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Beyond Braille: A Systematic Review of Assistive Technologies and Inclusive Pedagogy in STEM Higher Education for Students with Visual Impairments

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Abstract

Persistent reliance on braille and misconceptions about its role continue to influence discussions on inclusion for students with visual impairments in STEM higher education. This systematic qualitative review examines 52 peer-reviewed articles from an initial pool of 142, exploring how assistive technologies, Universal Design for Learning, and inclusive strategies improve students with visual impairments participation in STEM. Findings highlight the importance of accessibility, educator training, and interdisciplinary collaboration. The study recommends a multidimensional approach by combining haptic-tactile, auditory, and kinesthetic strategies with traditional teaching methods. Instead of using assistive tools alone, a comprehensive framework is proposed to meet these students diverse learning needs. Universal design for learning-guided resources such as audio materials, haptic-tactile graphics, and interactive content can enhance engagement and academic success. The review advocates for systemic reforms in higher education and equitable access to STEM in African and European settings. Future research should test inclusive models across STEM and non-STEM courses in various institutions and evaluate their long-term effects on learning and participation.

Keywords accessibility of assistive technologies; beyond braille; STEM higher education; visually impaired students

Background to the Study

Teaching students with visual impairments in science, technology, engineering, and mathematics (STEM) presents unique challenges because these disciplines rely on visual elements such as diagrams, graphs, spatial representations, and laboratory activities. Although STEM subjects promote innovation and critical thinking, their visual orientation can restrict full participation for students with visual difficulties.

Educators play an essential role in promoting inclusion, as their perceptions and instructional practices strongly influence learning outcomes (Kızılaslan et al., 2019; McDaniel, 2024). However, many VIs face persistent difficulties adapting visually complex materials such as mathematical symbols, experimental data, and spatial concepts into accessible formats that preserve accuracy and depth of understanding (Hong, 2021; Mukhiddinov & Kim, 2021; Nashleanas, 2021). This challenge intensifies when translating abstract or highly conceptual scientific ideas into non-visual formats that remain pedagogically meaningful (Rosenblum et al., 2018; Rosenblum & Herzberg, 2015).

Although various strategies including tactile models, auditory resources, speech-to-text applications, and built-in digital

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accessibility tools have been introduced to improve access for students with visual impairments in STEM, their implementation remains uneven and often insufficient. Research consistently points to limitations in educator training, institutional support, and curriculum design, which hinder the full integration of these resources into classroom and laboratory settings (Koehler & Picard, 2024; McDaniel, 2024).

Furthermore, most existing assistive technologies are designed for general accessibility rather than the discipline-specific demands of STEM education, resulting in persistent gaps in both theoretical and practical learning experiences. These shortcomings highlight the necessity of a comprehensive review of current assistive technologies and inclusive pedagogical practices to better understand their effectiveness and inform future innovations in STEM higher education.

Problem Statement

Despite the growing interest in multimodal adaptations such as tactile models, auditory tools, speech-to-text applications, and built-in digital accessibility features, their implementation for students with visual impairments remains inconsistent (Castaneda et al., 2025). These innovations are often constrained by insufficient tutor/teacher preparation, limited institutional support, and the absence of standardized inclusive curricula (Koehler & Picard, 2024; Quiño, 2024; Sharma et al., 2025; Shaw, 2023).

In addition, persistent infrastructural barriers in laboratories and research settings hinder full participation in STEM programs, underscoring the need for assistive technologies (ATs) tailored not only for general accessibility but also for the discipline-specific requirements of STEM education (Felicia et al., 2014; Supalo et al., 2014). While general ATs facilitate basic inclusion, STEM courses demand subject-specific adaptations that integrate adaptive tools into both theoretical and practical components of learning (Mukhiddinov & Kim, 2021; Supalo et al., 2014). This gap highlights the necessity of systematically reviewing current assistive technologies and inclusive pedagogical strategies to inform evidence-based practices in STEM higher education.

Purpose of the Review

This review synthesizes current literature on ATs and inclusive pedagogical approaches for students with visual impairments in STEM higher education. It examines accessibility gaps, educator preparedness, instructional limitations, and emerging alternative teaching strategies reported in the literature. In doing so, the review highlights the need for technological innovation and sustainable curriculum reforms that move beyond isolated accommodations toward integrated, discipline-specific solutions in higher education.

Accessibility challenges in STEM extend beyond instructional strategies to include infrastructural barriers. Laboratories, research spaces, and technological tools often lack the necessary modifications, limiting the participation of students with visual impairments (VIs) or the visually impaired students (VISs) in practical science and mathematics learning. Despite advances in inclusive practices, the visual intensity of STEM education through graphs, geometric figures, observations, and mathematical notation continues to hinder VIs' participation (Fichten et al., 2020; Montalbano et al., 2024).

Educators often struggle to adapt teaching methods that ensure accessibility and academic engagement, highlighting the need for targeted training and institutional support (Nashleanas, 2021; Rhoads et al., 2022). Proposed solutions include haptic-tactile models, auditory explanations, screen readers, and speech-to-text tools (Castaneda et al., 2025; Mukhiddinov & Kim, 2021); however, gaps persist in effectively embedding these approaches into STEM curricula (Felicia et al., 2014; Quiño, 2024; Rumjan et al., 2024).

