored the following research questions:

RQ1 How are microelectronics and microcontrollers integrated into first-year and sophomore engineering programs?

RQ2 What pedagogical approaches were utilized to teach microelectronics and microcontrollers in the first and second years of undergraduate engineering curricula?

RQ3 How do different engineering disciplines incorporate microelectronics and microcontrollers, and how do these methods differ?

Literature Review

SLRs are vital in engineering education, providing a structured way to consolidate findings, highlight trends, and reveal gaps in existing research. Borrego and Froyd (2015) emphasize the value of SLRs in education research, noting that such reviews prevent redundant studies and offer a more cohesive understanding of complex topics. While many SLRs in engineering education have focused broadly on categories like educational robotics or single-board computers (Ariza & Baez, 2018), this broad research may lack the specificity necessary to guide detailed curriculum development in microcontrollers and microelectronics.

Existing SLRs have highlighted the critical role of microelectronics education in integrating theory and practice. For instance, Dickerson and Clark (2018) highlighted the value of simulation-based learning with SPICE tools, which develop circuit design skills and enhance students' understanding of complex concepts through experiential learning. Similarly, Lyshevski et al. (2012) explored how incorporating MEMS and nanotechnology reflects the interdisciplinary demands of modern microelectronics education. Karabulut (2017) noted that innovative pedagogical models, such as the flipped classroom approach, engage students in active, self-reflective learning, critical for learning transferable skills using microcontrollers (Karabulut-Ilgu et al., 2017).

Engineering educators began integrating microcontrollers, such as Arduino, Raspberry Pi, or Texas Instruments Launchpads, in engineering courses due to their affordability and versatility. Research indicates that microcontroller-based projects enhance student interest and engagement, from after-school programs (Lee, 2020) to software engineering and IoT applications in higher education (Yusop, 2024). Studies by Tupac-Yupanqui et al. (2022) and Serrano-Pérez et al. (2019) show that microcontroller projects build confidence and enhance programming skills, while Swart (2021) highlights the popularity of microcontrollers in fostering innovation across various educational stages. Challenge-based learning using microcontrollers prepares students for real-world problem-solving, a crucial skill in engineering as explored by Lara-Prieto et al. (2023).

Microcontrollers can also enrich STEM education beyond traditional engineering fields. Çoban (2020) and El-Abd (2017) showcased the appeal of microcontrollers across multiple non-engineering disciplines, such as physics, computer science, and information technology, as well as within engineering disciplines(Martin-Ramos et al., 2017). Candelas et al. (2015) and Choi (2014) further demonstrated the adaptability of these devices across multiple engineering laboratories. In addition, Anwar et al. (2019) noted the potential of educational robotics in K–12 settings, although they also highlighted the lack of rigorous experimental studies examining the impact on student outcomes. This underscores the need for further exploration on the impact of microcontrollers at the undergraduate level. Therefore, integrating microcontrollers in engineering curricula promotes hands-on learning and fosters interdisciplinary skills crucial for addressing contemporary engineering challenges.

Several authors have advocated for the use of microelectronics education in early engineering through the use of project-based learning. For example, Robinson et al. (2020) advocated for maker-space-based courses in the first year, where hands-on learning encourages creativity and problem-solving. Bonnaud (2019) advocated training students to be updated with equipment and tools like microelectronics to enhance industry skill matching. Rosen and Carr (2010) similarly support application-based approaches, which enhance student engagement and understanding of theoretical concepts. Jawaharlal et al. (2016) use diverse pedagogical approaches, promoting project-based learning that fosters critical thinking and teamwork, particularly in mechanical engineering. Nedic et al. (2009) advocate for project-based labs in standard first-year courses, as they foster collaboration and community. Humbi et al. (2024) also note that it is essential to student retention.

Different disciplines adapt microelectronics and microcontrollers to meet specific curricular and industry demands. For instance, Rosen et al. (2014) tailored an Arduino-based racecar project to engineering technology students, demonstrating the customization of hands-on projects to specific needs. Zhu and Trowbridge (2023) examine design projects that nurture intrinsic motivation in first-year students, demonstrating the need for diverse strategies across disciplines. Research has shown that hands-on learning effectively increases retention, actively engages students, and motivates them to pursue engineering (Mascaro et al., 2011; Robinson et al., 2020). Additionally, Goulart et al. (2021) highlighted the need for students to develop skills that will bridge the skills gap in the industry.

Literature on integrating microelectronics and microcontrollers in early engineering education addresses the foundational importance of these technologies across fields, such as the move from robotics to data processing (Lewis et al., 2020). This shift aligns with the industry's demand for graduates skilled in microelectronics and semiconductors within diverse engineering fields, not only in electrical engineering but also in fields like mechanical and biomedical engineering. While Dickerson and Clark (2018) outline core competencies for microelectronics education, they stop short of exploring integration strategies at the first-year and sophomore levels. In contrast, Wu and Shen (2016) discuss how sustainable development frameworks guide broader curriculum changes, suggesting a potential model for targeted reviews of microelectronics integration. Despite these advancements, a systematic assessment explicitly focused on early microelectronics and microcontroller education remains limited. For instance, although SPICE-based simulations are beneficial (Dickerson & Clark, 2018), strategies to foster engagement in early coursework are often overlooked. Wright (2018) posits that the early introduction of computational methods in engineering is crucial. However, there is a dearth of evidence on the most effective implementation of these methods in foundational courses. Borrego et al. (2014) critique the lack of robust theoretical frameworks in engineering education research, a gap also noted by Karabulut-Ilgu et al. (2017) in their analysis of flipped learning models. Fauzi (2024) emphasizes how interdisciplinary approaches can address these challenges, highlighting the need to bridge this gap in microelectronics education. Therefore, the absence of a consolidated approach to integration highlights the need for a systematic review to identify the most effective strategies for early engineering education.

