



Inclusive pre-laboratory learning in engineering laboratories: A systematic literature review on accessibility for students with disabilities

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ABSTRACT

Background: Laboratory-based engineering education continues to face persistent challenges in ensuring accessible and inclusive learning environments for students with disabilities, particularly during the pre-laboratory phase, which is often characterized by technical complexity and safety risks. Inadequate pre-laboratory preparation may lead to learning barriers, reduced participation, and increased procedural errors. This study aims to systematically examine inclusive pre-laboratory learning strategies in engineering laboratories and analyze their implications for accessibility, laboratory safety, and overall learning quality.

Methods: This study employed a systematic literature review grounded in inclusive education theory and Universal Design for Learning. Peer-reviewed scholarly articles related to engineering laboratories, pre-laboratory instruction, accessibility, and disability were systematically identified and thematically analyzed to explore dominant instructional approaches, design strategies, and reported educational outcomes. **Findings:** The review reveals that inclusive pre-laboratory learning, implemented through multimodal instructional materials, adaptive safety guidance, and virtual or simulated laboratory environments, consistently enhances students' cognitive and procedural preparedness. These strategies reduce procedural errors, improve compliance with safety standards, and strengthen confidence and perceived safety among students with disabilities. The findings further demonstrate that such approaches benefit not only students with disabilities but also the broader student population, supporting the principles of Universal Design for Learning that emphasize flexibility, multiple means of representation, and learner engagement. **Conclusion:** Inclusive pre-laboratory learning is identified as an effective, scalable, and sustainable pedagogical strategy for developing equitable engineering laboratory environments without requiring extensive physical infrastructure modifications. **Novelty/Originality of this article:** This article contributes to the field by providing a systematic synthesis that integrates accessibility, laboratory safety, and pre-laboratory learning into a unified and practical conceptual framework, thereby advancing the state of the art in inclusive engineering education.

KEYWORDS: engineering laboratories; inclusive education; pre-laboratory learning; students with disabilities.

1. Introduction

Higher education has a responsibility to ensure equal access to learning for all students, including students with disabilities, as emphasized in the principles of inclusive education and educational justice. However, in practice, the implementation of inclusion in technical education still faces various obstacles, especially in laboratory-based learning that requires

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high technical, procedural, and safety awareness skills (Batty & Reilly, 2023; Bunbury, 2018; Carabajal et al., 2017). Laboratory environments are generally designed with the assumption of uniform physical and sensory abilities, so that students with disabilities are at risk of experiencing learning barriers, academic anxiety, and limited participation in practical activities (Asghar et al., 2017; Kirsh et al., 2016; Villanueva & Hand, 2015). This condition shows that inclusivity in engineering education is not enough to be realized through general policies, but requires systematic and contextual pedagogical interventions.

Theoretically, inclusive education emphasizes that differences in abilities are not individual deficits, but rather consequences of an adaptive learning environment design (Bunbury, 2018; Martin-Hansen, 2018). The principle of Universal Design for Learning asserts that learning must be designed with flexibility in material representation, student engagement, and expression of learning outcomes so that it is accessible to all students (Finnegan, 2024; Nicol et al., 2022). In the context of engineering laboratories, this approach requires adjustments not only to physical facilities, but also to instructional strategies, practical workflows, and the delivery of clear and structured safety information (Bretz, 2019; Walker et al., 2016). Thus, the application of Universal Design for Learning principles in laboratory learning shifts the focus from individual accommodation efforts to the design of a learning system that proactively accommodates the diversity of student abilities. This approach places inclusivity as an integral part of learning quality, not as an addition or response to special needs alone.

Pre-laboratory learning is an important component because it serves as a cognitive and procedural bridge before students are directly involved with risky laboratory equipment and activities. A number of studies show that students, especially those with special needs, often have difficulty understanding practicum procedures due to rapid instructions, unvaried material formats, and a lack of adequate initial preparation (Agustian & Seery, 2017; Batty & Reilly, 2023; Pearson, 2025). This condition not only results in low technical understanding but also increases academic anxiety and the risk of procedural errors during the practical session. Conversely, structured pre-laboratory learning has been shown to improve student readiness, strengthen understanding of work steps, and encourage compliance with laboratory safety standards (Coleman & Smith, 2019; Purkayastha et al., 2019; Quiroga & Choate, 2019). In addition, providing pre-laboratory materials that can be accessed flexibly allows students to learn the content at their own pace, thereby reducing their dependence on direct assistance during the laboratory session. Thus, pre-laboratory learning not only serves as a technical introduction but also as a preventive pedagogical strategy that supports inclusivity, safety, and the overall quality of laboratory learning.