Laboratory-based learning poses challenges, as hands-on experiments rely on visual observation and manipulation. While assistive tools, such as haptic-tactile devices, offer potential, their effectiveness is limited by high costs, availability issues, and the need for specialized educator training (Supalo et al., 2014; Quiño, 2024; Rumjan et al., 2024). Consequently, many educators feel ill-equipped, leaving students with VIs to rely on sighted peers or aides, which can compromise their independence (Pujaningsih et al., 2021; Quiño, 2024).

Institutional support remains vital but insufficient. Studies highlight inadequate professional development and resources for inclusive teaching (Koehler & Picard, 2024; McDaniel, 2024). Infrastructural barriers, particularly in laboratories and research spaces, further restrict participation (Bayar & Aggul, 2023; Quiño, 2024). Comparative studies have shown that, unlike non-STEM educators who often rely on textual or auditory adaptations, STEM instructors need to address the challenge of presenting spatial and quantitative information in accessible formats (Wild, 2013). Although inquiry-based approaches hold promise through active exploration and guided learning, they require institutional investment in faculty training and multimodal curriculum development (Lazar et al., 2020).

Recent research highlights the need for a comprehensive approach to STEM accessibility, integrating technological innovation, faculty training, and institutional policy reform. Researchers advocate for the use of ATs, such as haptic devices, tactile tools, screen readers, and tactile graphics, to enhance the engagement of students with VIs in complex STEM areas (Koehler & Picard, 2024; Mukhiddinov & Kim, 2021). Effective inclusion depends on sustained collaboration among general educators, special education professionals, and mobility specialists, reinforced by continuous professional development. These perceptions highlight the urgent need for curriculum reform, faculty preparedness, and institutional commitment to advancing truly inclusive STEM education.

Contextual Exploration

Building on this purpose, the next section presents a contextual exploration of STEM higher education environments, highlighting institutional, disciplinary, and technological factors that influence accessibility and inclusion for students with visual impairments. This examination considers how curricula, teaching practices, laboratory infrastructures, and available assistive technologies shape learning experiences, providing the necessary context for understanding the effectiveness and limitations of current inclusive strategies.

This systematic review (Alexander, 2020; Booth et al., 2016) analyzes 52 studies spanning qualitative, quantitative, and mixed-methods research from 2002 to March 2025, employing narrative analysis techniques (Braun & Clarke, 2012; Creswell, 2013). University educators are positioned as central agents in implementing and recommending Universal Design for Learning (UDL) frameworks (Borrego et al., 2025; Friedensen et al., 2021). However, a vital gap persists in the inclusion of disabled authors' positionality within STEM education research, particularly those with VIs. Moreover, many quantitative studies continue to adopt a deficit-oriented framing of disability, limiting critical engagement with the lived experiences of VISs in postsecondary STEM settings.

Despite broader movements toward inclusive education in higher education (National Center for Science and Education Statistics, 2023), non-sighted and VIs remain underrepresented in STEM areas (Chasen & Pfeifer, 2024). Most STEM learning environments still lack universally designed infrastructures and adequate accommodations to address the diverse needs of students (Bettencourt et al., 2018; Friedensen et al., 2021). This emphasizes the pressing need for research based on lived experiences and inclusive pedagogical strategies. Specifically, this review shows that educators' approaches to VIs differ across disciplines, with STEM instructors often viewing their subjects as more difficult to adapt for VIs, compared to their non-STEM counterparts who report fewer obstacles (McDaniel, 2024).

Sharma et al. (2025), Quiño (2024), and Shaw (2023) emphasize that educators' attitudes toward inclusion are shaped by their confidence and familiarity with inclusive practices. While some struggle due to limited training, others, aware of systemic ableism to actively implement inclusive strategies. Both studies stress the importance of institutional support through targeted training and adequate resource provision.

In the UK, Shaw's (2023) work on faculty beliefs about VIs in higher education reveals varied levels of self-efficacy. While some educators express cautious commitment, doubting their ability to meet VIs' diverse learning needs, others are confidently committed, yet they still call for additional training and resources.

A key concern is faculty preparedness in providing accessible materials such as audio content, enlarged text, and screen-reader-compatible formats (Quiño, 2024; Shaw, 2023). Shaw further argues that educators with greater awareness of ableism are more likely to adopt inclusive pedagogies, whereas those without such awareness risk reinforcing exclusion. Overall, committed educators acknowledge that institutional barriers, particularly insufficient training and resources, undermine effective inclusion.

Beyond Braille: Inclusive Strategies for Visually Impaired Students

Beyond Braille, this review explores inclusive strategies for VIs in STEM. Ghai et al. (2022) advocate for integrating low-cost ATs, such as Arduino UNO-based modules, to create inclusive science laboratories that enable independent learning through tasks involving measurement, spatial graphics, mathematical symbols, contrast, and color detection. STEM educators also emphasize the need for increased institutional funding to support the acquisition of adaptive laboratory equipment and ATs to improve accessibility (Fichten et al., 2020; Montalbano et al., 2024).