This systematic review will aid educators and curriculum designers by synthesizing existing studies and providing actionable recommendations for integrating microcontrollers and microelectronics into early engineering programs. Froyd et al. (2015) note that systematic reviews translate research insights into practical applications, enhancing curriculum design and instructional strategies. Anwar et al. (2019) further stress the importance of adherence to SLR guidelines, such as PRISMA, to maintain rigor and credibility. However, several studies lack this level of detail, limiting their utility in guiding pedagogical practices. This literature review consolidates the best practices and aligns educational approaches with industry needs for graduates proficient in microcontroller applications (Bonnaud & Fesquet, 2017). Spencer and Eldredge (2018) emphasize that identifying research gaps is essential for advancing fields, especially those with emerging technologies, an area this review addresses for microelectronics. By focusing on retention, as Henderson (2023) suggests, this SLR will highlight instructional strategies that support student engagement and persistence. This review will guide both current educational practices and future research, contributing to an improved engineering education landscape.

Methodology

We selected a systematized literature review to incorporate the essential components of a systematic review process (comprehensive search, evaluation, and integration of existing research). However, owing to a singular reviewer, it cannot be classified as a complete systematic review (Grant & Booth, 2009). We report this review according to the preferred reporting guidelines for systematic reviews and meta-analysis, PRISMA 2020, which provides the basic guidance for reporting the different sections of systematic reviews (*PRISMA statement*, n.d.).

Inclusion Criteria

Studies were selected for inclusion according to the following criteria. These studies must (a) contain empirical research on microelectronics or microcontrollers; (b) relate to first-year students, freshmen, or sophomores; (c) be journal or conference papers; and (d) examine microelectronics and microcontrollers instruction and curricula.

Search Methods

We conducted a systematic review of the literature to find relevant articles. We individually searched three scholarly engineering databases and excluded grey literature. We used advanced search criteria and Boolean logic search parameters for each database. We used four categories of search terms as part of our search strategy to retrieve relevant literature. These were (1) microelectronics, (2) microcontrollers, (3) first-year or sophomore, (4) engineering education, as well as Arduino. We analyzed only literature published in the past 10 years (2015-2024) for inclusion in the study. Seventy-three records were identified in Scopus, and 196 were identified in Compendex and Inspec. The search strings used to search the literature are included below to ensure transparency and allow for replication of our methods.

Scopus Search String

(TITLE-ABS-KEY (microelectronics OR microcontrollers) AND TITLE-ABS-KEY (first-year OR sophomore OR freshm*n) AND TITLE-ABS-KEY (engineering)) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (EXCLUDE (DOCTYPE , "bk") OR EXCLUDE (DOCTYPE , "cr")) AND (EXCLUDE (LANGUAGE , "Japanese"))

Compendex and Inspec Search string

((((((Microelectronics or Microcontrollers) WN KY) AND ((Freshm*n or First-Year or Sophomore) WN KY)) AND ((Engineering) WN KY))) NOT (({ds} OR {bk} OR {ch}) WN DT)) AND ((2024 OR 2023 OR 2022 OR 2021 OR 2020 OR 2019 OR 2018 OR 2017 OR 2016 OR 2015) WN YR))