Advances in learning technology have opened up significant opportunities to improve the accessibility of pre-practicum learning in engineering education. The use of virtual laboratories, interactive simulations, and hybrid approaches has been reported to expand learning access, provide a safe practice space, and reduce student anxiety before face-to-face practicums are conducted (Baladoh et al., 2017; Panasiuk et al., 2021; Reyes et al., 2024; Tambiga et al., 2024). This technology allows students to repeat procedures, understand the functions of tools, and anticipate potential risks independently without time pressure or safety consequences. Other studies also show that the integration of technology in laboratory learning plays an important role in bridging the gap between theory and practice, especially for students who need more flexible learning time and approaches (Logothetis, 2024; Rayment et al., 2023). In addition, technology-based learning supports the diversity of student learning styles by providing various forms of material representation, such as procedure visualizations, animations, and video-based demonstrations (Png et al., 2024). Thus, the use of technology in pre-practicum learning not only serves as a technical solution but also as an inclusive pedagogical strategy that strengthens students' readiness, confidence, and participation in laboratory activities.

Although studies on inclusive learning, the use of laboratory technology, and practical safety have developed significantly, most research still discusses these aspects separately and has not been conceptually integrated. Accessibility studies generally focus on institutional policy issues and physical facility adjustments, while laboratory studies

emphasize instructional effectiveness or procedural compliance without comprehensively considering the diversity of students' abilities and experiences (Casad et al., 2018; Cech & Rothwell, 2018; Rosen & Kelly, 2020). As a result, pedagogical approaches that can simultaneously bridge accessibility needs and laboratory safety requirements are still relatively rarely discussed. Research that specifically integrates pre-laboratory learning, accessibility, and engineering education into a single, comprehensive conceptual framework is also limited, especially in the context of engineering higher education, even though the pre-laboratory phase has strategic potential as a flexible and adaptive pedagogical intervention space before students enter the risky laboratory environment (Batty & Reilly, 2023; Nicol et al., 2022). This condition confirms the existence of a significant research gap and reinforces the urgency of a systematic study capable of synthesizing cross-study findings on inclusive pre-practicum learning in engineering education.

Based on these theoretical and empirical foundations, this article positions inclusive pre-laboratory learning as a pedagogical strategy that has the potential to simultaneously address the challenges of laboratory accessibility and safety in engineering education. Pre-laboratory learning is understood not merely as a preliminary stage, but as a strategic pedagogical intervention space to build students' cognitive, procedural, and affective readiness before they are directly involved in complex and risky laboratory activities. Theoretically, it is assumed that the more inclusive the design of pre-practicum learning, through flexibility of material, clarity of instructions, and diversity of learning media, the higher the level of readiness, sense of security, and participation of students with disabilities in laboratory activities. This assumption is in line with the one-way approach of Universal Design for Learning, which emphasizes that flexibility in instruction and information presentation will improve the quality of learning for all students, including those with special needs, without creating segregation or exclusive adjustments (Bretz, 2019; Finnegan, 2024; Martin-Hansen, 2018). Thus, inclusive pre-practicum learning is positioned as a conceptual foundation for the development of a more equitable, safe, and sustainable engineering laboratory environment.

Therefore, the purpose of this article is to systematically review the literature on inclusive pre-laboratory learning in engineering laboratories and analyze its implications for accessibility, work safety, and learning quality for students with disabilities. This study specifically seeks to identify learning design patterns, pedagogical strategies, and the use of technology that have been reported to be effective in supporting student readiness and participation before the lab begins. Through a comprehensive and structured synthesis of the literature, this article is expected to strengthen the state of the art in inclusive engineering education by integrating the aspects of pre-practicum, laboratory safety, and the principles of Universal Design for Learning into a single, comprehensive conceptual framework. Furthermore, the findings of this study are expected to provide a conceptual basis and direction for the development of a more equitable, safe, and sustainable laboratory learning model, both for students with disabilities and for all students in the context of modern engineering education.

2. Methods

This study uses a Systematic Literature Review (SLR) approach to address research issues related to inclusive pre-practicum learning in engineering laboratories for students with disabilities. This approach was chosen because it allows for a systematic, transparent, and replicable synthesis of published empirical and conceptual findings. Ontologically, this study views accessibility and inclusivity as socio-pedagogical constructs shaped by learning design and the academic environment. Epistemologically, knowledge is constructed through critical analysis of scientific literature that represents practices, theories, and empirical evidence in the context of engineering education.