Further, Ramdoss et al. (2021) work with United States postgraduate VIs in online STEM programs reveals challenges including limited access to visual content, insufficient accessible materials, and inadequate real-time support. Nevertheless, digital accessibility standards and inclusive practices help reduce learning barriers, suggesting blended learning as a better alternative to online education. Non-STEM educators advocate for policy-driven curriculum modifications to ensure VIs' equitable participation in discussions and assessments (Bayar & Aggul, 2023), emphasizing that curricula must address the diverse learning needs of students.

Moreover, ATs are transformative in education for the VIs. Felicia et al. (2014) and Quiño (2024) have shown that assistive technology (AT) innovations enhance multimodal learning by integrating critical thinking, motivational tools, and adaptive platforms to ensure equal access. Castaneda et al. (2025) extended this view by advocating for sensory-based methods, audio-text, videos, high-contrast materials, and adaptive laboratory equipment in STEM to enhance participation and retention.

Kızılaslan et al. (2019) investigate how to make scientific concepts accessible for VISs using tactile and experimental materials. Their findings align with Supalo et al. (2014), who advocate for hands-on chemistry learning with tactile models, auditory descriptions, and specialized laboratory equipment. While Felicia et al. (2014) focus on theoretical assistive technology frameworks, studies including Castaneda et al. (2025) and Supalo et al. (2014) have demonstrated practical STEM applications.

Unmet Needs in Inclusive Teaching

Several studies highlight the need for inclusive STEM education for VIs (Jamali et al., 2022; McDaniel, 2024; Rumjan et al., 2024). The VIs encounter substantial impediments, particularly in STEM disciplines. Non-STEM subjects like literature, history, psychology, and the arts are generally more adaptable through tools including braille, audiobooks, and screen readers (Rumjan et al., 2024). Nonetheless, educators in these disciplines also report difficulties when visual media or emphasized text is absent. This expresses the need for inclusive strategies across all areas of study in higher education (Castaneda et al., 2025; Gazzaniga et al., 2022).

Concerns remain regarding the limitations of current accessibility tools and the potential loss of content specificity in adapted learning materials. Although ATs and inclusive practices offer promising interventions, VIs continue to face academic, social, and developmental obstacles in STEM disciplines (Bahreini, 2024; Castaneda et al., 2025; Gazzaniga et al., 2022; Shaw, 2023). By comparison, educators in non-STEM areas report greater confidence in supporting VIs largely due to the reduced dependence on visual instruction (Guanoluisa et al., 2022; Shaw, 2023). For example, English language educators frequently work with students with varying degrees of visual impairment. However, visual disability affects English language acquisition, limiting VIs' engagement compared to their sighted peers.

A study by Guanoluisa et al. (2022) in Ecuador revealed that VISs and their tutors held positive attitudes toward inclusive teaching, despite limited specialized training, practical strategies, and resources to support language learning. Ghai et al. (2022), Guanoluisa et al. (2022), and Shaw (2023) identified ongoing challenges toward inclusive teaching, including supporting diverse learning needs, insufficient faculty preparation, inadequate instructional resources, and classroom management difficulties. Institutional policies and support structures play a crucial role in shaping educators' perceptions of inclusion. Thus, non-STEM faculty tend to express more positive attitudes toward VIs in reading-intensive disciplines, while STEM faculty exhibit more varied perspectives.

A study by Ghai et al. (2022) unveiled that challenges in teaching VIs STEM subjects stem from inadequate pedagogy, limited resources, and negative teacher attitudes. These systemic issues often result in VIs being excluded from STEM pathways and redirected toward humanities, commerce, or vocational areas. This exclusion is further exacerbated by scarce adaptive materials and instructional strategies.

Global Gaps in Inclusive STEM Education for Visually Impaired Students or VIs

There is a critical need for more geographically diverse research on how educators support students with disabilities across STEM disciplines. Borrego et al. (2025) note that although progress has been made in the U.S., persistent gaps remain, particularly in understanding how non-sighted and VIs are supported globally, especially in chemistry and mathematics, and among students with neurodivergence or learning difficulties.

These gaps are especially pronounced in visually intensive disciplines such as physics, biology, and engineering, where conventional teaching methods and inaccessible laboratory environments present major hindrances to inclusion. United States court rulings, as reported in *Disability Compliance for Higher Education*, highlight these barriers while identifying effective accommodations. Addressing such issues requires the application of critical disability theories that challenge normative assumptions and prioritize inclusion grounded in lived experience. Collaborating directly with VIs can enrich theory and ensure practices remain contextually relevant and globally responsive.

Blended learning (BL) further supports accessibility through the integration of videos, audio, and high-contrast materials, expanding assistive technology applications across disciplines (Quiño, 2024; Sharma et al., 2025). In Taiwan, Chen et al. (2025) indicate that subject-specific modifications and interactive platforms enhance academic engagement and performance among students with disabilities in STEM areas. Their findings support the need for tailored, rather than generalized, inclusive frameworks.

Recent research also advocates for integrated, discipline-specific approaches to accessibility in STEM education (Alamri, 2023; Chidarikire et al., 2024; Fornauf & Erickson, 2020). Embedding adaptable technologies within curricula promotes inclusion and improves learning outcomes for VIs. However, educator preparedness continues to vary across disciplines. STEM instructors often struggle to adapt visual and laboratory-based content, while non-STEM educators face challenges in making text-heavy materials more engaging.

