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Bridging the Gap: How Universal Design for Learning Can Transform Biology Education – A Systematic Review

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Abstract

Despite significant advancements in pedagogical models, Biology education still relies on the one-size-fits-all teaching methods that overlook the diverse needs and strengths of learners. This impacts students with diverse learning needs and abilities, contributing to disengagement and a decline in motivation. The Universal Design for Learning (UDL) framework offers a promising alternative by promoting inclusivity through multiple means of representation, engagement, and expression. This systematic review explores how UDL has been applied in STEM education, particularly Biology, using the updated CAST 2024 UDL checkpoints as an analytical framework. Ten peer-reviewed studies published between 2020 and 2025 were selected and analyzed following PRISMA guidelines. The review identified three recurring themes: choice, variety, and technology. These themes highlight effective strategies such as gamified assessments, digital tools, and differentiated learning tasks that support inclusivity and student engagement. While promising, the findings also reveal gaps in implementation, especially in underused UDL checkpoints related to feedback and self-regulation. This review emphasizes the importance of aligning instructional design with UDL principles to foster inclusive, student-centered Biology education.

Keywords: *Universal Design for Learning (UDL); biology education, inclusive pedagogy; differentiated instruction; educational technology; STEM education*

INTRODUCTION

Even though teaching and learning have experienced significant advances and extensive research into multiple pedagogical models, the general education classroom continues to operate under a one-size-fits-all approach (*Financial Times*, 2024; Hall et al., 2012; Meyer et al., 2014). In many classrooms, a single teacher delivers uniform instruction, assigns standardized tasks, and assesses students through a singular approach, regardless of the diverse abilities, needs, strengths, and challenges within the learning environment (CAST, 2018; Tomlinson, 2014). This rigid structure often leads to disengagement, as students who struggle to understand receive insufficient support, while those who excel are left unchallenged (Darling-Hammond et al., 2020; *New York Post*, 2023).

Such a standardized model directly contradicts Sustainable Development Goal 4 (SDG 4), which advocates for inclusive and equitable quality education and the promotion of lifelong learning opportunities for all (UNESCO, 2023). A one-size-fits-all paradigm marginalizes diverse learners and inhibits progress toward global educational equity. One STEM subject that remains affected by this uniform approach is Biology. Despite its relevance to everyday life and vast career opportunities, the enrolment in Biology courses at high schools globally has experienced a notable drop (Ramsurrun et al., 2025; Rumjaun et al., 2022), including in Malaysia. A significant factor contributing to this decline is conventional teaching methods which are more lecture-focused (Aguiar & Calabrese, 2025; Hymers & Newton, 2019). Furthermore, the existing single-mode assessments worldwide, does not align with SDG 4's call for inclusive and equitable education (Garcia & Weiss, 2020; UNESCO, 2022). Globally, STEM assessments still lack differentiation which hampers student interest and motivation and fails to accommodate diverse learning needs (Kaya et al., 2021; Thoma et al., 2023; Zhang et al., 2024).

To tackle these issues, there is an increasing necessity to move away from didactic methods and to reconsider the design and delivery of Biology, and STEM education in general. The inability to support various learners highlights the increasing demand for more adaptable, inclusive models (Flood et al., 2023). A promising strategy is the Universal Design for Learning (UDL) framework, which promotes multiple methods of engagement, representation, and expression to meet the needs of diverse learners (Meyer et al., 2014). Incorporating UDL principles into Biology education allows educators to move beyond the rigid, one-size-fits-all approach and create opportunities for active participation and personalized learning pathways.

UDL aligns closely with several SDG 4 targets, including Target 4.5 (eliminate disparities in education and ensure equal access for vulnerable populations) and Target 4.A (build inclusive and effective learning environments) (UNESCO, 2023). By nurturing autonomy, equity, and personalized learning pathways, UDL enables education systems to shift towards more responsive pedagogical approaches. Other than that, UDL also aligns to other SDGs. For instance, SDG 9 (Industry, Innovation, and Infrastructure) by encouraging the use of educational technology and innovative teaching methods to create more flexible, resilient learning environments. UDL also contributes to SDG 10 (Reduced Inequalities) by removing barriers for marginalized learners, including those with disabilities, from low-income backgrounds, or facing language and cultural differences.

Moreover, classrooms are growing increasingly diverse. The presence of neurodivergent students such as those with autism spectrum disorder (ASD), ADHD, dyslexia, and other cognitive profiles, strongly encourages the need for inclusive instructional design. No two students experience learning in the same way. Hence, neurodivergent learners often face barriers in traditional learning (Ramos Aguiar et al., 2023; Roski et al., 2024). The UDL framework provides a proactive approach to addressing this variability by anticipating learner needs and accommodations (Bray et al., 2024; Flood et al., 2023). By embedding flexibility, choice, and scaffolded supports into instruction, UDL enables all students to engage with content, process information, and demonstrate understanding in meaningful ways. Thus, UDL is not merely a pedagogical enhancement but a foundational strategy for achieving equity in STEM education (CAST, 2024; Montgomery et al., 2024).

OBJECTIVES OF THE REVIEW

The objectives of this review are threefold: to examine how UDL checkpoints are applied within selected STEM studies, to identify and analyse recurring instructional themes that support inclusive learning, and to explore existing gaps in UDL implementation that hold implications for advancing inclusive practices in Biology education.

Therefore, this review is guided by the following research questions:

1. To what extent are Universal Design for Learning (UDL) checkpoints applied in STEM-related studies, particularly in Biology education?
2. What recurring instructional strategies align with UDL principles in STEM classrooms, and how do they support inclusive teaching practices?
3. What implementation gaps exist in current UDL-based STEM interventions, and what implications do these gaps hold for future inclusive Biology education?

LITERATURE REVIEW

Introduction to Universal Design for Learning (UDL)

The UDL framework challenges the traditional one-size-fits-all approach that still dominates many general education classrooms (Boysen, 2021; Novak, 2024). UDL advocates flexible instructional strategies that accommodate varying learning needs, abilities, and preferences. UDL ensures that all students, regardless of their background or learning profile, have equitable access to meaningful learning experiences (Flood et al., 2023; Hovey et al., 2022). This shift from rigid, standardized instruction to an inclusive, learner-centered model is essential for fostering deeper engagement and improved outcomes in education. Table 1 provides a structured overview of the three core principles of UDL: Multiple Means of Representation, Multiple Means of Engagement, and Multiple Means of Expression.

Table 1

UDL Principles and Examples Adapted from CAST (2024).

UDL Principle	Description	Example
Multiple Means of Representation	Presenting content in various formats to accommodate different learning styles.	Text, videos, infographics, hands-on models, audio explanations.
Multiple Means of Engagement	Encouraging motivation and interest through choice and relevance.	Gamification, real-world applications, self-paced learning.
Multiple Means of Expression	Allowing students to demonstrate knowledge in diverse ways.	Essays, presentations, digital storytelling, projects, gamified quiz.

Adopting UDL in STEM Education

UDL has gained significance as a framework to support inclusive and differentiated pedagogy, particularly in content-heavy and cognitively demanding disciplines such as STEM. Studies have shown that UDL improves engagement and learning outcomes in science (Edyburn, 2020), chemistry (King-Sears et al., 2020), and engineering (Basham et al., 2020). According to Edyburn (2020), UDL offers a proactive design approach that benefits not only students with disabilities but all learners through structured flexibility. Furthermore, CAST (2021) emphasized that applying UDL in STEM education promotes autonomy, enhances accessibility, and supports mastery learning. Similarly, Montgomery et al. (2024) argue that UDL-aligned instruction fosters scientific skills development and active learning, particularly in Biology classrooms that traditionally rely on passive delivery.