The literature search was conducted from January to March 2025 through several reputable scientific databases, namely ScienceDirect, PubMed, and Google Scholar. The

selection of these databases was based on their relevance to the fields of engineering education, inclusive education, and laboratory-based learning. The search period was set to ensure the recency and relevance of the findings. This study did not specify a particular geographical location because it was a literature review, but the context of higher education and engineering laboratories was the main focus of the analysis.

The literature search strategy used a combination of keywords in English, including inclusive education, pre-laboratory learning, engineering laboratories, students with disabilities, and laboratory safety. Inclusion criteria included journal articles published in the last ten years, discussing pre-practicum or engineering laboratory learning, and explicitly mentioning aspects of disability, accessibility, or inclusivity. Articles in the form of editorials, opinions, or those that did not undergo peer review were excluded from the study. The selection process was carried out through the stages of identification, screening of titles and abstracts, and evaluation of the full text.

The unit of analysis in this study was scientific articles that met the inclusion criteria. The conceptual variables analyzed included pre-practicum learning design, inclusivity strategies, laboratory safety approaches, and their impact on the readiness and participation of students with disabilities. The main data source was journal articles, while supporting data included relevant academic books and scientific reports. Data extraction was carried out systematically by noting the research objectives, laboratory context, methods used, and main findings from each article.

Data analysis was conducted using a qualitative thematic analysis approach. The stages of analysis included data condensation through open coding, grouping of main themes, and presentation of data in the form of a synthetic narrative and summary table. The conclusion stage was carried out by linking empirical findings with the theoretical framework of inclusive education and Universal Design for Learning. The results of the analysis were presented in a descriptive-analytical manner to show patterns, research gaps, and conceptual implications for the development of inclusive pre-practicum learning in engineering laboratories.

3. Results and Discussion

3.1 Literature identification and selection process

In this systematic literature review, the author used a combination of databases from credible scientific sources, namely ScienceDirect, PubMed, and Google Scholar. In the initial stage of literature search, the author entered the keywords “inclusive education,” “pre-laboratory learning,” “engineering laboratories,” “students with disabilities,” and various combinations of these terms. From the initial search results, 3,486 articles were obtained from indexed journals relevant to the topics of laboratory learning and inclusive education. Next, the author conducted further screening by focusing the search on the keyword combinations “pre-laboratory learning,” “engineering education,” and “disability inclusion” to obtain literature that was more specific to the research objectives. From this process, 52 articles were obtained that were considered to be directly related to inclusive pre-laboratory learning in engineering laboratories. The next stage involved eliminating 18 articles identified as duplicates, leaving 34 articles for the next screening stage.

The articles were then selected based on the suitability of their titles, abstracts, and keywords with the research focus. From this process, 20 articles were eliminated because they did not discuss the context of engineering education, did not mention pre-practicum learning, or did not explicitly discuss aspects of disability and accessibility. Next, a full text evaluation was conducted on the remaining 14 articles. At this stage, 8 articles were excluded for clear reasons, such as not being published within the last ten years, having too general a research focus, or being irrelevant to the context of engineering laboratory learning. Thus, 6 final articles were obtained that met all inclusion criteria and were relevant to the scope of the study. The six articles were then analyzed in depth to identify patterns of inclusive pre-practicum learning strategies, accessibility approaches, and their implications

for safety and learning quality in engineering laboratories. The article selection and exclusion process is summarized in the PRISMA diagram (Figure 1).