These issues call for targeted professional development, investment in ATs, and curriculum reform. Comparative studies further emphasize the need for discipline-specific strategies to support VISs effectively (Castaneda et al., 2025; Felicia et al., 2014; Supalo et al., 2014).

Although general assistive technology solutions can improve inclusion, STEM education demands multimodal, interactive approaches that combine hands-on learning with digital accessibility to enhance participation and academic achievement. Educators' lack of training remains a critical barrier, highlighting the need for focused professional development in inclusive pedagogy and technology-assisted instruction.

Integrating ATs and UDL for STEM Inclusion

Accessibility in STEM has evolved beyond traditional braille to include speech-to-text applications, real-time auditory feedback, and tactile-haptic devices (Abner & Lahm, 2002; Castaneda et al., 2025; Supalo et al., 2014). These innovations reflect a shift toward adaptable, integrated technologies designed to address diverse learning needs. Effective implementation requires a holistic approach that embraces inclusive, technology-driven pedagogies to equitable access for VIs in higher education.

The Universal Design for Learning (UDL) framework plays a critical role in promoting inclusive STEM environments. Iqbal et al. (2022), Meyer et al. (2014), and Opie (2018) highlight that providing multiple means of engagement, representation, and expression supports the diverse learning abilities of students, especially in technology and BL contexts.

Furthermore, Al-Azawei et al. (2016) unveil that the successful adoption of ATs is shaped by educators' attitudes, institutional support, and perceived usability, aligning with the Technology Acceptance Model. These factors express the need for professional development and systemic backing to embed AT in STEM instruction for VIs.

Recent advancements in multimodal sensory substitution and haptic feedback offer additional avenues for enhancing accessibility, enabling VIs to engage with complex STEM content through tactile and auditory means (Saal & Bensmaia, 2014). Together, these perspectives support the importance of interdisciplinary, learner-centered, and technology-enhanced strategies to advance inclusion and accessibility in STEM higher education.

Informed by the identified gaps in assistive technologies and inclusive pedagogies for students with visual impairments in STEM, the following research questions guide this review in examining current practices, challenges, and opportunities for enhancing accessibility and inclusion in higher education.

Research Questions

Drawing on the literature review, this study is guided by the following main research question (*MRQ*): How can inclusive pedagogical strategies enhance the participation of university STEM students with visual impairments? In addition, the review explores two supplementary research questions to further examine specific aspects of assistive technologies and inclusive practices.

1. What challenges do VIs face in accessing STEM courses and laboratory-based visual materials?
2. How effective are current ATs in supporting the learning and engagement of VIs in STEM higher education?

Methodology

This systematic qualitative review follows five stages (Table 1), with Stages 1–4 based on peer-reviewed literature. Stage 5, conducted by the lead author, involved a qualitative cross-examination of descriptors and phrases from the review to deepen understanding of the topic (Creswell, 2015).

Stages 1–4: Data Sources

Table 1 Stages and Activities for Descriptor Identification

Stages	Activities Exhibited for the Key Identifiers of Descriptors
Stage One	Electronic database search using ProQuest, EBSCOhost, SAGE Journals, ERIC, PubMed, Google Scholar, SpringerLink, Taylor & Francis, Emerald, Web of Science, Wiley Online, and PsycINFO (2002–March, 2025). The lead corresponding researcher identified 52 out of 142 articles meeting the criteria.
Stage Two	The lead and corresponding author reviewed abstracts and titles for key descriptors. Two researchers independently examined full texts and resolved disagreements through discussion.
Stage Three	The lead corresponding researcher reviewed abstracts and titles again for descriptors. Two researchers independently analyzed the full texts and resolved any disagreements through discussion.
Stage Four	The two researchers re-read and classified articles for descriptors using thematic qualitative narrative coding. They resolved disagreements through discussion.

A systematic search was conducted using STEM higher education databases, including ProQuest, EBSCOhost, Sage Journals, ERIC, PubMed, Google Scholar, SpringerLink, Taylor & Francis, Emerald, Web of Science, Wiley Online, and PsycINFO. Search terms/keywords identified included phrases such as 'ATs and adaptive instruction' or 'traditional instruction'; 'assistive laboratory setups' or 'hands-on learning spaces'; 'braille', 'visually impaired', 'visual impairment', 'low vision', or 'blind'; 'STEM higher education and VISs inclusion'; 'academic achievement in STEM'; and 'integrated pedagogical strategies in STEM', 'multimodal pedagogy', or 'modified ATs linked with curriculum'. Articles were first screened by title and abstract (Stage 2) and then reviewed in full (Stage 3) for discussion, analysis, and findings, with disagreements resolved through discussion between two researchers. The inclusion criteria were:

- Articles published in English peer-reviewed journals between 2002 and March 2025.
- Articles focus on inclusive and STEM education for VISs (undergraduate/postgraduate; non-sighted or low vision) in higher education contexts.
- Articles address STEM VISs without other disabilities unless synthesizing specific disorders.

The lead corresponding researcher defined the final criterion as challenges for VISs in STEM-inclusive higher education varying by impairment level (Nashleanas, 2021; Rhoads et al., 2022; Rosenblum et al., 2018). Stage three yielded 52 articles, re-read, and independently coded using thematic qualitative narrative analysis (Stage 4). Discrepancies were resolved through discussion, resulting in five main themes and 16 sub-themes: 'AI-driven voice assistants' or 'cloud-based platforms'; 'tactile educational materials and braille', 'auditory learning resources and ATs', or 'blended learning materials'; 'integrated assistive instructional technologies'; 'STEM and non-STEM disciplines' or 'discipline-specific'.