Recent studies have also begun exploring the practical application of UDL in secondary Biology contexts. For instance, Thoma, Farassopoulos, and Lousta (2023) implemented UDL-aligned STEAM activities in primary science settings, emphasizing early inclusion and differentiated instruction. Likewise, Ramos Aguiar et al. (2023) utilized gamified and extended reality tools grounded in UDL to support learners with visual and developmental impairments in science-based learning. Although limited, these examples reflect a growing recognition of UDL's potential to transform traditional science classrooms into accessible, engaging, and learner-centered environments.

With STEM classrooms becoming increasingly neurodiverse (Ramos Aguiar et al., 2023; Roski et al., 2024; Zhang et al., 2024), the present mainstream STEM curricula that still rely heavily on standardized testing and single-modal delivery, fails to accommodate this diversity (Ewell et al., 2023; Zhang et al., 2024). Previous studies show that neurodivergent learners are often underrepresented and underserved in science and technology courses, leading to lower engagement, higher attrition, and significant equity gaps (Flood et al., 2023; King-Sears et al., 2020). This mismatch between learner diversity and instructional design highlights an urgent need for inclusive frameworks like UDL (CAST, 2024; Montgomery et al., 2024). Without such shifts, STEM education risks perpetuating systemic exclusion rather than fostering innovation and equal opportunity. Without these changes, STEM education may continue to exclude many learners instead of promoting fairness and innovation

In addition to this, adopting UDL into STEM aligns with broader educational improvement agendas such as the United Nations' SDG goals specifically, SDG 4 and SDG 9. For example, Bray et al. (2024) highlighted how technology-based UDL tools foster participation among marginalized students, while Zhang et al. (2024) emphasized the framework's potential to close achievement gaps in diverse classrooms. These findings affirm that adopting UDL in STEM instruction does more than improve academic performance; it contributes to building a more inclusive, innovative, and sustainable education system.

Gaps in UDL-Based STEM Education and Implementation

The present research has found that the implementation of UDL in STEM remains limited and uneven. Many interventions adopt surface-level strategies, like offering student choice, without addressing deeper supports such as self-regulation, mastery feedback, or metacognitive development (Bray et al., 2024; Zhang et al., 2024). Most studies continue to rely on the older CAST 2018 guidelines, missing out on the equity-focused, tech-integrated structure of the 2024 update. Even when UDL is referenced, its application often lacks fidelity or systematic alignment to checkpoints, making impact measurement difficult (Flood et al., 2023; Parker et al., 2020). Neurodivergent learners are also underrepresented in STEM-focused UDL research, despite being among the most marginalized by traditional methods. Finally, while technology holds great promise for UDL, its integration is inconsistent, often hindered by infrastructure gaps, cost, or lack of teacher training (Montgomery et al., 2024; Ramos Aguiar et al., 2023). These gaps show the need for deeper, more inclusive UDL adoption tailored to the complexity of STEM education.

Another significant and often overlooked gap in UDL-based STEM education lies in the continued reliance on rigid, summative assessment practices. Traditional assessments, dominated by timed, text-heavy, and standardized formats, are fundamentally misaligned with UDL principles (CAST, 2024). As Ewell et al. (2023) and Aguiar and Calabrese (2025) highlight, such one-size-fits-all evaluations fail to capture the full scope of student understanding, particularly for neurodivergent learners and those with diverse cognitive, linguistic, or sensory profiles. This mismatch not only hinders equity but also limits meaningful engagement and deeper learning. Without a parallel reform in how learning is assessed, even well-designed UDL instruction risks falling short of its inclusive potential. Therefore, reimagining STEM assessments to include multimodal responses, authentic tasks, and continuous feedback is not just a pedagogical enhancement, it is a necessary shift toward educational justice and deeper conceptual mastery.

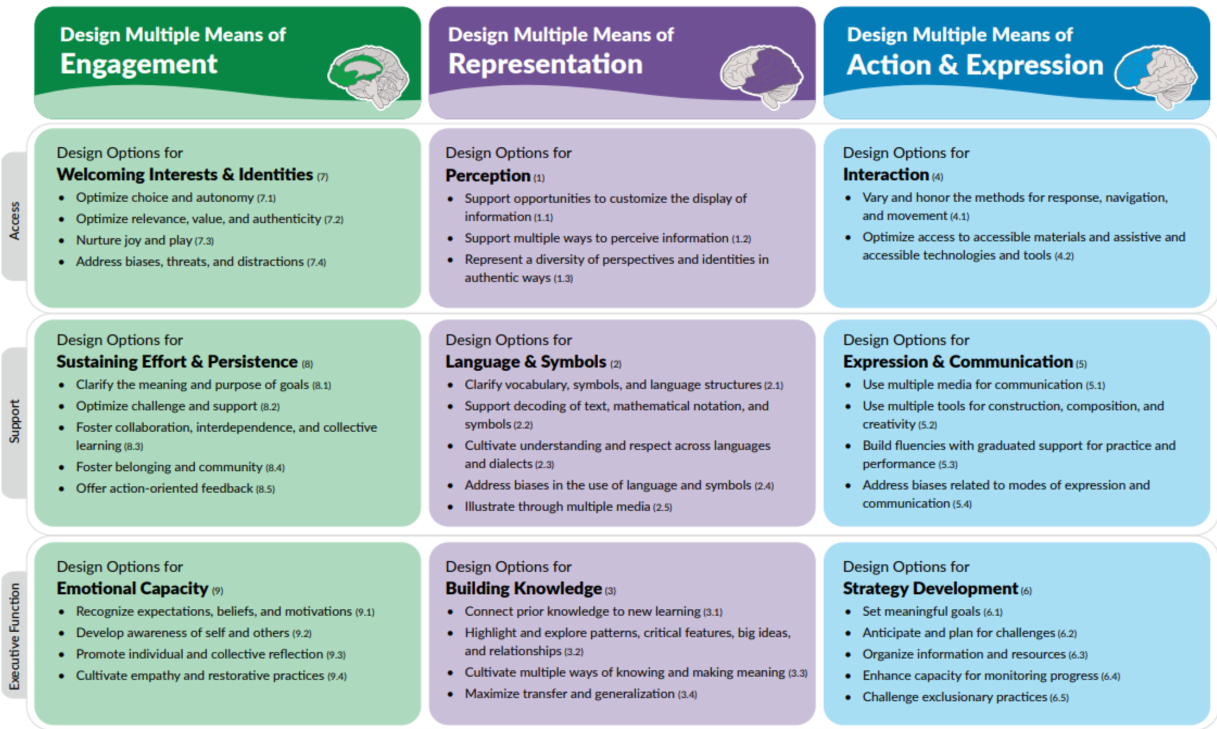
Checkpoint Alignment in UDL Literature

The three core principles of UDL are further divided into checkpoints. Checkpoints refer to specific, actionable strategies within each of the three UDL principles that guide educators in designing flexible, equitable learning experiences (CAST, 2024). Other systematic literature reviews that examined UDL have primarily relied on the CAST 2018 version (v2.2) of checkpoints in their analysis, such as Bray et al. (2024) and Zhang et al. (2024). However, as educational contexts continue to evolve, so too has the framework guiding inclusive instructional design.

In 2024, CAST released an updated version (v3.0) that restructured and clarified the checkpoints, placed greater emphasis on equity, self-regulation, and technology integration, and reorganized some of the guideline groupings to reflect current educational priorities. These additions are directly related to SDGs 4, 9, and 10. The most recent version of the UDL framework, CAST 2024 (v3.0), is summarized in Figure 1.

Figure 1

The Universal Design for Learning Checkpoints (v3.0) by CAST (2024)



Footnote: Reproduced with permission from CAST (2024) under Creative Commons CC-BY-NC-SA 4.0 licence

As the present review focuses on the 2024 UDL checkpoint, it is important to note the differences and evolution between the CAST 2018 and CAST 2024 checkpoints. Table 2 shows a comparison of the two versions based on the themes of technology, choice and variety.