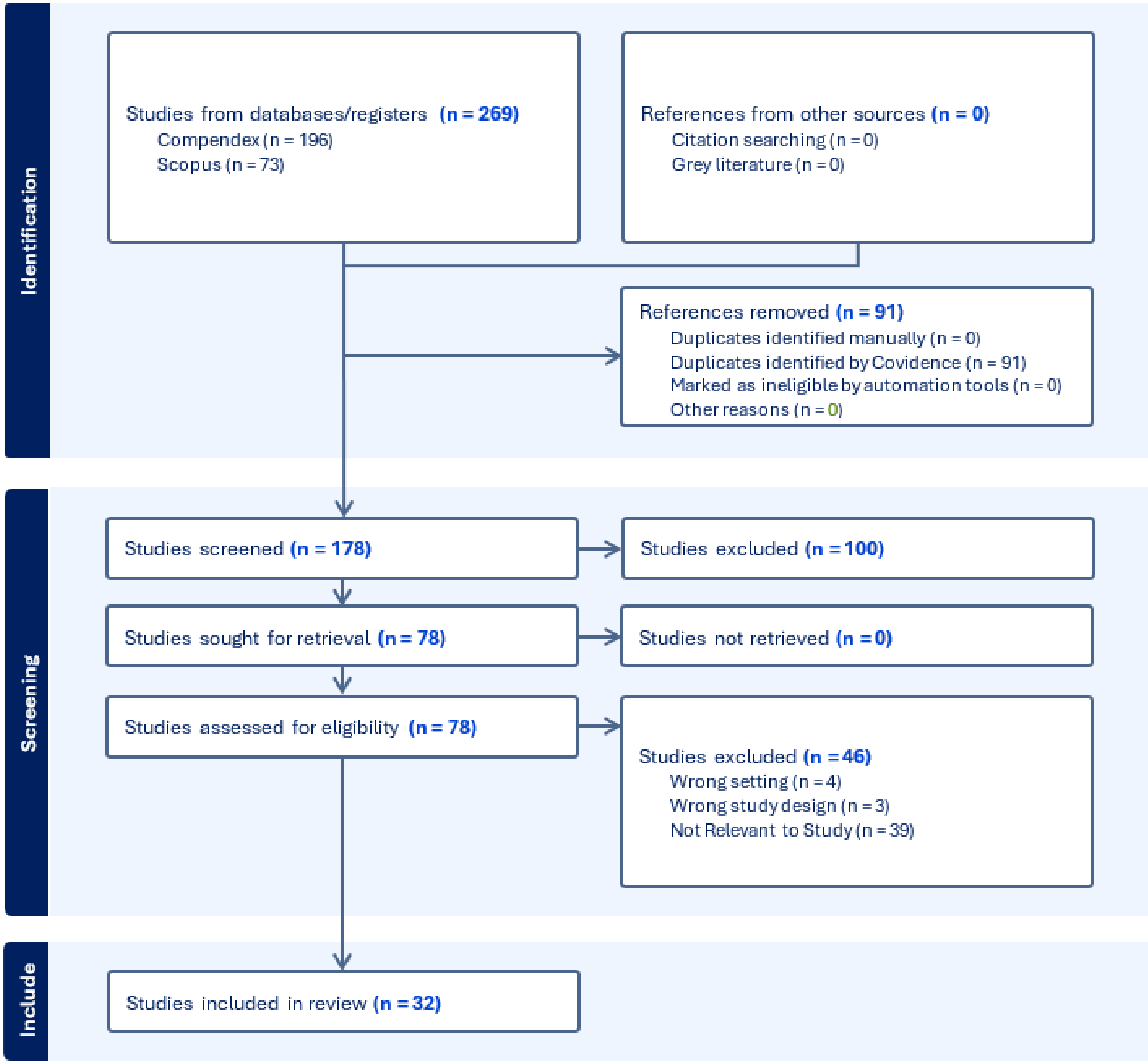

Fig 1. Study's inclusion and exclusion flowchart based on PRISMA–2020.

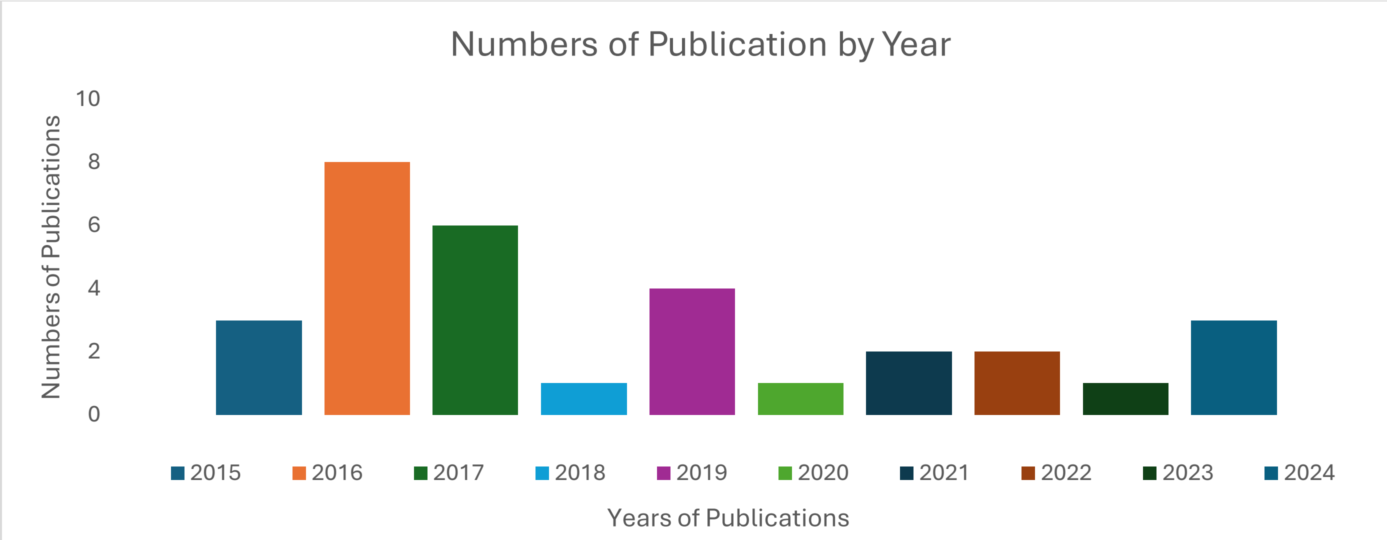

Fig. 2. Papers per year included in the study

Findings

Qualitative thematic analysis was used to identify the primary classification of thirty-two articles. The literature was classified into themes based on seven features: (1) First-year or sophomore engineering vs. non-first-year or sophomore; (2) hands-on vs. non-hands-on; (3) whether the study was on first-year curriculum design (4) types of microcontroller use (5) If the study involves microelectronics, (6) Identify the goal(s) of the study, and (7) Present the findings and conclusions. The three identified themes were (1) curriculum design, (2) student learning outcomes, and (3) challenges and limitations. The thirty-two papers in the study provided information on each theme except "challenges and limitations," which only included 31 papers, as one did not mention any challenges.

Table 1: Differentiation of articles based on curriculum designs, Device Type, and Level.

Differentiation Type	Classification		
Curriculum Designs	New Course	Redesign of the existing curriculum	Lab Sessions
	2	27	3
Device Type	Microelectronics	Microcontrollers/Arduino	Both Devices
	5	22	5
Level	First Year	Sophomore	Not Specified
	22	7	3