Initial Coding – Stage 5

Stage 5 involved a systematic background check of key descriptors and phrases generated in Stages 1 through 4, using initial coding procedures in line with Braun and Clarke's (2012) thematic analysis framework. This process identified 14 codes that were grouped into five themes and 16 sub-themes: two for integrated ATs and adaptive methods; two for multimodal BL and curriculum modifications; three for accessible laboratory setups and specialized equipment; two for integrated auditory, tactile, and kinesthetic elements beyond braille; two for traditional teaching strategies and physical accommodations; and three for insufficient educator professional preparation.

These codes were applied to 52 articles, with the study focusing on three main topics: 'Educator preparedness and inclusive practices'; (addressing inadequate training in ATs, limited adaptive teaching strategies, and inconsistent inclusive practices); 'accessibility gaps in STEM instructional materials'; (highlighting the scarcity of STEM-specific resources, missing curriculum adaptations, and over-reliance on visual materials), and 'interdisciplinary approaches for inclusive STEM education '; (emphasizing cross-disciplinary collaboration and multimodal learning). In total, all 52 articles discussed professional development gaps, 38 addressed STEM material accessibility, and 14 focused on interdisciplinary approaches.

A narrative analysis summary was created for each article following Braun and Clarke (2012), and Creswell (2013). After reassessing eligibility, five articles under 'Faculty Training and AT Use' and two under Interdisciplinary Approaches for Inclusive STEM Education were excluded due to insufficient methodological details, leading to contradictions. Stage five also conducted a systematic background check of descriptors and phrases, using initial coding based on Braun and Clarke (2012) to identify 14 keywords from Stages 1–4. These were grouped into five themes and 16 sub-themes: two under integrated ATs and adaptive methods, two under multimodal BL and curriculum modifications, three under accessible laboratory setups and specialized equipment, two under integrated auditory, tactile, and kinesthetic elements beyond braille, two under traditional braille and physical accommodations, and three under insufficient educator professional preparation.

These initial codes were combined using 52 articles identified in Stages 1–4. As themes emerged, the study focused on three topics: 'Educator Preparedness and Inclusive Practice Challenges' which includes insufficient professional training in AT use, the limited adaptation of teaching strategies for VISs, and inconsistent implementation of inclusive practices; 'Accessibility Gaps in STEM Instructional Materials' covering inadequate STEM-specific accessible learning resources, limited curriculum adaptations including tactile models and auditory resources, over-reliance on visual materials and misconceptions about braille use; and 'Interdisciplinary Approaches for Inclusive STEM Education' emphasizing collaboration across disciplines, integration of ATs (e.g., haptic devices, AI tools), and promotion of multimodal learning.

All articles reported inadequate professional development in using ATs, with 38 addressing accessibility gaps and 14 focusing on interdisciplinary approaches. A narrative analysis was conducted following Braun and Clarke (2012), and Creswell (2013). Upon reevaluation, five articles under 'Faculty Training and AT Use' and two under 'Interdisciplinary Approaches for Inclusive STEM Education' were excluded due to insufficient methodological information.

Participants and Instruments

The articles often reported participant numbers, with 34 studies detailing sample sizes ranging from 2 to 223, including control groups when applicable. Of the 52 reviewed articles, nine focused on a single STEM discipline, and 43 incorporated multiple studies with varying participant counts. In particular, no reported participants' age or gender aspects were included, as the focus was on VIs in STEM programs.

In addition, 43 articles indicated that some or all participants came from low-income households, and all expressed that participants had visual impairments, with most identified as first-generation university students. These findings emphasize the need of inclusive education and further research to promote greater awareness and equitable access for VISs in STEM higher education.

Qualitative Thematic Analysis

Analysis of the literature was structured around four primary phases based on the research questions that guided the review: The main research question (*MRQ*) consists of the specific challenges VISs encounter in accessing STEM content, particularly laboratory-based and visual learning materials; research question one (*RQ1*) deliberates on the effectiveness of current ATs and adaptive pedagogical approaches in enhancing the academic experiences and outcomes of VIs in STEM; and research question two (*RQ2*) considers how ATs and inclusive pedagogical strategies can improve the participation and academic success of VISs in STEM higher education.

All 52 of 142 articles underwent analysis with predetermined codes assigned to the attributes such as; 'availability of tactile models,' auditory resources', 'curriculum adaptations', 'over-reliance on visual aids', 'braille misconception as an accessible medium', 'accessible STEM content', 'haptic-tactile devices and emerging AI tools', 'adaptive pedagogical approaches', 'preparedness of educators and interdisciplinary approach'.

Eleven articles were reviewed, highlighting concerns about moving away from relying solely on braille to incorporating adaptive methods into broader teaching practices. An inductive coding approach was used to create categories that captured both unintended actions and the impacts of inconsistent teaching strategies. These categories included the effectiveness of ATs, adaptive teaching approaches, and differences in educator training for curriculum modifications that support VIs in STEM education.