Table 2

CAST 2018 vs CAST 2024: Evolution in Technology, Choice, Empathy, and Variety

Category	CAST 2018 checkpoint	Cast 2024 Checkpoint
Technology	Tech was present (e.g., basic accessibility tools, LMS, early immersive tech like VR being introduced) but not deeply embedded everywhere yet.	Massive tech integration: AI, AR/VR, advanced UDL-based platforms, personalized learning environments, and better accessible design.
Choice	Choice was advocated, especially in learning paths and engagement options, but practical examples were sometimes limited.	Big emphasis on learner autonomy: customizable pathways, multiple modes of expression, lots of “build-your-own-experience” sessions.
Variety	Some variety in session types (panels, lectures, workshops), but most sessions still leaned traditional.	Huge variety: micro-workshops, immersive experiences, panels, asynchronous options, hackathons, live design labs.

While UDL promises inclusiveness, flexibility, and differentiation, further research is needed to determine the most effective ways to implement this framework in practice. Understanding how UDL can be strategically applied is essential to truly challenge the prevailing one-size-fits-all approach in education. UDL holds immense potential but remains underexplored in STEM education. When effectively understood and applied, UDL can engage a diverse range of students in general education Biology classrooms. Hence, this systematic review examines how UDL can transform STEM education, particularly Biology, by fostering student engagement, improving accessibility, and enhancing learning outcomes for all learners.

METHODOLOGY

Review Methodology

This study employs a systematic literature review (SLR) approach to examine the integration of the UDL framework in STEM education, particularly in Biology. The review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This guideline ensures transparency, rigor, and reduces potential bias (Page et al., 2021).

Based on the objective, this SLR addressed gaps in previous UDL-related reviews, which often lacked subject specificity, used outdated checkpoint frameworks, or provided only surface-level analysis. This review builds on that foundation by first conducting a descriptive analysis of selected STEM-related studies. Each study was then systematically aligned with the updated CAST 2024 UDL checkpoints to examine the extent and depth of UDL integration. A cross-study comparison was conducted to evaluate the instructional strategies used, highlighting both successes and limitations in implementation. Finally, a thematic analysis was performed to identify recurring patterns and key themes.

Identification Phase

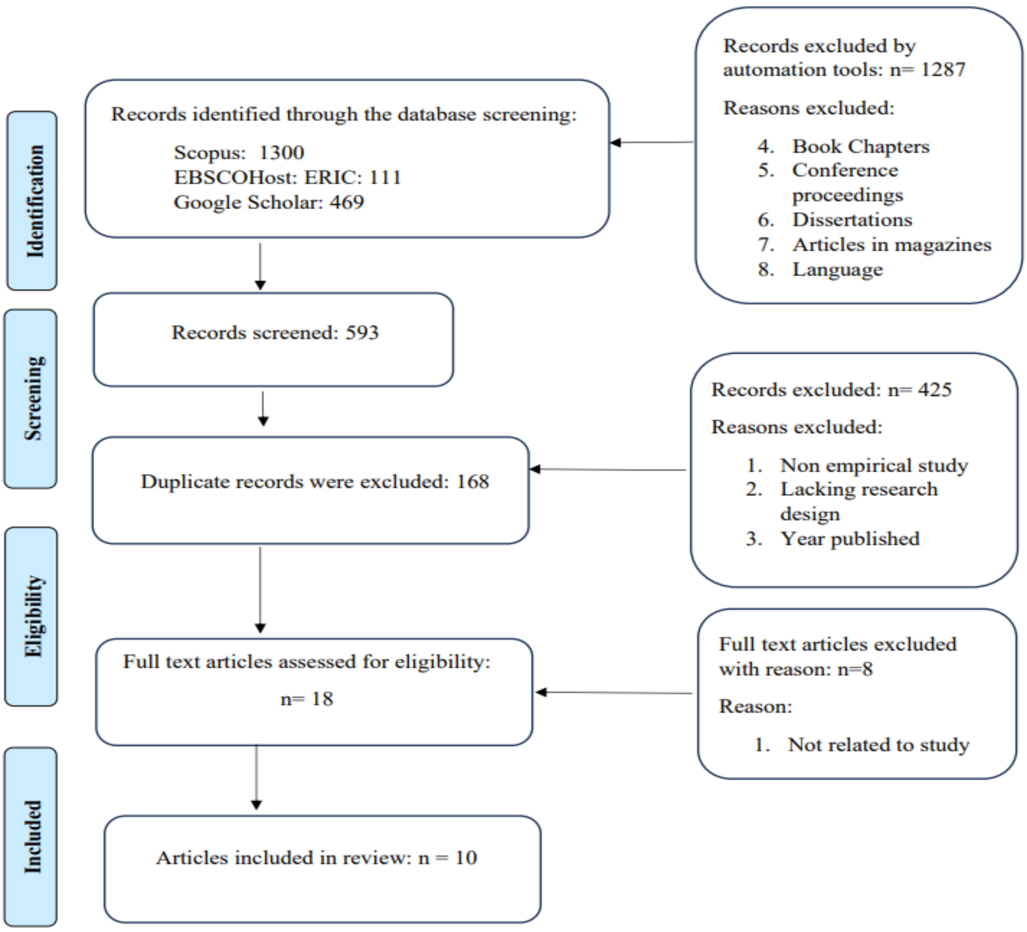
In the identification phase, a comprehensive search was conducted to retrieve relevant literature from a range of academic databases including Scopus, ERIC, and Google Scholar. These databases were selected to capture a wide spectrum of interdisciplinary research across education, science, and pedagogy. Scopus includes a vast range of peer-reviewed articles from prominent publishers like Elsevier, Wiley, Springer, and MDPI, ensuring access to high-quality research across various disciplines. ERIC was chosen for its extensive database of education-related resources, which is ideal for academic research in this field. Google Scholar offers a wide range of scholarly articles, including theses, books, and conference papers, making it a versatile tool for research. Moreover, Google Scholar was used to identify any overlooked literature and to ensure all pertinent articles were identified.

The Boolean Operator technique (AND) was applied using keywords such as "Universal Design for Learning AND Biology" and "UDL AND Biology education" to retrieve relevant studies. To ensure the relevance and quality of the selected studies, only peer-reviewed journal articles and conference papers were considered. The preliminary search revealed a lack of studies exclusively targeting high school Biology education, necessitating the inclusion of research from various subject areas under STEM education where UDL principles were implemented.

The scope was broadened to include interdisciplinary studies in STEM education such as Chemistry, Sciences, Mathematics, Information Technology, and others, as UDL principles are universally applicable. Hence, a new search string was used, incorporating Boolean operators: "Universal Design for Learning" AND "STEM education", "UDL" AND "inclusive pedagogy", "UDL" AND "science education", "differentiated instruction" AND "STEM". All searches were conducted using the abstracts of the articles, and the search criteria were matched against the screening criteria. In total, studies meeting the inclusion criteria were analyzed. The PRISMA flow diagram in Figure 2 illustrates the article selection process.

Figure 2

PRISMA Flowchart



Screening Phase

In the screening phase, titles and abstracts were reviewed to determine relevance based on predefined inclusion criteria. The following criteria were applied sequentially to the article abstracts: (1) studies must be published between 2020 to 2025; (2) studies must be published in a scholarly journal; (3) studies must have employed UDL teaching approaches; (4) studies must be quantitative (quasi-experimental) design or mixed method. Studies not written in English or not focusing on UDL in STEM education were excluded. The initial database search yielded 1880 records. These articles were then screened as previously defined and duplicates were removed, and a total of 168 articles were forwarded to determine the eligibility.