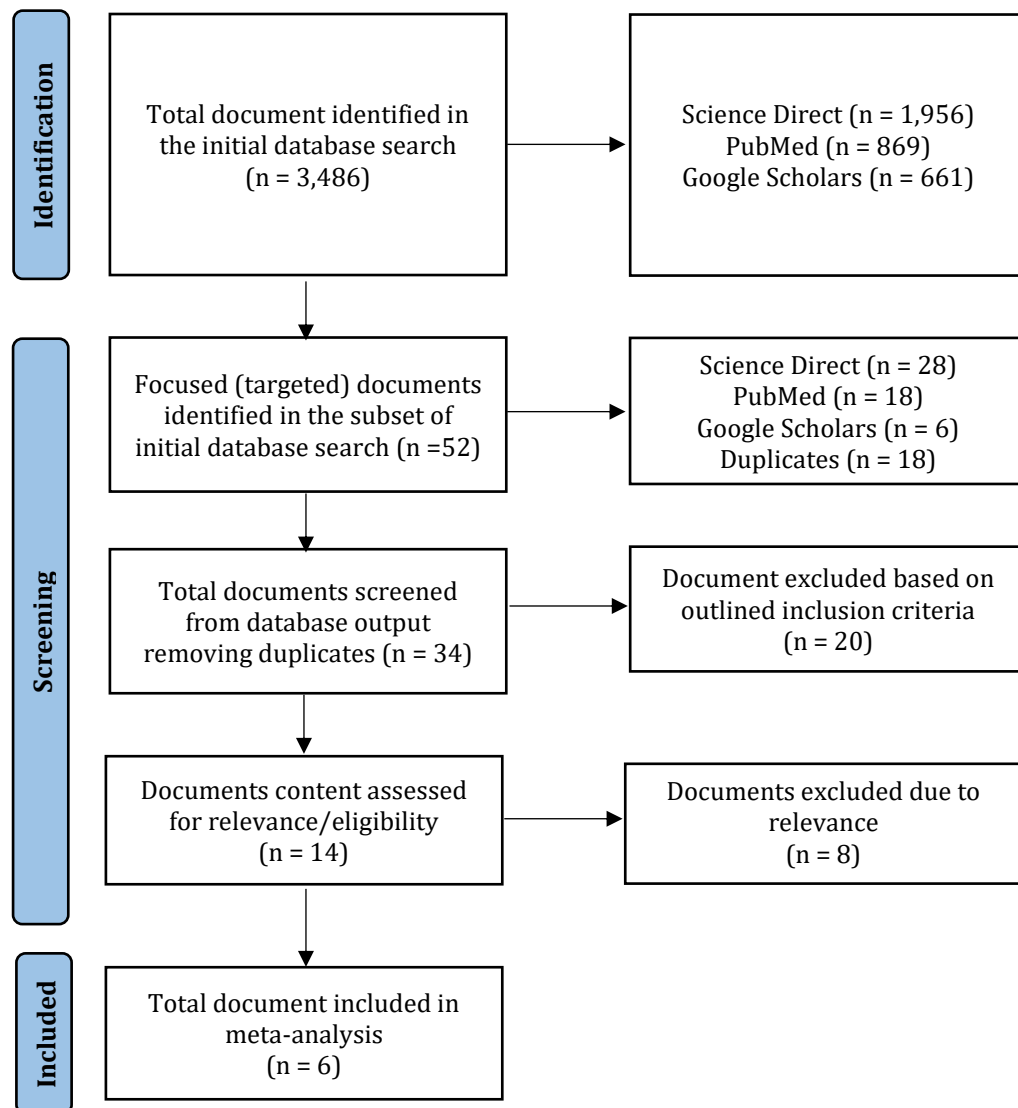


Fig. 1. PRISMA diagram

Furthermore, based on the results of literature identification and selection, this study includes an analysis of six scientific articles discussing pre-practicum learning, virtual laboratories, accessibility, and the inclusivity of laboratory learning for students with diverse needs, including students with disabilities. The articles analyzed in this study were published between 2017 and 2025, with a distribution of publications consisting of 2017 (17%), 2022 (17%), 2023 (33%), 2024 (17%), and 2025 (16%). This time frame shows the continuous development of studies related to the use of pre-laboratory learning design and technology to improve the quality and accessibility of laboratory learning.

From a methodological perspective, the articles reviewed used various research approaches, predominantly qualitative methods, systematic literature reviews, and narrative-conceptual methods, as well as several studies that integrated technology-based learning designs. The main focus of the study includes the design of pre-practicum modules, virtual laboratories, barriers to student participation in Science, Technology, Engineering, and Mathematics (STEM) practicums, and the role of technology in bridging the gap between theory and practice. A summary of the literature studies analyzed is presented in Table 1.

Table 1. Literature review summary

Researcher Name and Year	Research Objectives	Research Method	Research Results
Baladoh et al. (2017)	Assessing the effectiveness of virtual laboratories in improving the learning outcomes of deaf students in electronics.	Educational experiments with a quantitative approach.	Virtual laboratories significantly improve the learning outcomes and conceptual understanding of deaf students.
Pearson (2025)	Designing pre-laboratory modules in a planned manner to improve first-year students' readiness for chemistry learning.	Conceptual learning and evaluation design.	Systematically designed pre-laboratory modules improve students' readiness, understanding of procedures, and engagement.
Batty & Reilly (2023)	Identifying barriers to student participation in STEM laboratories and their implications for inclusive curricula.	Qualitative study based on interviews and thematic analysis.	Physical, pedagogical, and cultural barriers affect student participation, necessitating a more inclusive laboratory curriculum.
Nicol et al. (2022)	Reviewing students' perceptions and experiences of science laboratory learning.	Systematic literature review.	Students' positive perceptions increase when laboratory learning is designed in a structured and adaptive manner.
Reyes et al. (2024)	Examining the role of virtual laboratories in enhancing experiential science learning.	Conceptual narrative and case studies.	Virtual laboratories expand access to learning, although they require strong design readiness and pedagogical support.
Rayment et al. (2023)	Analyzing the role of technology in bridging the gap between theory and practice in bioscience laboratories.	Qualitative study using a literature review approach.	Laboratory learning technology improves the connection between theory and practice and supports more inclusive learning.