Descriptions related to VIs' experiences in visually intensive environments were analyzed. For example, studies by Kim (2017), Rhoads et al. (2022), and Rosenblum et al. (2018) reported challenges with audio-assistive technology, including issues with test validity, technical problems, and the stigma associated with AT use. All 52 articles expressed concerns about how higher education tutors develop skills to foster inclusive STEM education without segregation.

The next phase involved inductive coding to analyze educator readiness and inclusive practices in interdisciplinary STEM education (*RQ2*). Twenty-five articles were reviewed to identify and code key descriptors of VIs' experiences and challenges, including educators' perspectives. Discrepancies between researchers were resolved through discussion, following Braun and Clarke (2012). In the final phase, codes were organized to explore challenges faced by educators and VIs in STEM higher education.

Themes and patterns were identified by examining similarities and differences, and the analysis was refined using Creswell's (2013) concept of lean coding, consolidating useful categories. The lead and corresponding researcher restructured classifications, proposed a conceptual framework for inclusion, and identified additional datasets aligned with emerging themes, and disagreements were moderated in consultation with the second author.

This study scientifically presented the findings from the literature review, organizing them according to emerging categories. The findings were carefully associated with these categories to ensure coherence. Divergences identified in the literature encompassed key areas, including challenges in accessing STEM content, re-evaluating the effectiveness of ATs and adaptive instructional strategies beyond braille, educator preparation and inclusive practices, and interdisciplinary approaches to support VIs in STEM disciplines. The theme development was guided by a synthesis of the coded data, with both authors thoroughly reviewing and reflecting on the identified codes and corresponding data examples to ensure consistency with the established categories. The synthesized summaries were validated through the corroboration of recurring themes for addressing the study's three research questions.

Results

The findings are presented in four stages based on the research questions where new datasets occurred and disagreements were resolved, accounting for the four stages. First, following M*RQ,* emerging themes occurred regarding challenges that impede VISs' accessibility in STEM education.

Challenges in accessing STEM content: A thematic analysis of the selected studies reveals some recurring challenges in accessing STEM content knowledge. Accessibility gap in STEM instructional materials is the most recurring. The literature frequently pointed out a scarcity of accessible learning resources tailored to STEM disciplines, including the limited availability of tactile models, auditory resources, and other curriculum adaptations that could be alternatives to predominant visual materials.

Furthermore, many studies highlight the over-reliance on visual learning aids, which was accompanied by misconceptions about braille use as the sole accessible medium. These findings suggest that both the quantity and the quality of accessible STEM content are insufficient to meet the diverse learning needs of VIs, impeding their full participation in laboratory and other visually intensive learning environments. In their 2024 study on improving STEM accessibility for VIs, Koehler and Picard express the importance of supporting educators in adopting assistive technological tools; describing that using screen readers, tactile graphics, and 3D models can enhance VIs' understanding and engagement with complex STEM concepts.

Second, the review highlights the integration of ATs to improve the effectiveness of instructional strategies, extending beyond the sole reliance on braille (*RQ1*).

Effectiveness of ATs and adaptive pedagogical approaches: The review further examined the impact of current ATs and adaptive pedagogical approaches relating to the learning experiences and academic outcomes of VIs.

The analysis of data indicates that while ATs, haptic devices, and emerging digital tools hold promise for creating more inclusive learning environments, their effectiveness is often constrained by inadequate integration with broader pedagogical strategies. For instance, students with visual impairments use ATs including screen-reading software (e.g., JAWS, NVDA) and screen magnification tools, to access digital content. These technologies enable users to navigate and interact with computers and the internet effectively using tactile graphics and 3D models to facilitate tactile representations of visual information; enhancing understanding of complex diagrams and spatial concepts in science and mathematics (Australian Disability Clearinghouse on Education and Training, 2025; Kim, 2017; Rosenblum, et al., 2018; Stone, 2020; Supalo et al., 2014).

The findings indicate that teaching strategies, when integrated with pedagogical technologies and a systematic curriculum, can alleviate challenges associated with inaccessible STEM content, such as daily tasks, navigation, reading, and object identification. Hersh (2020) emphasizes that ATs are central for promoting inclusive education and enhancing accessibility for VISs, including those with other learning difficulties, especially in STEM disciplines. The study highlights the need for equal access to digital tools and educator training. Although technologies including screen readers, braille displays, and voice-assisted software support the daily learning needs of VISs beyond traditional braille, their use in STEM education remains inconsistent (Memeo et al., 2021).

This misalignment between assistive tools and formal STEM curricula extends educational disparities, highlighting the need for institutions to adopt a standardized approach to integrating these technologies (Memeo et al., 2021). Although resources, including screen readers, refreshable braille displays, speech-to-math converters, and accessible laboratory equipment, are available, their implementation in STEM learning environments remains unused (Kim, 2017; Memeo et al., 2021; Rosenblum et al., 2018). This inconsistency is attributed to inequalities in educator training and the extent to which formal curricula are adapted to accommodate these technologies, limiting their effectiveness. Furthermore, adaptive technologies and methods improved accessibility in isolated aspects of the curriculum but failed to address systemic challenges, underlining the need for a more holistic approach to inclusive STEM education.