Eligibility

During the eligibility phase, the full-text articles of shortlisted studies were carefully reviewed to determine their suitability for inclusion in the final synthesis. The evaluation focused on whether each study explicitly addressed the integration of UDL in STEM education, particularly in the context of Biology. Priority was given to studies that presented empirical data or well-defined conceptual frameworks related to UDL. Additionally, eligible studies needed to discuss specific instructional strategies, implementation methods, or educational outcomes associated with UDL practices. Articles that only made cursory mentions of UDL without providing in-depth analysis or relevant data were excluded. As a result of this detailed screening, a total of ten studies were deemed eligible and included in the final analysis.

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the studies included in this review, specific inclusion and exclusion criteria were applied. Studies were included if they focused on the application of the UDL framework within STEM education contexts and were published in peer-reviewed journals between 2020 and 2025. Both empirical studies and conceptual papers were considered, provided they offered substantial discussion on UDL strategies, implementation practices, or outcomes. Articles had to be published in English and accessible in full text. Conversely, studies were excluded if they lacked a clear focus on UDL, did not pertain to STEM, were opinion pieces or editorials, or were not peer-reviewed. Duplicates and conference abstracts without full papers were also excluded from the final review.

The review included studies that examined any aspect of the impact of UDL principles within a STEM educational context. No specific participant population was predefined, as long as the subjects were engaged in some form of academic activity. Studies that reported on cognitive, affective, behavioral, or qualitative learner outcomes were included. In contrast, studies with methodological flaws or those that did not demonstrate any measurable impact on learners were excluded. After applying these criteria, ten articles were selected for final analysis.

DATA ANALYSIS

Analysis of Previous Reviews

The present SLR builds on the work of previous authors who have conducted reviews on UDL implementation, such as Al-Azawei et al. (2016), Bray et al. (2024), Rusconi and Squillaci (2023), Schreffler et al. (2019), and Zhang et al. (2024). While these earlier SLRs provided valuable insights into UDL perceptions, framework applications, and impacts on learner performance and accessibility, there remain significant gaps in the literature. Table 3 shows a summary of past reviews.

Table 3
A Summary of Past Reviews

Author	Year published	Articles from	Content area	No of Articles chosen	Analysis focus	Sample details	UDL Checkpoint Analysis	Limitations
Al-Azawel, A. et al.	2016	2012-2015	Various	12	Measuring learner perceptions; Performance evaluation; Curricula alignment with UDL principles	Students with & without disability	✗	Not STEM-specific; No relation to UDL checkpoints
Schreffler, J., et al.	2019	2006 onwards	STEM	4	Methods using UDL framework in STEM post-secondary majors	With disability only	✗	No UDL checkpoint analysis; Postsecondary only
Rusconi, L., & Squillaci, M	2023	2000-2021	Various	12	UDL on lesson accessibility and student attitudes	NA	✗	Focused on teacher education and professional development, not general education students; No UDL checkpoint analysis.
Zhang, L., et al.	2024	1999-2023	various	32	Cognitive, motivational, and behavioral impacts; Specific UDL checkpoint focus	NA	✅ (2018 checkpoints)	Not STEM specific; UDL checkpoint is 2018 version
Bray, et al.	2024	2007-2020	various	15	Technology use within UDL framework; Specific UDL checkpoint focus	Mainstream; SEN students	✅ (2018 checkpoints)	Technology focus; Not STEM specific; UDL checkpoint is 2018 version

Numerous studies have explored the Universal Design for Learning (UDL) framework, yet few offer subject-specific guidance, particularly for secondary STEM education. While reviews by

Al-Azawei et al. (2016) and Parker et al. (2020) underscore UDL's promise in inclusive and postsecondary settings, they do not examine how the three core UDL principles are integrated within specific STEM subjects. Similarly, reviews by Schreffler et al. (2019) and Rusconi and Squillaci (2023) rely on the earlier CAST 2018 guidelines and lack checkpoint-level analysis, limiting their practical utility for educators. As shown in Table 3, past reviews often provide broad thematic insights but rarely offer structured mapping aligned to specific UDL checkpoints.

In response, this review narrows its focus to secondary STEM classrooms and adopts the updated CAST 2024 checkpoint framework to provide a more targeted and practical analysis. This approach also addresses concerns raised by Zhang et al. (2024), who noted that many UDL interventions remain superficial, emphasizing choice without embedding deeper cognitive and metacognitive supports. Bray et al. (2024) further highlight the lack of professional development supporting meaningful UDL implementation, especially around mastery-oriented feedback and student self-assessment. Together, these findings point to a need for more rigorous, subject-aligned studies to guide effective UDL practices in STEM education.

Descriptive Analysis of Studies Reviewed

To provide a comprehensive understanding of the included studies, the contextual characteristics were analyzed. This analysis included factors such as sample size, research methodology, content area assessed, and the types of participant population. Mapping these contextual features helped identify patterns and gaps in how UDL is integrated across diverse STEM educational settings. Table 4 is a summary of the context across synthesized studies.

Table 4

Descriptive Profile of Included Studies

Aspects	Specifics	Percentage
Sample size	<10	10 %
	10 to 100	20&
	101 to 1000	70%
Research method employed	Quasi Experimental Design	20%
	Mixed methods	70%
	Other (design based)	10%
Subject content	STEM education	30%
	Chemistry	20%
	Science	20%
	Mathematics	10%
	Biology	10%
	Engineering	10%
Student Population	Only students with disabilities	10%
	Only students without disabilities	50%
	Mixed populations	40%
Disability Types	Autism spectrum disorder	7.15 %
	Other health impairments (Eg ADHD, blindness)	21.4%
	Other Learning disabilities	14.3 %
	Dyslexia	14.3%
	Emotional disorders	14.3%
	Not specified	35.7%

Studies were coded multiple times when information provided on types of disability fell under multiple categories.

Alignment of Selected Studies to UDL 2024 Checkpoints

Table 5 presents an analysis of how UDL principles and checkpoints were applied in the selected studies. While the studies included in the systematic literature review referenced UDL principles in the design of their interventions and instruments, explicit alignment with the detailed checkpoints was often not clearly articulated. Therefore, this review conducted a deeper analysis to map the implementation of 26 individual UDL checkpoints based on CAST 2024, across the selected studies. This approach aimed to uncover recurring themes and best practices, offering valuable insights into effective UDL implementation within STEM education contexts.

The alignment analysis of the selected studies against the UDL checkpoints revealed interesting patterns as certain checkpoints were consistently addressed, while others were notably underrepresented. The most commonly aligned checkpoints were 6.4 (Enhance capacity for monitoring progress) and 9.1 (Promote expectations and beliefs that optimize motivation), each appearing in 9 studies. These emphasize the importance placed on developing learner motivation and prioritizing reflective practices. Similarly, 6.3 (Facilitate managing information and resources), 5.3 (Build fluencies with graduated levels of support), and 4.2 (Optimize access to tools and assistive technologies) each appeared in 8 studies, indicating that resource accessibility and strategic scaffolding are common priorities in UDL-aligned STEM programs.

Next, a noteworthy finding is that checkpoints related to assessments and how students express what they have learnt, appeared only once or twice. This includes 9.4 (Develop self-assessment and reflection), 8.5 (Offer feedback) and 7.4 (Increase mastery-oriented feedback). The underutilization of these checkpoints reflects a broader misalignment between UDL pedagogy and traditional assessment practices in STEM. The lack of flexible assessment reinforces inequalities for students who learn and demonstrate understanding in different ways. Without rethinking how learning is assessed, even well-designed inclusive instruction may fall short in fostering meaningful student progress. Checkpoints like 5.2 (Use multiple tools for construction and composition) and 7.2 (Optimize relevance, value, and authenticity), with only two studies each, also indicate limited integration of a variety of expression tools and personally meaningful contexts.

Engagement-related checkpoints (e.g., 7.1–9.4) and strategic learning checkpoints (6.1–6.5) appeared more frequently than those related to representation (1.1–3.4). This could reflect a shift in focus toward empowering learners through motivation, self-regulation, and choice rather than solely varying content presentation. That said, checkpoints 1.1 and 6.1, each aligned in 8 studies, show that customizing information presentation and guiding goal setting are still key entry points for UDL implementation.