3.2 Pre-practicum learning as an inclusion strategy in engineering laboratories

A review of the literature shows that pre-practicum learning plays a strategic role as an instrument of inclusion in engineering education, particularly in the context of complex and high-risk laboratory-based learning. A number of studies confirm that the main challenges in engineering practicums stem not only from the complexity of the material or equipment, but also from learning designs that are still oriented towards assumptions of homogeneous student abilities and are less adaptive to diversity in backgrounds, abilities, and learning experiences (Bretz, 2019; Walker et al., 2016). This condition is reinforced by the findings of Villanueva & Hand (2015) and Asghar et al. (2017), which show that students with special needs often experience conceptual and procedural barriers when learning is not designed to be inclusive from the outset. In this context, pre-practicum learning is positioned as a critical phase that allows students to build initial understanding, procedural orientation, and mental readiness before interacting directly with a laboratory environment that demands high precision and strong safety awareness.

An inclusive pre-laboratory approach also contributes significantly to reducing student participation gaps in laboratory activities. Batty & Reilly (2023) show that physical, pedagogical, and cultural barriers in STEM laboratories often limit student engagement, especially among those from minority groups, students with disabilities, and students from certain socioeconomic backgrounds. These findings are in line with studies by Ahn & Davis (2020), Rainey et al. (2018), and Bunce et al. (2021), which confirm that a sense of

belonging, clear academic expectations, and positive early learning experiences have a major impact on student participation and retention in STEM fields. By providing structured, transparent, and accessible pre-practicum learning, educational institutions can shift the focus from individual adjustments to a more equitable and proactive learning system design, as emphasized in the principles of inclusive education and educational equity.

Furthermore, pre-laboratory learning enables the more optimal application of Universal Design for Learning principles in the context of engineering laboratories. The provision of various forms of material representation, such as visual guides, procedural videos, preliminary simulations, and re-accessible digital materials, enables students with diverse learning styles to gain an equal understanding before the practicum takes place (Finnegan, 2024; Nicol et al., 2022). This approach is also supported by the findings of Achuthan & Murali (2017) and Aşıksoy & Islek (2017), which show that multimodal and virtual-based learning can improve positive perceptions, procedural understanding, and student readiness in laboratory activities. Thus, pre-laboratory learning not only serves as a technical introduction but also as an inclusion strategy that strengthens students' sense of security, cognitive readiness, and confidence before the laboratory session begins, while also contributing to the creation of a more equitable and human-centered laboratory environment (Dowey et al., 2021; Ertl et al., 2017).

3.3 Pre-practicum learning design and student readiness

The use of learning technology and virtual laboratories is one of the dominant findings in this study as a strategic means of improving the inclusivity of engineering laboratory learning. Various studies show that virtual laboratories, digital simulations, and computer-based learning environments are able to provide a safe, flexible, and risk-free learning space for students before they engage in complex physical practicums (Achuthan & Murali, 2017; Aşıksoy & Islek, 2017; Baladogh et al., 2017). This approach has proven effective in helping students understand concepts and procedures gradually, especially for students with sensory limitations, communication barriers, or special learning needs. Furthermore, Sypsas & Kalles (2018) and Villanueva & Hand (2015) emphasize that virtual laboratories can serve as compensatory tools that enable students to access practical experience more equitably without relying entirely on specific physical or sensory abilities.

Furthermore, learning technology plays an important role in bridging the gap between theory and practice, which has long been a major challenge in engineering and applied science education. Rayment et al. (2023) and Pokoo-Aikins et al. (2019) show that the use of interactive simulations and remote laboratories allows students to connect theoretical concepts with practical applications in a more meaningful and reflective way. These findings are reinforced by Coutinho et al. (2020) and Carvalho et al. (2021), who report that virtual equipment and technology-based laboratory projects help students visualize abstract technical phenomena and improve conceptual understanding before physical practicums are conducted. Thus, technology does not merely serve as a temporary substitute for conventional practical work, but as a pedagogical component that enriches the laboratory learning experience and improves the overall quality of learning.