Theme 1: Curriculum Design

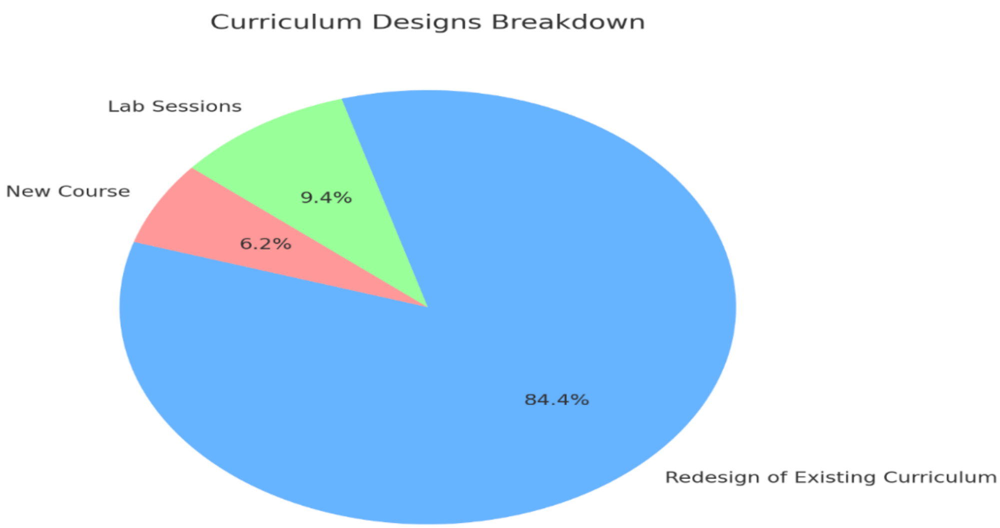

Fig. 3.: Curriculum Design Breakdown

All thirty-two scholarly articles we incorporated in this study presented insights regarding the effective methodologies in integrating microelectronics and microcontrollers within their educational frameworks. A minority of the articles (6.2%) concentrated on a novel pedagogical strategy (New Course) to embed extensive, practical projects into the microelectronics syllabus. The authors ensured that the coursework and projects undertaken by the students effectively addressed the competencies deficit (Rumpf et al., 2016; Whalen & Hertz, 2023). A subset of the studies (9.2%) developed new laboratory experiences for extant courses to familiarize students with the operation and use of these devices (e.g., Coonley et al., 2020; Daugherity, 2019). This methodology signifies a novel application within the current curriculum, seeking to infuse additional practical, experiential projects into foundational first-year and second-year engineering courses (Abouhilal et al., 2019). Most studies (84.4%) concentrated on reforming the existing curriculum. The objective was to contemporize the syllabus by incorporating microcontrollers and microelectronics. This modification included simulation software and hands-on projects to equip students more effectively for the transforming requirements of the engineering profession and industry. (e.g., Kidd & Hilton, 2021; Mandic & Baric, 2017; Martin-Ramos et al., 2017; Tehrani et al., 2017;).

Pedagogical Method:

The thirty-two papers included in this study used several pedagogical approaches, which are summarized below:

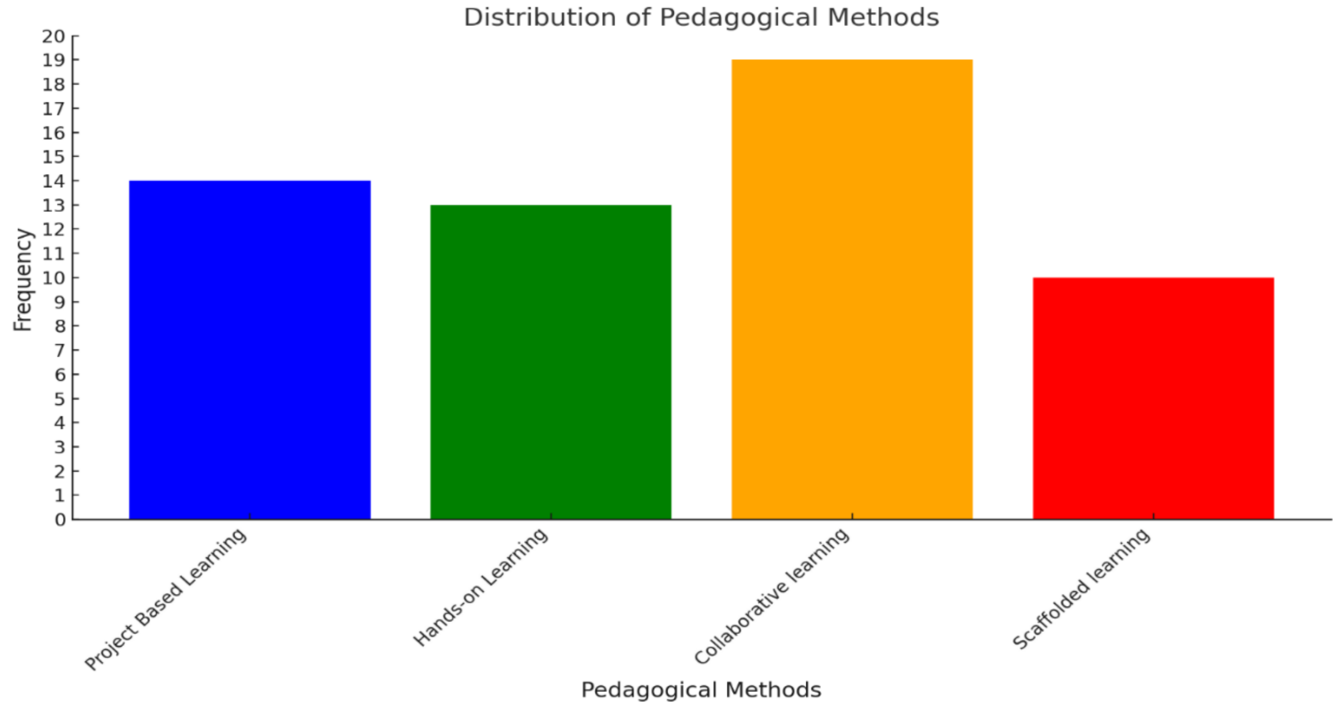

Figure 4: Distribution of Pedagogical Methods.