Overall, the review suggests a strong emphasis on building learner autonomy, motivation, and strategic learning capacity, but also reveals that some checkpoints, such as self-reflection, mastery feedback, and multiple modes of construction remain underexplored. This mapping exercise not only identifies trends in current practice but also highlights underutilized checkpoints that warrant more attention in future UDL-STEM research, particularly those that support executive functioning, emotional regulation, and deeper student autonomy.

Following Table 5, Table 6 presents the cross-study analysis conducted as part of this systematic literature review. This table provides a detailed synthesis of the key findings across the selected studies, highlighting the various engagement strategies employed to support UDL implementation. Additionally, it outlines the limitations acknowledged in each study and identifies gaps in relation to specific UDL checkpoints. This analysis serves to pinpoint areas where further research or practical attention is needed to enhance the effectiveness and comprehensiveness of UDL application in educational settings. Due to space constraints, the references in both Table 5 and Table 6 are denoted numerically (e.g., [19], [28] etc). Full APA-style citations can be found in the reference list.

Table 5

Alignment of UDL Checkpoints to Selected Studies

Author, Alignment to guidelines	**Alignment on UDL Checkpoints**																																			
	Multiple means of representation												**Multiple means of expression**											**Multiple means of engagement**												
	Perception			Language & symbols					Building knowledge				Interaction		Expression & Communication				Strategy Development					Interests & identities				Effort & Persistence					Emotional capacity			
	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	5.1	5.2	5.3	5.4	6.1	6.2	6.3	6.4	6.5	7.1	7.2	7.3	7.4	8.1	8.2	8.3	8.4	8.5	9.1	9.2	9.3	9.4
[20]	√	√	√			√		√		√	√		√	√	√		√		√		√		√	√					√			√			√	
[16]	√	√	√			√	√	√		√	√	√		√	√		√	√	√		√				√	√				√	√	√				
[15]				√	√				√	√									√		√			√			√	√		√	√		√	√		√
[19]		√	√	√	√			√	√	√	√		√		√	√	√	√			√	√		√	√	√	√	√	√			√	√			
[26]	√		√	√	√			√		√	√	√		√	√		√		√			√	√	√	√	√		√	√					√		√
[21]	√								√					√	√		√		√				√								√		√			
[29]	√	√	√	√	√		√	√	√	√	√	√	√	√	√	√			√	√	√			√				√	√	√	√			√		
[28]	√							√			√	√	√	√	√		√	√	√	√	√		√	√	√		√		√	√		√	√			
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No. of aligned checkpoints	8	6	7	6	5	2	4	8	5	6	8	4	6	8	9	4	6	3	9	3	7	3	5	8	5	6	3	5	6	6	4	5	5	4	1	2

Cross-Study Analysis: Successes, Limitations, and Gaps

Table 6
Cross Study Analysis of Selected Studies

Study	Key findings/ success	Engagement/ inclusion strategy	Limitations	UDL checkpoint gaps
[20]	• UDL-MI (Universal Design for Learning - Multiple Intelligences) oriented STEM program significantly improved students' attitudes towards STEM. • Positive attitudes were sustained over time, even during the follow-up test.	• UDL-MI successfully addressed diverse learning needs of rural students. • Multiple intelligence theory provided varied instruction (e.g., visual, verbal, kinaesthetic), engaging students meaningfully. • Experimental group showed higher levels of engagement and enthusiasm.	• Sample Scope: (n= 122) rural learners in Malaysia. • Short Duration of 10 weeks, which may not reflect long-term behavioural or academic changes. • Minimal mention of technology-enhanced learning tools, which is important for full UDL use.	• 7.2: Content was designed around environmental themes, the authentic connection to real-life local issues for rural learners was not deeply discussed. • 5.2: Students lacked technological tools or digital platforms to demonstrate knowledge in diverse ways (e.g. digital storytelling, simulations). • 8.1: The goals of the activities were not always made explicit to learners. • 6.4: Limited focus on self-regulation strategies or teaching learners to track their own learning
[16]	• UDL application boosted access and participation for learners with disabilities. • Teachers showed increased responsiveness to diverse needs. UDL fostered more proactive instructional planning	• Emphasized flexible materials, engagement options, and assessment alternatives. • Embedded accommodations within whole-class instruction. • Promoted choice and scaffolding to increase engagement.	• Mainly qualitative insights; limited quantitative evidence. • Lack of long-term impact data. • UDL was implemented in varying degrees across classrooms (inconsistency).	• 9.3**:** Limited evidence of students being taught to reflect on their learning. • 6.4**:** Lack of tools or support for students to track or manage their own progress.
[15]	• Active learning boosted learners' academic achievement. • Students developed more positive attitudes towards biology. • Higher classroom interaction and	• Employed discussion-based activities, group work, and hands-on tasks. • Promoted active student participation through problem-solving and inquiry.	• Strategies were applied broadly without personalization for varying needs. • The role of feedback in shaping learning was not discussed	• 1.2: Little mention of providing multiple means of input for diverse learners. • 5.3: Lacked differentiation for learners needing additional scaffolding. • 7.2: While engagement was active,

	motivation reported	• Encouraged collaboration and peer explanation to enhance understanding		connections to real-life contexts were underexplored.
[19]	• Students developed scientific reasoning, inquiry, and critical thinking skills. • UDL-based redesign removed common barriers to engagement for learners with disabilities and those from underrepresented groups. • Increased student autonomy and ownership over learning tasks	• Students had choices in how to access material, complete assessments, and collaborate. • Redesign used LMS tools, discussion boards, video lectures, and self-paced modules. • Scaffolded Skill Building	• Implementation was shaped by pandemic conditions only. • Students with limited access to digital tools or internet may have been disadvantaged. • Success depended on individual instructors' familiarity with UDL.	• 1.1: Some students still struggled to personalize formats for accessibility. • 4.2: Not all learners had equal access to the redesigned tools. • 9.3: While autonomy increased, structured reflection and self-monitoring were inconsistently embedded. • 6.3: No specific strategy for helping students organize materials or track progress independently.
[26]	• Effective inclusion of blind and Autistic Learners • Tangible interfaces and XR elements enhanced engagement and access. • Participants displayed high motivation, boosted attention, and better learning outcomes. • The study applied UDL in designing multisensory learning environments tailored to neurodiverse and visually impaired learners	• Gamification and tangible Interfaces increased interaction and enjoyment. • Extended Reality (XR) provided immersive experiences tailored to sensory needs. • Personalized learning paths adapted to the unique profiles of learners.	• Small sample size, limiting generalizability. • Required specialized technology and training. • Lacked long-term follow-up to assess sustained learning	• 1.2 - Visual elements were strong but auditory supports for blind users were not detailed. 2.3 –No mention of supports for interpreting complex symbolic language. 5.2 –Focused more on consumption than active composition by learners. 9.1 –Engagement was high but strategies to foster learner confidence and growth mindset were not described.
[21]	• Students reported greater comprehension and satisfaction when using video capsules. • Increased Engagement & Flexibility due to multimedia usage	• Video capsules with multiple modalities to support diverse learning preferences. • Interactive questions and real-world problems were integrated within the videos.	• Lack of Real-time Interaction or peer interaction. • Design and production require time and technical expertise. • The direct impact of video capsules on academic	• 6.3 –Study did not address how learners organized or applied information over time. 7.3 –No clear evidence of strategies to manage cognitive load 8.1 –Learning goals were not always