Research question two (*RQ2*) examines how faculty preparedness influences inclusive STEM learning for VISs and students in traditional and virtual environments. Educator readiness is key to successful inclusive STEM education. The analysis identified three interrelated challenges under the theme: *Educator preparedness and inclusive practice challenges:* Emerging subthemes include; 'insufficient professional training', 'limited teaching strategies', and 'inconsistent inclusive practices.

The review findings reveal that many educators reported insufficient training in AT use and strategies to modify STEM content. Additional findings show that while educators recognize the need for VIs adaptations in STEM education, institutions often lack the resources and support needed for effective implementation. This absence of institutional backing and professional development leads to inconsistent application of inclusive methods (See & Advincula, 2021).

Limited training in using ATs further reduces their impact, particularly in visually intensive STEM courses where alternatives are often difficult to provide. Challenges are also compounded by inconsistent assessment procedures and support for students with cerebral visual impairment (Lueck et al., 2023). Poon and Ovadia (2008) suggest that a blend of technologies and traditional methods (blended learning) can enhance accessibility and improve pedagogical interaction.

Blended learning (BL) approaches pose some challenges, such as technology adjustments, content adaptation, and communication barriers. Insufficient educator training in inclusive teaching often contributes to unintentional exclusion, requiring increased attention (Castaneda et al., 2025; Kızılaslan et al., 2019). Standardizing terminology, assessments, and support systems is vital for equitable STEM education. Inequalities in the availability of AT use persist, with some Australian universities failing to effectively integrate tools including screen readers and text-to-speech software, while inadequate tutor training limits their benefits.

At the graduate and postgraduate levels, VIs' silently encounter barriers to academic progress due to limited access to advanced ATs and digital resources despite basic digital literacy. While educators recognize the value of digital use, gaps in training persist (Hewett et al., 2019; Quiño, 2024). Educators with higher qualifications are more likely to integrate ATs, while older educators show more resistance (Quiño, 2024). Prioritizing professional development programs in higher education is essential to enhance educators' competencies in using ATs, benefiting VIs, and students with learning disabilities. This aligns with the need for faculty training to promote inclusive instructional environments.

The final session of *RQ2* explores the impact of an interdisciplinary approach to inclusive STEM education, highlighting themes including 'collaboration across disciplines', 'advanced technology integration', and 'promotion of multidimensional instruction'. Combining perspectives from areas including engineering, computer science, chemistry, and education, institutions can better design and implement effective ATs.

In summary, this study highlights the potential of tactile-haptic devices and other emerging tools as part of a multidimensional learning model to address diverse learning ability needs. Integrating tactile, auditory, and kinesthetic modalities with traditional methods creates a more inclusive learning environment in higher education. While advancements in ATs and pedagogical strategies are promising, a wide-ranging approach addressing material accessibility, educator training, and interdisciplinary collaboration is essential for the meaningful inclusion of VIs in STEM. Promoting resources beyond braille, including audio materials, tactile graphics, and interactive digital content, is critical for bridging accessibility gaps and enhancing VIs' academic experiences in STEM disciplines.

Discussion

Beyond Braille: Emerging Technologies in Inclusive STEM Education

This study examines findings from stages one to four in response to the research questions outlined in the review. Stage one focused on accessibility challenges that the VIs face in acquiring STEM knowledge, particularly academic engagement (*MRQ*). Stage two explored the integration of ATs to improve instructional approaches beyond braille (*RQ1*). Stage three assessed educator readiness and inclusive practices (*RQ2*), while stage four examined interdisciplinary approaches to support inclusion.

The findings align with existing literature, highlighting effectiveness of haptic-tactile devices and emerging technologies when used as part of a multidimensional model. The study also underlines ongoing challenges for VIs in STEM education due to inaccessible instructional materials and visually dependent learning environments (Sandoval, 2023; Thurston et al., 2017). However, recent research suggests that multimodal learning approaches can effectively mitigate these impediments (Alnahdi, 2020; Fichten et al., 2020; Restianty et al., 2024; Tennison et al., 2024; Tobin & Behling, 2018).

Integrating auditory, tactile, and kinesthetic elements to produce multidimensional learning models enhances content retention and understanding for VISs (Mayer, 2020; Phutane et al., 2022; Tennison et al., 2024). Moving beyond the traditional practice of converting visual materials into braille text, this approach promotes more dynamic and inclusive learning environments, allowing VISs to engage with STEM concepts through innovative, multi-sensory experiences (Kana & Hagos, 2024; See & Advincula, 2021; Thurston et al., 2017).

Interdisciplinary Collaboration in Inclusive STEM Pedagogy

Interdisciplinary collaboration is essential for improving inclusive pedagogical practices. Montalbano et al. (2024), Phutane et al. (2022), and Tennison et al. (2024) emphasize the importance of integrating cognitive science, disability studies, and educational psychology to develop instructional methods that prevent exclusion. This approach helps create learning environments tailored to the needs of VISs.

Studies by Seo et al. (2024) and Lindvig et al. (2025) demonstrate that collaboration among educators, technology developers, and disability experts enhances teaching aids, while Ibrahim (2015) highlights its role in promoting leadership and knowledge sharing. This current study views interdisciplinary learning as fostering collaboration, innovation, and participation. Building on Lara et al. (2022), it frames this approach as inclusive STEM education for all, extending beyond braille to include tactile-haptic graphics, technological resources, and adaptive platforms for engaging with complex STEM content.