Project-Based Learning: Fourteen articles included in this review employed Project-Based Learning methodologies to engage students in microelectronics projects over an extended period actively. These articles found that the activities enhanced the students' cognitive and practical competencies. Educators have emphasized real-world projects that necessitate applying theoretical knowledge within practical contexts (Butterfield & Branch, 2015; Davishahl, 2024; Faiz et al., 2023; Yu & Milburn, 2024). Nestor (2017) elucidates that in a project-based learning framework, students engage in open-ended design tasks that necessitate innovation and critical problem-solving abilities. Mandic and Baric (2017) assert that students are actively involved in experiential learning activities rather than remaining passive recipients of instructional discourse. Finally, Wilson (2023) posits that project-based learning methodologies have demonstrated efficacy in enhancing knowledge retention rates, particularly among first-generation students who may encounter additional obstacles in the learning process. A comprehensive list of the identified literature can be found in Appendix 2.

Hands-on Learning: Thirteen distinct scholarly studies implemented hands-on learning methodologies as the pedagogical approach to incorporate microcontrollers and microelectronics within first-year and sophomore engineering courses. These papers underscore the importance of engaging students in hands-on learning experiences through well-designed laboratory sessions. The lab sessions provided students with an invaluable opportunity to actively involve themselves in comprehensive design projects centered around microcontroller systems or microelectronic components. Frank et al. (2016) noted that the students engaged in practical projects requiring them to apply their theoretical knowledge in a tangible context. Furthermore, researchers have observed students utilizing microcontroller kits as a fundamental resource to complete various programming and microcontroller-related projects (Graven & Bjork, 2016). These hands-on initiatives fortify and reinforce by grounding abstract theoretical concepts in concrete and observable activities (Foist et al., 2018). A comprehensive list of identified literature can be found in Appendix 2.

Collaborative Learning: Nineteen scholarly papers utilized collaborative learning as a pedagogical strategy. These papers also tend to implement project-based or hands-on learning methodologies within their educational programs. Researchers like Butterfield & Branch (2015), Coonley et al. (2020), Daugherity (2019), and Tehrani et al. (2017) have made notable contributions to these studies. Collaborative learning encourages students to work in teams, creating an environment that fosters collaboration and enhances peer learning opportunities (Foist et al., 2018). Frank et al. (2016) highlighted that they systematically grouped students into teams to engage in the design and construction of their robots, while Tewolde (2016) implemented group projects to foster teamwork and facilitate peer learning experiences. Other research has also looked at combining collaborative learning with other teaching methods. Wilson (2023) is one example of this. The authors skillfully combined collaborative learning with project-based learning initiatives, which let students work together in teams on hands-on projects that seamlessly combine distinct parts of mechatronics, such as programming, electronics, and mechanical design**.**

Scaffolded Learning: Out of the 32 scholarly articles reviewed in this investigation, 10 employed scaffolded pedagogical techniques within the context of microelectronics and microcontrollers curricula in their educational environments. The projects are meticulously designed to progressively escalate in complexity, facilitating a step-by-step enhancement of students' knowledge and skills. This pedagogical approach systematically increases task difficulty, enhancing students' confidence and proficiency in their abilities (Butterfield & Branch, 2015; Martin-Ramos et al., 2017; Richardson, 2017; Wilson, 2023). Students engage in iterative cycles of prototyping, testing, and refining their respective projects (Fang et al., 2015; Tehrani et al., 2017).

Engineering discipline.

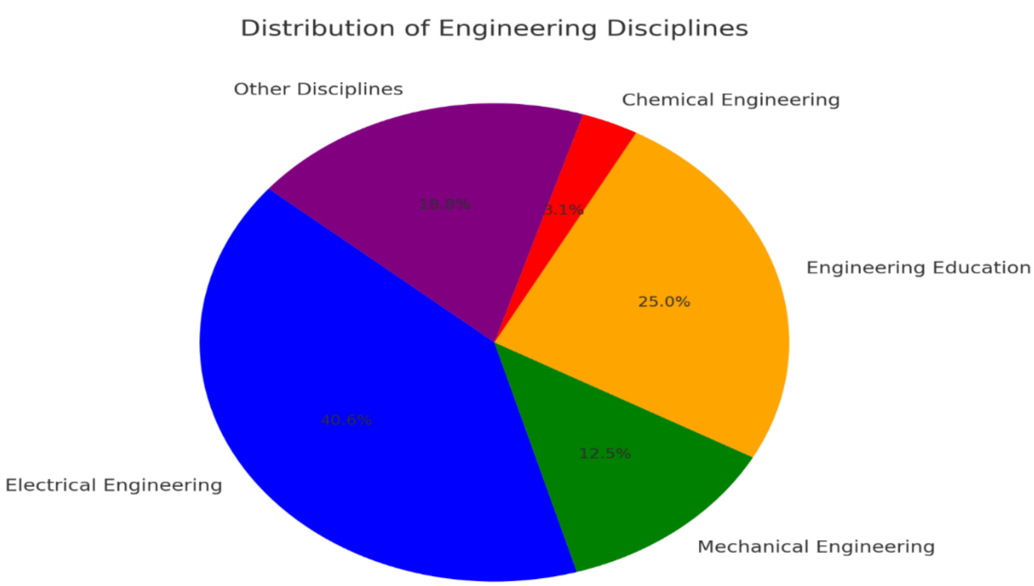

Figure 5: Distribution of Engineering Discipline.

The following engineering disciplines are involved in introducing their first and second-year students to the devices. Chemical Engineering (e.g., Butterfield & Branch, 2015), Electrical and Computer Engineering (e.g., Faiz et al., 2023; Fang et al., 2015), Engineering and Physics (e.g., Daugherity, 2019), Mechatronics (e.g., Wilson, 2023) Multidisciplinary Engineering (e.g., Tehrani et al., 2017), Microelectronics Engineering (e.g., Coonley et al., 2020) and Engineering Education (e.g., Davishahl, 2024; Dickrell & Virguez, 2019; Frank et al., 2016; Shepard et al., 2015; Taheri et al., 2019).