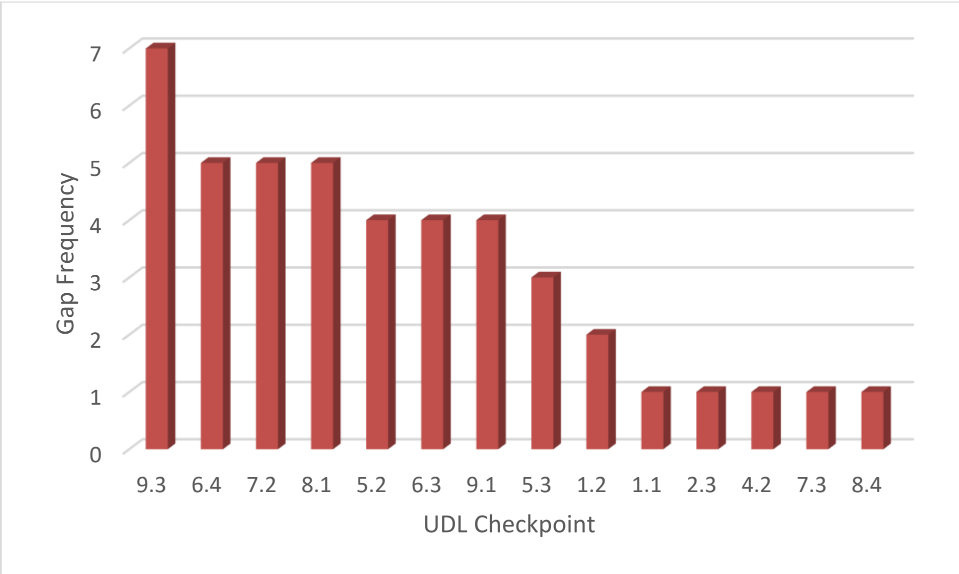
	• Self-paced learning • The incorporation of UDL was seen as effective in improving inclusivity and access	• Videos were designed with subtitles, clear audio, and structured layouts	performance was not extensively measured	explicitly reinforced • 9.3 –Reflection strategies or learner self-monitoring tools were not included.
[29]	• Clustering techniques enabled more personalized UDL use. • Tailored feedback and support strategies enhancing access and performance. • Use of analytics allowed aligned learning experiences with UDL through evidence-based design	• Collected behavioral and performance data to segment learners and adapt content accordingly. • Emphasis on differentiated pathways and materials depending on learner cluster profile. • Analytics-informed instructional adjustments were embedded in online learning environment	• Study was more conceptual and lacked long-term use results on student achievement. • Use of detailed learner data raises ethical considerations. • Clustering approach may not translate well across different subjects or educational contexts	• 5.3 –Scaffolding for skill development was not detailed. 6.4 –Self-monitoring tools were not implemented. 7.2 –Customization based on clusters didn't necessarily align tasks with learners' interests. 9.1 –Little discussion on how the personalized feedback influenced learners' self-efficacy or expectations.
[28]	• Students and educators built empathy of diverse needs. • Long-term personal narrative reflects continuous integration of UDL	• Collaborative Learning and Co-Teaching • Students were involved in shaping curriculum and assessments. • Both teacher and learners engaged in regular reflective practices. • Learning goals were personalized and adaptive	• Practices may not be generalizable across institutions. • Resource-Intensive • Co-creation and reflection require time and support structures	• 6.4 –Reflections were present but lacked structured tools for self-assessment. 8.1 –Goals were flexible but not always explicitly tied to performance outcomes. 5.2 –Specific digital or multimodal tools not described.
[33]	• Mobile App Design for Science Learning promoted flexibility and engagement • App used gamification, multimedia, and interactive tasks to explain science concepts. • App structure reflected UDL, including multiple means of engagement and representation	• Students could choose tasks, pace, and feedback. • Personalized Learning Paths enabled differentiated instruction via mobile interface. • Integrated video, simulations, quizzes	• Focused on app development, not learning outcomes. • Accessibility limited for learners without mobile devices. • Role of teacher in app integration was not fully detailed	• 8.4 –Feedback was not deeply formative or student-directed. • 9.3 –App lacked structured tools for reflection or metacognitive growth. • 7.2 –Contextual relevance of science tasks not elaborated.

[34]	• Demonstrated success using both unplugged (hands-on) and plugged (digital) activities. • Fostered social learning through networked experiences • Designed to address neurodiverse learners' needs.	• Combined physical tasks, storytelling, tech tools, and collaborative games. • Varied peer interaction based on learner needs. • Applied assistive technology and tangible objects.	• Focused more on engagement than achievement. • Requires teacher training in UDL pedagogy.	• 6.3 –Learner supports for organizing materials were not detailed. 8.1 –Learning objectives often implicit, not explicit. 9.1 –Motivation was fostered through activity, but beliefs about learning weren't systematically addressed.

Figure 3 shows the frequency of under-addressed UDL checkpoints across the reviewed studies created based on the data in Table 4.5 on the cross study. This graph illustrates the frequency with which each UDL checkpoint emerged as a gap, providing a clearer understanding of recurring weaknesses in implementation. This helps highlight areas that require greater attention in future UDL-based STEM interventions.

Figure 3

UDL Checkpoints Gap Frequency



DISCUSSION

Unpacking UDL: Key Themes for Inclusive STEM Education

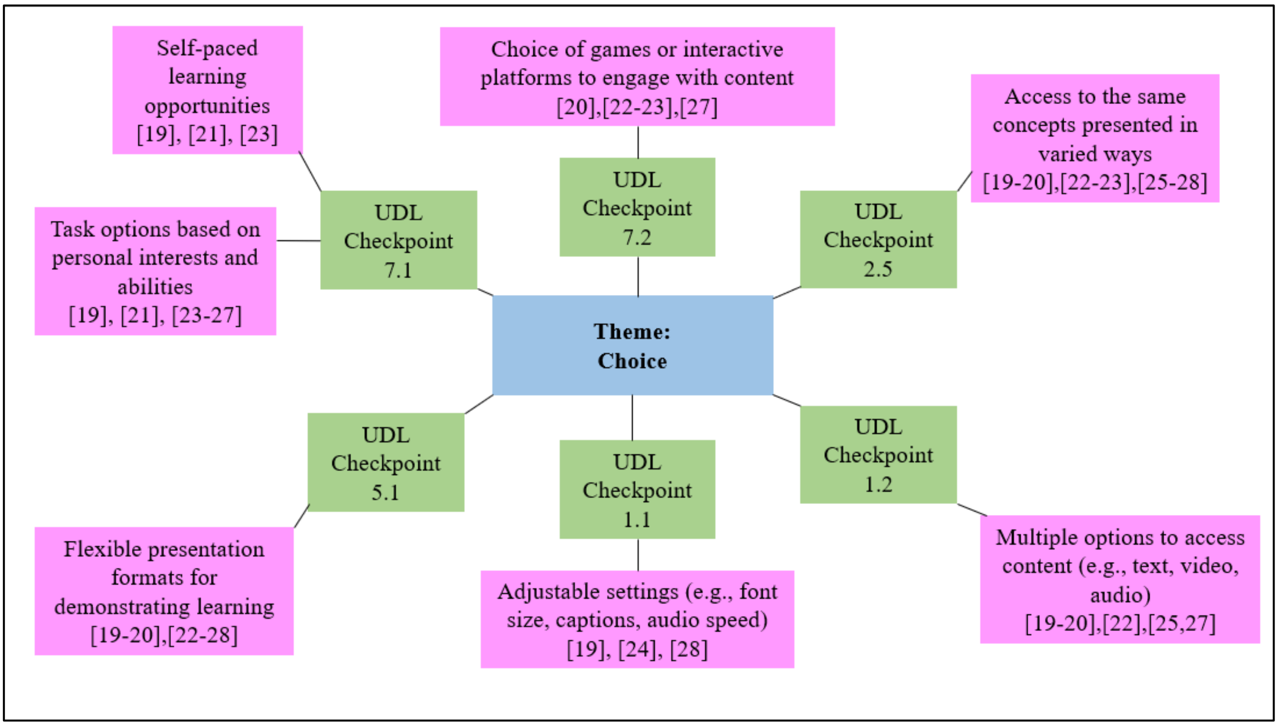
Following the checkpoint alignment, the next stage aimed to explore recurring themes across the studies. This thematic analysis was conducted to better understand how the aligned UDL checkpoints were reflected in real classroom strategies and teaching approaches within STEM education. Three key themes surfaced: Choice, Variety, and Technology.