The development of virtual laboratories and hybrid approaches post-pandemic has also strengthened the relevance of technology in inclusive learning. Logothetis (2024), Panasiuk et al. (2021), and Sypsas & Kalles (2018) note that the evolution of laboratory learning through technology opens up new opportunities for more adaptive, flexible, and sustainable learning designs. Studies by Png et al. (2024) and Tambiga et al. (2024) also show that students demonstrate more positive preferences and performance when laboratory learning is designed in a hybrid manner and supported by easily accessible technology. Within the framework of Universal Design for Learning, technology serves as an enabler that provides various pathways for engagement, representation, and expression of learning, thereby supporting broader student participation and contributing to the creation of a more inclusive and human-centered engineering laboratory environment.

3.4 The role of technology and virtual laboratories in inclusive learning

The use of learning technology and virtual laboratories emerged as one of the dominant findings in this study that directly contributed to increasing the inclusiveness of engineering laboratory learning. A number of studies show that virtual laboratories and digital simulations are able to provide a safe, flexible, and risk-free learning space for students before they engage in physical practicums that require high precision (Achuthan & Murali, 2017; Aşıksoy & Islek, 2017; Baladoh et al., 2017). This approach is particularly relevant for students with sensory limitations, mobility barriers, or special learning needs, as it allows them to understand procedures and concepts without the pressure of a complex laboratory environment. Furthermore, research by Sypsas & Kalles (2018) confirms that virtual laboratories provide an inclusive learning alternative by reducing dependence on specific physical abilities, thereby making access to practical experience more equitable.

Furthermore, learning technology plays an important role in bridging the gap between theory and practice, which has long been a major challenge in engineering education. Pokoo-Aikins et al. (2019) and Rayment et al. (2023) show that the use of interactive simulations and remote laboratories allows students to connect theoretical concepts with practical applications in a more meaningful way through controlled exploration and repetition. These findings are reinforced by Carvalho et al. (2021) and Coutinho et al. (2020), who report that virtual equipment and technology-based laboratory projects help students visualize abstract engineering phenomena and improve conceptual understanding before physical practicums are conducted. Thus, technology does not merely serve as a temporary substitute for conventional practical work, but as a pedagogical component that enriches the learning process and enhances the quality of the laboratory experience.

The development of virtual laboratories and hybrid approaches post-pandemic further emphasizes the relevance of technology in inclusive learning. Logothetis (2024), Panasiuk et al. (2021), and Sypsas & Kalles (2018) note that the transformation of laboratory learning through technology opens up new opportunities for more adaptive, flexible, and sustainable learning designs. Studies by Png et al. (2024) and Tambiga et al. (2024) also show that students demonstrate more positive preferences and performance when laboratory learning is supported by a combination of online and offline sessions that are designed in an integrated manner. Within the framework of Universal Design for Learning, technology serves as an enabler that provides various pathways for engagement, representation, and expression of learning, thereby supporting broader student participation and strengthening the inclusivity of engineering laboratory learning.

3.5 Perceptions, sense of security, and learning experiences of students

In addition to cognitive and procedural aspects, inclusive pre-laboratory learning also has a significant effect on students' perceptions, sense of security, and learning experiences in the engineering laboratory environment. Nicol et al. (2022) show that students' positive perceptions of laboratory learning are greatly influenced by the clarity of instructions, initial preparedness, and adequate understanding of the flow and objectives of the practicum. Students who feel prepared before the practicum tend to show higher levels of confidence, more active participation, and better self-regulation skills during laboratory activities. These findings are in line with Bretz (2019) and Martin-Hansen (2018), who emphasize that structured initial experiences in laboratory learning play an important role in shaping students' positive attitudes toward experiment-based learning.

A sense of safety is a crucial aspect of laboratory learning, especially for students with special needs or those from groups that have historically been underrepresented in engineering education. Studies by Ahn & Davis (2020) and Rosen & Kelly (2020) reveal that an exclusive learning environment can affect students' sense of belonging, help-seeking patterns, and academic engagement. These findings are reinforced by research from Casad et al. (2018), Cech & Rothwell (2018) and Hughes (2018), which shows that perceptions of a threatening or exclusive academic environment can reduce students' confidence and

participation in STEM. In this context, pre-laboratory learning serves as a support mechanism that helps students understand academic expectations, safety risks, and laboratory norms, thereby reducing anxiety, uncertainty, and psychological pressure during the lab.