Theme 2: Student Learning Outcomes

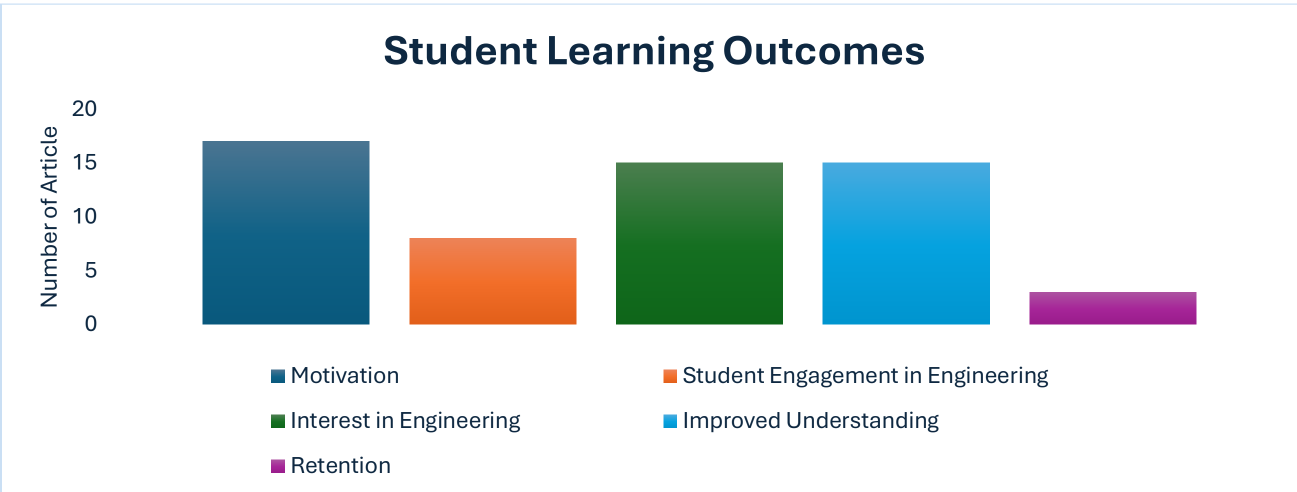

Fig. 5. Distribution of Student Learning Outcomes

The student learning outcomes category theme comprises studies that shed light on how implementing microelectronics and microcontrollers impacts students' learning and their ability to construct new knowledge. The category highlighted how using these devices enhanced students' engagement in an active learning process. For instance, the student satisfaction survey conducted by Coonley et al. (2020) revealed that these implementations effectively enhance understanding and engagement with microelectronic concepts. Out of the 32 pieces of literature included in this study, 17 documented improved motivation (Fang et al., 2015; Gero et al., 2016; Graven & Bjork, 2016; Mandic & Baric, 2017; Martin-Ramos et al., 2017; Nestor, 2017). Eight articles document that microcontrollers and microelectronics enhanced student engagement in engineering. For instance, Abouhilal et al. (2019) attributed this to the hands-on nature of the experiments. Pre- and post-tests conducted by Butterfield & Branch (2015) revealed that usage data from online simulations demonstrated the course's success in enhancing student engagement and learning. Coonley et al. (2020) also proposed that the course fosters problem-solving abilities and teamwork. Fifteen publications reported that the course successfully maintained students' interest in engineering. According to Butterfield and Branch (2015), microcontrollers stimulated students' interest in pursuing further studies and careers in chemical engineering. Likewise, Tennison et al. (2020) note an increased interest in pursuing engineering studies and careers in mechanical engineering. Fifteen literatures documented that microcontrollers and microelectronics in first and sophomore engineering programs helped students have a better understanding of complex engineering concepts (Daugherity, 2019; Davishahl, 2024; Fang et al., 2015;

Farook et al., 2017; Foist et al., 2018; Frank et al., 2016; Gero et al., 2016; Mandic & Baric, 2017; Tewolde, 2016; Wilson, 2023). For example, Davishahl (2024) noted gains in students' confidence and understanding of engineering concepts comparable to those in traditional summer research programs. Three studies noted that including microelectronics and microcontrollers improved student retention (Nestor, 2017; Shepard et al., 2015; Wilson, 2023). For instance, Wilson (2023) asserts that including microcontrollers in first-year engineering courses enhances retention rates, especially for first-generation students who may encounter additional challenges. Faiz concluded that incorporating microelectronics and microcontrollers enhances students' critical thinking and problem-solving abilities while keeping them motivated and interested through interactive and practical projects (Faiz et al., 2023). Other literature, like Tehrani et al. (2017), noted an enhanced ability to design and implement engineering solutions as students engaged with these devices.

Theme 3: Challenges and Limitations

Thirty articles noted that integrating microelectronics and microcontrollers can be resource-intensive; the course requires significant resources, including materials and equipment for project execution (Davishahl, 2024; Foist et al., 2018; Graven & Bjork, 2016; Richardson, 2017; Yu & Milburn, 2024). Fifteen articles posited that balancing project work with other coursework can be challenging for students, raising the challenge of managing time constraints on microcontrollers and microelectronics implementation. According to several studies, balancing project work with other coursework can be challenging for students (Graven & Bjork, 2016; Martin-Ramos et al., 2017; Nestor, 2017; Taheri et al., 2019; Wong & Hsieh, 2016). Fifteen articles mentioned the additional challenge of the gap in knowledge and skills between students, where students enter the course with varying levels of prior knowledge and skills. The diversity in students' prior experience can affect the pace of learning and slow down progress on projects (Faiz et al., 2023; Foist et al., 2018; Martin-Ramos et al., 2017; Meah, 2016; Richardson, 2017; Tehrani et al., 2017; Tewolde, 2016; Yu & Milburn, 2024).