The elements highlighted in Figure 4 reflect practical applications of the choice theme across the reviewed studies. Each element aligns with specific UDL checkpoints, offering insight into how learner autonomy and personalization were embedded in UDL-based STEM interventions. The concept map captures various ways choice was embedded across the reviewed studies.

The theme of choice continues to be a cornerstone in UDL-based STEM education (CAST, 2024; Hall et al., 2012). Many of the reviewed studies highlighted strategies allowing students to select learning tasks, formats of content consumption (text, video, audio), or modes of assessment. This aligns closely with highly utilized checkpoints such as 7.1 (Optimize individual choice and autonomy) and 7.2 (Optimize relevance, value, and authenticity). The importance given to these checkpoints confirms that offering learner agency is not only conceptually supported but practically implemented across multiple interventions.

Figure 4

Concept Map of Choice Theme



Next, Figure 5 illustrates the theme of variety, which emerged as a key feature in how UDL was implemented across the reviewed studies. The elements in the map, such as gamified assessments, video and audio formats, simulations, and collaborative tasks, reflect the intent to cater to diverse learning preferences, abilities, and strengths. These strategies were commonly included to remove barriers, sustain engagement, and ensure students had multiple ways to access content and demonstrate understanding (Boysen, 2021; Meyer et al., 2014). By offering varied formats and approaches, the studies aimed to create more inclusive and flexible STEM learning environments. Variety is essential in differentiated learning, as it challenges the one-size-fits-all approach by offering multiple means of engagement and expression to accommodate diverse learners (Hall et al., 2012; Tomlinson, 2014).

Finally, Figure 6 presents the theme of technology, which was consistently integrated across the reviewed studies to support flexible, inclusive, and engaging learning environments. The use of static resources like PDFs and slides, interactive platforms such as simulations and gamified apps, and assistive features like captioning and font adjustments reflect purposeful design to accommodate diverse learner needs. Additionally, centralized systems like Learning Management Systems (LMS) were employed to streamline content delivery and organization. These technological features are valuable in Biology education, where abstract and dynamic processes can be difficult to visualize through traditional methods. Interactive platforms like simulations and gamification can promote deeper conceptual understanding by allowing students to manipulate biological systems, observe outcomes, and receive immediate feedback (Thoma et al., 2023). Assistive tools such as captioning and customizable displays also support neurodivergent learners, ensuring that all students can meaningfully engage with complex content.

These technological elements align with core UDL principles by enabling multiple means of representation, engagement, and expression, allowing students to interact with content in ways that best suit their abilities and preferences. Technology, when thoughtfully integrated, can help remove learning barriers and challenge the traditional one-size-fits-all approach by offering flexible, personalized pathways for diverse learners in a classroom (Meyer et al., 2014; CAST, 2018; CAST, 2024).

Figure 5

Concept Map of Variety Theme

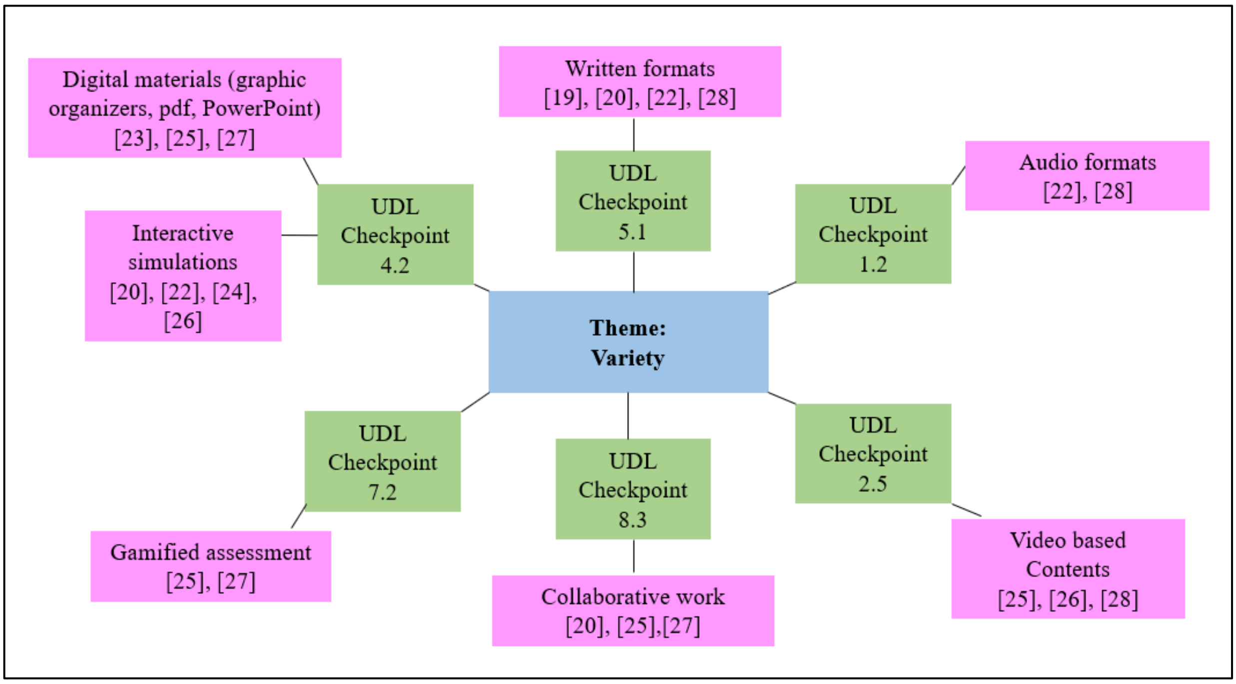
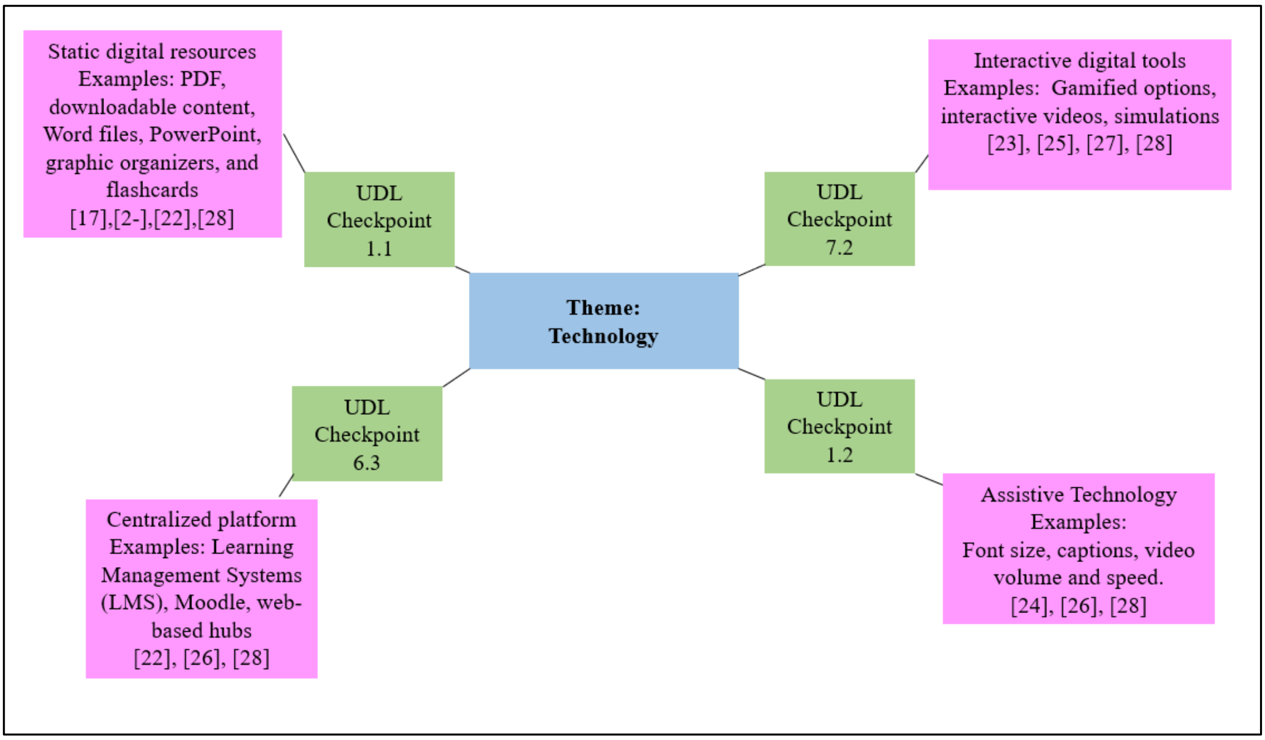