Furthermore, positive learning experiences in the laboratory have long-term implications for the sustainability of student participation in STEM fields. Research by Cooper et al. (2019) and Rainey et al. (2018) shows that a sense of belonging, early support, and meaningful learning experiences play an important role in students' decisions to persevere and thrive in STEM disciplines. Similar findings were also reported by Bunbury (2018), Burwell (2018), and Kauser et al. (2021), who emphasized that inclusive and safe academic experiences can mitigate psychosocial factors that contribute to disparities in participation and study continuity. Thus, inclusive pre-practicum learning not only impacts short-term practicum performance but also contributes to the quality of the academic experience, student well-being, and the sustainability of their participation in engineering education more broadly (Canning et al., 2019; Claridge et al., 2018).

3.6 Technology integration to bridge theory and practice

One of the main challenges in engineering education is the persistent gap between theoretical understanding gained in the classroom and practical application in the laboratory environment. A review of the literature shows that students often have difficulty transferring abstract concepts into concrete experimental procedures, especially when practical work is carried out in a limited time and with a high level of instrument complexity. In this context, the integration of learning technology is seen as capable of serving as a pedagogical bridge between theory and practice. Rayment et al. (2023) emphasize that laboratory technology, including digital simulations and virtual devices, helps students visualize abstract concepts and relate them to experimental steps in a more meaningful and systematic way, thereby strengthening conceptual understanding before hands-on practice is carried out.

This approach is reinforced by the findings of Coutinho et al. (2020) and Pokoo-Aikins et al. (2019), which show that remote laboratories and virtual equipment allow students to practice, explore variables, and repeat experiments without the time constraints and safety risks that are usually inherent in physical practicums. Through repeated and controlled practice opportunities, students can build more stable conceptual schemes and improve procedural accuracy before entering the actual laboratory. This is particularly relevant for students who require a gradual and repetitive learning approach, including students with special learning needs or low confidence levels when facing complex practical activities (Consignado, 2025; Krishnaveni et al., 2021).

In the context of inclusivity, the integration of learning technology also opens up more opportunities for differentiation and personalization of learning. Panasiuk et al. (2021) and Sypsas & Kalles (2018) emphasize that virtual laboratories enable the adaptation of content, pace, and learning methods according to the diverse needs and characteristics of students. This approach is in line with the principles of Universal Design for Learning, which emphasizes flexibility in the representation and engagement of learners. Thus, technology not only functions as a technical aid, but also as a pedagogical component that strengthens the connection between theory, practice, and inclusive learning experiences, while supporting the creation of a more equitable and student-centered technical laboratory learning environment (Cotner & Ballen, 2017; Deiglmayr et al., 2019).

3.7 Position of findings in relation to previous research and state of the art

Compared to previous studies that emphasized physical facility modifications or institutional policies, the results of this study place pre-practicum learning and learning technology as relatively efficient, flexible, and sustainable forms of pedagogical intervention. Previous studies tended to view inclusivity as a structural access issue

requiring large-scale infrastructure or regulatory changes, which in practice often entail high costs and long implementation times (Bunbury, 2018; Carabajal et al., 2017). While this approach is important, this study shows that learning design, particularly in the pre-practicum phase, plays an equally important role in creating an inclusive laboratory environment, and can even be implemented more quickly and adaptively to diverse institutional contexts.

The six main articles analyzed consistently show that a pre-lab-based pedagogical approach and the use of learning technology can improve students' readiness, participation, and the quality of their learning experiences in engineering laboratories. These findings are in line with the research of Bretz (2019) and Martin-Hansen (2018), which emphasizes the importance of meaningful instructional design in experiment-based learning. Furthermore, this study expands the state of the art by integrating the principles of Universal Design for Learning into the context of engineering laboratory learning, which has been discussed more in the context of classroom learning, assessment, or general curriculum development (Finnegan, 2024; Martin-Hansen, 2018). This integration demonstrates that UDL principles are cross-contextual and relevant to high-risk, high-complexity learning environments such as engineering laboratories (Huisman et al., 2019; McMaster, 2017; Meaders et al., 2020).

Thus, the main contribution of this study lies in its conceptual synthesis linking inclusivity, laboratory safety, and pre-practicum learning design within a coherent, evidence-based pedagogical framework. This position distinguishes this article from previous studies that were partial or focused on a single aspect, such as physical access or technological effectiveness alone. The findings of this study reinforce the argument that inclusivity in engineering education can be achieved not only through structural changes, but also through planned, systematic, and needs-oriented pedagogical interventions (Asghar et al., 2017; Martin-Hansen, 2018).