Educator Preparedness and Assistive Technology Gaps

Impediments in educator preparation and the implementation of inclusive teaching practices in STEM for VIs remain a primary concern. A key barrier is insufficient professional development in using ATs. Many educators lack the skills and confidence to integrate these tools, limiting accessible learning opportunities. This supports earlier research calling for all-inclusive training to build educators' competence (Hong, 2021; Fichten et al., 2020; Montalbano et al., 2024; Sandoval, 2023; Thurston et al., 2017).

Although tools like screen readers, braille displays, speech-to-math converters, and accessible laboratory equipment exist, their use in STEM curricula is inconsistent. Hong (2021) also reveals that limited faculty training reduces the effectiveness of these technologies in enhancing student academic outcomes.

A promising technology highlighted in current literature is the use of haptic devices, which allow users to interact with digital content through touch. Memeo et al. (2021) explore the use of haptic feedback in geometry courses for VISs, showing that touch-based interaction with three-dimensional models greatly enhances spatial awareness and understanding. Additionally, studies by Koehler and Picard, (2024), Phutane et al. (2022), Reynaga-Peña et al. (2019), and Tennison et al. (2024) highlight that haptic technologies can be beneficial in STEM subjects, including physics, chemistry, mathematics, and engineering, where spatial reasoning and 3D visualization are indispensable.

Furthermore, technological advancements have facilitated the development of technology-driven assistants that offer context-sensitive support to VISs. For instance, Alper and Raharinirina (2006), Nourian et al. (2024), and Phutane et al. (2022) report on the use of technology-based voice recognition systems to help VIs navigate academic materials in real-time improve accessibility. These systems not only provide navigation support but also read and describe complex visual elements, including graphs and charts, enabling students to comprehend academic content that was previously inaccessible.

Similarly, Tennison et al. (2024) provide evidence for integrating touchscreen technology into curriculum materials to support multimodal learning for students with blindness and low vision. In their study, 20 VIs identified touchscreens as more engaging and easier to use than traditional print graphics when interpreting bar charts and geometric figures in mathematics and science.

These findings suggest that touchscreen-based content can improve understanding of graphical information. Aligning such tools with curriculum materials enables interactive, accessible learning. Additionally, combining audio feedback and tactile interactions through touchscreen features supports VISs to navigate and interpret visual data in STEM disciplines (Phutane et al., 2022; Restianty et al., 2024; Reynaga-Peña et al., 2019; Tennison et al., 2024).

Enhancing STEM Accessibility through Multisensory Learning

The findings reinforce the effectiveness of multisensory approaches in making STEM content more accessible to VISs, aligning with existing literature on inclusive learning strategies. Reynaga-Peña et al. (2019) examined an interdisciplinary project in Mexico that focused on designing inclusive STEM materials for students with disabilities.

Findings emphasized the value of adjustable resources to enhance accessibility and student engagement. This supports Tennison et al. (2024), who identified that students with blindness and low vision preferred touchscreen technology for accessing graphical content. Echoing Reynaga-Peña et al.'s call for inclusive tools, this study highlights the potential of integrating touchscreen technology and multidimensional instruction into curricula to support understanding. These studies collectively highlight the need for diverse, flexible learning materials to promote a more inclusive and interactive STEM education for all.

Despite the promise of innovation, some studies express that interdisciplinary collaboration can be resource-intensive and lack consistent institutional support. Lara et al. (2022), Lindvig et al. (2025), Seo et al. (2024), and Thurston et al. (2017) detail that integrating educational technologies into higher education requires strong institutional commitment and funding. Without this, such innovations risk being unused. Such findings underscore the need for systematic integration of these tools into educational curricula-policies and teaching frameworks to ensure long-term adoption and impact.

Conclusion and Implication for Future Studies

Inclusion of students with visual impairments (VIs) in STEM higher education is shaped by four key factors: The integration of haptic-tactile and emerging technologies within multimodal learning environments; persistent gaps in inclusive pedagogical practices; limited faculty training; and weak interdisciplinary collaboration. Addressing these challenges requires moving beyond braille-centric approaches toward inclusive, technology-integrated strategies grounded in blended learning (BL) and Universal Design for Learning (UDL) principles.

Assistive technologies including tactile, haptic, and AI-enhanced devices, show significant potential when combined with BL and UDL-informed strategies to enhance accessibility and foster equitable STEM participation for students with VIs.

Future research should center the voices of students with VIs through participatory, empirical studies involving both students and academic staff. Mixed-methods investigations across diverse cultural and institutional contexts, encompassing STEM and non-STEM courses at the postsecondary level, are essential to inform inclusive practices tailored to varied disciplinary and local learning needs.

Author Contributions

Conceptualizations, Methodology; Formal analysis, discussion and investigation; Writing - original draft preparation; Writing - review and editing: [Gladys Ami Allotey]. Supervision: [Prof Benedetto Di Paola]. This article is primarily based on the PhD dissertation of Gladys Ami Allotey. The first and corresponding author conceived the study, conducted the literature search and data analysis, and was responsible for drafting and critically revising the manuscript, and hence the principal author.

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Competing Interests

The authors declare that there is no conflict of interest

Ethical Approval Statement

This study was conducted following the Academic Integrity Code of University of Palermo-Italy.

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