Another issue noted in fourteen articles concerns the difficulty of fairly assessing individual students' contributions within group projects(e.g., Nestor, 2017; Schuman et al., 2022; Taheri et al., 2019; Thomas & Theriault, 2016; Wong & Hsieh, 2016). The authors of these studies noted the difficulty in addressing this assessment challenge during their execution of microelectronics curricula. Twelve of the 32 texts noted that managing and coordinating multiple projects and ensuring all students have access to necessary tools can be complex, which can put a limit on tool access. (Coonley et al., 2020; Daugherity, 2019; Davishahl, 2024; Dickrell & Virguez, 2019; Schuman et al., 2022; Taheri et al., 2019; and Thomas & Theriault, 2016). Two of the 32 articles suggest that implementing such resource-intensive courses on a larger scale may pose logistical challenges, potentially rendering them unscalable and lacking sustainability (Faiz et al., 2023; Frank et al., 2016). However, recent work by Morphew and colleagues has examined the impact of microelectronics integration within a large enrollment first-year engineering course that serves more than 2,000 students each year, suggesting that these challenges can be overcome (Turner et al., under review).

Lastly, the study identified additional challenges, such as the need for instructors to receive training in the effective implementation and management of active learning strategies, a category that includes microcontrollers and microelectronics (Mandic & Baric, 2017; Shepard et al., 2015). These authors posited that while student choice can enhance learning outcomes, too much choice can overwhelm students and negatively impact their performance. In addition, Butterfield and Branch (2015) noted that including options for students can result in space constraints and the need for more prototyping equipment.

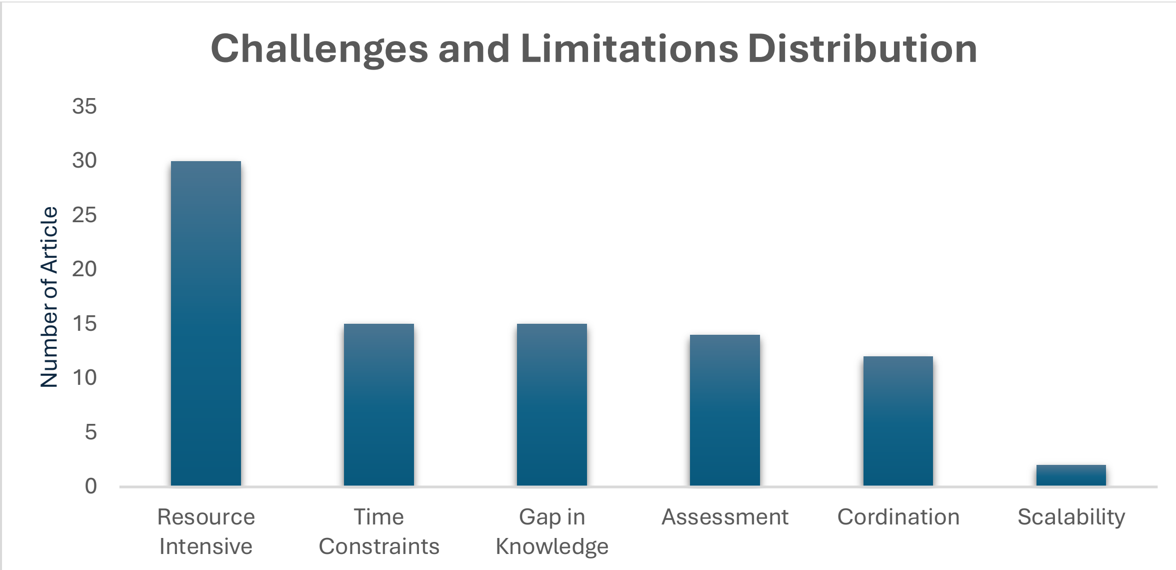

Fig. 6. Challenges and Limitations

Discussion.

Our systematized review found 32 studies published between 2015 and 2024 that focused on microelectronics integration in first-year and second-year engineering courses. We classified these articles under three themes: (1) curriculum design, (2) students' learning outcomes, and (3) challenges and limitations. Upon careful evaluation of each study with detailed summaries, this review demonstrated the trend of incorporating microcontrollers and microelectronics into undergraduate engineering programs, particularly in first-year engineering across various academic institutions. Findings from these studies show that microelectronics and microcontroller projects helped first-year and sophomore students understand abstract engineering concepts (Daugherity, 2019; Tehrani et al., 2017), providing students with a platform to engage in real-world designs (Wilson, 2023), giving students a collaborative learning environment (Butterfield & Branch, 2015; Coonley et al., 2020), and engaging students in a scaffolded engineering design process (Butterfield & Branch, 2015).

The 32 studies under the 'curriculum design' theme addressed the three research questions. We asked these questions primarily to comprehend current practices, the learning outcomes methods, and the pedagogical methods used. We noted that most engineering disciplines redesigned their existing courses to incorporate these devices, while fewer created new courses with laboratory sessions. Redesigning an existing course from the data gathered was the most efficient way to incorporate these technologies into programs. The pedagogical methods employed were project-based, collaborative, scaffolded, and hands-on learning, which facilitated student engagement with microcontrollers. Engineering disciplines that implemented curricula modifications were electrical and computer engineering, chemical engineering, mechanical engineering, mechatronics, agricultural science, and physics. This addressed the crucial question of whether programs beyond engineering can implement microelectronics and microcontrollers.