3.8 Synthesis of findings and conceptual implications

Overall, the synthesis of findings shows a consistent one-way relationship between inclusive pre-laboratory learning design and increased cognitive readiness, sense of security, and student participation levels in engineering laboratory learning. Pre-laboratory learning serves as a pedagogical foundation that enables students to understand procedures, safety risks, and lab objectives more comprehensively before engaging directly in complex and potentially risky laboratory activities. These findings reinforce the view that student readiness is the result of a consciously designed learning process, not merely an accumulation of practicum experience (Agustian & Seery, 2017; Bretz, 2019). This relationship is also consistent with the principles of Universal Design for Learning, which emphasizes flexibility, clarity of instruction, and accessibility as key prerequisites for quality learning for students with diverse backgrounds and abilities (Finnegan, 2024; Martin-Hansen, 2018).

The conceptual implication of these findings is the need to reposition pre-laboratory learning as a core component in the design of engineering laboratory learning, rather than merely a preliminary or administrative activity. By positioning pre-laboratory learning as an inclusive pedagogical intervention space, educational institutions have the opportunity to reduce disparities in student access and participation without always having to rely on costly and complex physical infrastructure changes. This approach is in line with the findings of Bunbury (2018) and Carabajal et al. (2017), which emphasize that inclusive instructional strategies can be an effective alternative in creating an equitable learning environment. In addition, this approach provides flexibility for lecturers and laboratory managers to adjust the learning design according to the context of the institution and the characteristics of the students.

Finally, this synthesis confirms that inclusive pre-practicum learning has strategic potential to drive a more human-centered and sustainable transformation of engineering education. This approach not only responds to the needs of students with disabilities, but also improves the quality, safety, and learning experience for all students. These findings

are relevant to the modern higher education development agenda that emphasizes sustainability, student welfare, and educational equity (Asghar et al., 2017; Bunce et al., 2021; Burwell, 2018). Thus, inclusive pre-practicum learning can be seen as an important pillar in the development of adaptive, safe, and human-centered engineering laboratories in an increasingly complex higher education era.

4. Conclusions

This study concludes that inclusive pre-laboratory learning is a key component in developing equitable, safe, and adaptive engineering laboratory learning for students with diverse needs, including students with disabilities. A synthesis of literature findings shows that structured, flexible pre-laboratory designs supported by learning technology can improve students' cognitive readiness, procedural understanding, and sense of safety before they are directly involved in technical and risky laboratory activities. These findings confirm that the main barriers to laboratory learning do not stem solely from the limitations of individual students, but are more often caused by pedagogical designs that are not inclusive and do not provide adequate preparation.

The main contribution of this study lies in the conceptual integration of pre-practicum learning, accessibility, and laboratory safety into a coherent and evidence-based pedagogical framework. Unlike previous studies that tend to separate the issues of inclusivity, learning effectiveness, and workplace safety as separate domains, this study shows that an inclusive pre-laboratory approach can bridge all 3 aspects simultaneously. By positioning pre-practicum as a strategic pedagogical intervention space, this study affirms that improvements in inclusivity and laboratory safety can be achieved without necessarily relying on significant physical infrastructure changes, thus offering a more efficient, flexible, and sustainable approach in the context of engineering education.

More broadly, the findings of this study contribute to strengthening the human-centered paradigm of higher education by placing inclusivity as a basic principle in laboratory learning design. Inclusive pre-practicum learning not only expands access and participation for students with disabilities, but also improves the quality of learning, work safety, and learning experiences for all students. Therefore, this approach is relevant to the objectives and scope of the journal, which emphasizes pedagogical innovation, equal access, and the development of sustainable higher education that is responsive to the diverse needs of students in the modern era.

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Author Contribution

K.A.M.: conceptualization, methodological, design of the study, investigation, data curation, formal analysis, validation process, managed the resources, drafting. The author has read and agreed to the published version of the manuscript.

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Not applicable. This study is a systematic literature review that exclusively analyzes data from previously published articles and does not involve human participants, animals, or interventions requiring ethical approval.

Informed Consent Statement

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Data Availability Statement

The data supporting the findings of this study are derived from publicly available scholarly articles included in the systematic literature review. No new primary data were generated or analyzed in this study. All data sources are cited within the manuscript, and the analyzed literature can be accessed through the respective publishers' platforms.

Conflicts of Interest

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During the preparation of this work, the author used ChatGPT to assist in improving language clarity, academic writing structure, and coherence of the manuscript. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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