Studies categorized under the theme "Student learning outcomes" allowed us to understand how this integration impacted students' learning and motivation. Students understand engineering concepts, establish a link with real-world design, and develop an interest in engineering. Additionally, students were motivated to pursue their engineering studies and careers. The last section tackled the difficulties encountered in implementing the curriculum, highlighting issues such as resource intensity, time constraints, individual assessments, and coordination of these projects. The final two themes contextualized the advantages and benefits of incorporating microelectronics and microcontrollers into first-year and sophomore engineering programs while highlighting potential pitfalls that need attention to improve their effectiveness and scalability.

Gaps in Literature

While conducting the review, we noted gaps in the studies. One of the most notable was the lack of scalability of these studies, as they were centered on what worked for their specific institution (Wilson, 2023), the lack of longitudinal studies and comprehensive data on the long-term impact of microelectronics and microcontrollers on students' academic and career trajectories. In addition, most of the studies did not conduct pre- and post-implementation assessments, which limits the understanding of the actual impact of this integration. Few studies concentrated on the post-implementation assessments, while others disregarded both assessments and solely reported the actions taken.

Future Directions

We propose recommendations for future scholarly inquiries to encourage the synthesis of literature across various databases and investigate the long-term effects of these integrations on engineering education and the career trajectories of these students. Explore long-term impacts and refine integration methodologies.

Limitations

This review highlights the incorporation of various methods in the literature, detailing their application, discipline, and outcomes. The sample primarily utilized qualitative methods, thematic analysis, and convenience sampling, which led to a lack of rigorous evaluations of alternative methodologies available to researchers.

Conclusion

This review addressed research questions on how microcontrollers and microelectronics were integrated into first-year and sophomore engineering programs. To answer this question, we systematically reviewed three scholarly databases to synthesize insights from published articles in the engineering field. Keywords were used to guide the search, i.e., microelectronics or microcontroller. The findings showed that these devices can be adapted into a curriculum, demonstrating their potential as a teaching tool to enrich students' learning experience. In addition, our evidence shows that microelectronics systems can enhance students’ motivation, interest, and understanding of engineering concepts, coding, and real-world applications. Furthermore, adopting a multi-disciplinary approach in the implementation process will encourage the incorporation of microcontrollers and microelectronics into fields beyond engineering, such as the social sciences and medical fields. This approach will foster problem-solving skills and critical thinking and promote teamwork and collaboration across disciplines. Our findings for institutions, researchers, and educators showed the importance of embedding these technologies in early curricula to improve student motivation, retention, and learning efficacy. By integrating these devices alongside other essential tools into curricula, institutions can prepare students with the practical and collaborative skills necessary for success in the semiconductor industry and today's interdisciplinary world.

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Appendix 1. Table of authors included in the study.

Author/s	**Year of Publication**	**Citation**
Davishahl	2024	16
Yu & Milburn	2024	78

Faiz et al.	2023	20
Whalen & Hertz	2023	73
Wilson	2023	74
Schuman et al.	2022	60
Fidai et al.	2021	24
Kidd & Hilton	2021	38
Coonley et al.	2020	14
Tennison et al.	2020	67
Abouhilal et al.	2019	1
Daugherity	2019	15
Dickrell & Virguez	2019	18
Taheri et al.	2019	65
Foist et al.	2018	25
Farook et al.	2017	22
Mandic & Baric	2017	44
Martin-Ramos et al.	2017	45
Nestor	2017	49
Richardson	2017	54
Tehrani et al.	2017	66
Frank et al.	2016	26
Gero et al.	2016	28
Graven & Bjork	2016	31
Meah	2016	47
Rumpf et al.	2016	59
Tewolde	2016	6869
Thomas & Theriault	2016	69
Wong & Hsieh	2016	75
Butterfield & Branch	2015	10
Fang et al.	2015	21
Shepard et al.	2015	62

Appendix 2. Table of Pedagogical Methods: Authors' Distribution

Project-Based Learning	**Hands-on Learning**	**Collaborative learning**	**Scaffolded learning**
Butterfield & Branch, 2015	Coonley et al., 2020	Butterfield & Branch, 2015	Butterfield & Branch, 2015
Davishahl, (2024).	Daugherity, 2019	Davishahl, 2024	Foist et al., 2018
Dickrell & Virguez, 2019	Fang et al., 2015	Fang et al., 2015	Graven & Bjork, 2016

Kidd & Hilton, 2021	Fidai et al., 2021	Foist et al., 2018	Kidd & Hilton, 2021
Nestor, 2017	Foist et al., 2018	Frank et al., 2016	Martin-Ramos et al., 2017
Rumpf et al., 2016	Frank et al., 2016	Graven & Bjork, 2016	Meah, 2016
Schuman et al., 2022	Graven & Bjork, (2016).	Kidd & Hilton, 2021	Richardson, 2017
Shepard et al., 2015	Mandic & Baric, (2017).	Mandic & Baric, 2017	Tehrani et al., 2017
Taheri et al., 2019	Martin-Ramos et al., 2017	Martin-Ramos et al., 2017	Thomas & Theriault, 2016
Tehrani et al., 2017	Meah, (2016).	Meah, 2016	Wilson, 2023
Tennison et al., 2020	Nestor, 2017	Nestor, 2017	
Thomas & Theriault, 2016	Richardson, 2017	Richardson, 2017	
Wilson, 2023	Tewolde, 2016	Rumpf et al., 2016	
Yu & Milburn, 2024	Whalen & Hertz, 2023	Taheri et al., 2019	
	Wong & Hsieh, 2016	Tehrani et al., 2017	
	Wong & Hsieh, 2016)	Tewolde, 2016	

		Thomas & Theriault, 2016	
		Wilson, 2023	
		Yu & Milburn, 2024	