Figure 6

Concept Map of Technology Theme



When unpacking the key themes and patterns that recur throughout the studies analyzed, it is clear that the themes of choice, variety, and technology not only align with UDL principles but are also widely recognized in the literature as mechanisms that enhance engagement, motivation, and accessibility. Choice empowers students to select content formats, tasks, or assessment modes that align with their interests and strengths, thereby fostering autonomy and intrinsic motivation (CAST, 2024; Meyer et al., 2014). Variety, in turn, addresses the limitations of the one-size-fits-all approach by providing multiple pathways to understand, engage with, and express learning, supporting both struggling and advanced learners (CAST, 2018; Rumjaun et al., 2022; Tomlinson, 2014). Finally, technology serves as a critical enabler of UDL by facilitating multimodal content delivery, interactive learning experiences, and personalized feedback, which are particularly important in concept-heavy STEM disciplines (Al-Azawei et al., 2016; King-Sears et al. 2020). Collectively, these themes reflect a shift toward more learner-centered, differentiated instructional practices, which many of the reviewed studies cited as essential for fostering inclusive and effective STEM education.

Bridging the Gap: Positioning the Present Review within the CAST 2024 Framework

The findings of this review echo what others have observed: despite growing awareness of UDL in STEM education, real-world implementation still faces persistent challenges. Basham et al. (2020) and Smith and Lowrey (2017) found that while many educators understand UDL in theory, its use in classrooms often stays at a surface level. This is often due to a lack of professional development, limited institutional support, and the difficulty of applying UDL principles within rigid, exam-driven systems. Flood et al. (2023) further point out that even technology-enhanced UDL strategies can be hard to sustain without the right infrastructure and teaching frameworks. These issues highlight the need for more focused research, practical implementation models, and stronger policy support to make UDL a meaningful part of STEM education.

The findings showed that most of the studies demonstrated alignment with frequently used checkpoints such as 7.1 (*Optimize individual choice and autonomy*), which is known to enhance student engagement and promote ownership of learning (Al-Azawei et al., 2016; CAST, 2024). Next is checkpoint 1.1 (*Customize the display of information*) and 1.2 (*Offer alternatives for auditory and visual information*), which contribute to accessibility and reduce cognitive overload by providing multimodal input (CAST, 2024; Hall et al., 2012; Tomlinson, 2014). Checkpoint 4.2 (*Optimize access to tools and assistive technologies*) was also noted as a key enabler in reducing barriers for learners with disabilities and improving task independence (Darling-Hammond et al., 2020; Novak, 2024).

However, checkpoints related to differentiated and inclusive assessments such as 9.4 and 8.5 were rarely addressed across the selected studies. This gap points to a broader issue in current UDL applications where assessment practices remain largely unchanged. Another pressing implication from the findings is the need to reconsider traditional assessment approaches in STEM education. While many UDL interventions emphasized content delivery, few extended these principles into assessment design. Conventional assessment practices continue to disadvantage students who are neurodivergent (Al-Azawei et al., 2016; King-Sears et al., 2020). Scholars increasingly argue that aligning assessments with UDL principles such as incorporating multimodal response not only improves accessibility but also supports deeper conceptual understanding and sustained motivation (Kaya et al., 2021; Thoma et al., 2023). Modifying STEM assessments is therefore not just a matter of accommodation, but a pedagogical necessity for fostering equity and meaningful learning

When considering reasons for the underuse of these checkpoints, it could be that these are time-intensive processes that may not align well with the rigid pacing of curriculum-driven STEM courses, especially in high-stakes exam settings (Aguiar & Calabrese, 2025; Hall et al., 2012). Teachers may also lack awareness of how to integrate these checkpoints (Al-Azawei et al., 2016).

By grounding this review in the CAST 2024 framework, a more significant and structured analysis was possible. This approach not only revealed which instructional practices are currently prioritized but also illuminated areas where UDL implementation remains partial or superficial. It positions this review to guide future research and practice toward more holistic, checkpoint-level fidelity, ensuring that inclusive STEM education truly supports all learners, not just through access, but through meaningful engagement and sustained learning outcomes.

Implications for Biology Education

How, then, does the present SLR demonstrate its implications for enhancing student engagement and motivation in Biology education?

Building on the checkpoint-level analysis and thematic findings, this review highlights the potential of UDL to transform the teaching and learning of Biology. The alignment of selected STEM studies with CAST 2024 checkpoints supports the significance of UDL principles in mainstream education settings, particularly when addressing the diverse needs of learners.

The results of this SLR underscore that UDL, when implemented with thoughtful integration of choice, variety, and technology, creates a more inclusive and differentiated Biology classroom. These principles allow students to engage with content in ways that reflect their individual strengths and preferences, promoting both accessibility and motivation. However, despite the promising strategies identified in the literature, practical implementation remains inconsistent. Many educators struggle to apply UDL principles effectively due to limited time, professional training, or systemic constraints (Al-Azawei et al., 2016; Hall et al., 2012; King-Sears et al. 2020; Tomlinson, 2014).

While the UDL framework supports multiple means of engagement, representation, and expression, there remains a significant gap between research and classroom practice (Tomlinson, 2014; Zhang et al., 2024). Schools must move beyond viewing inclusion as merely providing accommodations such as extra time on tests or modified seating arrangements and instead embrace a fundamental redesign of instructional approaches. This involves planning curricula and learning environments that anticipate learner variability from the outset, as advocated by the UDL framework, rather than modifying lessons to meet individual needs after the fact (Bray et al., 2024; CAST, 2024; Tomlinson, 2014).

Technology, as a UDL enabler, holds promise in Biology education. The reviewed studies distinguish between static tools (e.g., PDFs, PowerPoint slides, graphic organizers) and interactive tools (e.g., simulations, gamified assessments, collaborative platforms). While the latter support engagement and self-paced learning, challenges such as digital literacy, cost, and uneven infrastructure remain significant, particularly in underserved contexts. Future research should explore equitable models for integrating assistive technologies and digital learning platforms into Biology classrooms in ways that do not impair existing educational inequalities (Rusconi & Squillaci, 2023; Thoma et al., 2023).

Despite highlighting key themes, this review also reveals underexplored areas. For instance, the ideal balance of flexibility remains an open question: how much choice is optimal before students become overwhelmed or disengaged? Furthermore, while technology facilitates UDL, its long-term impact on learning outcomes, particularly in conceptual mastery of Biology, requires further longitudinal study. Future research should also examine how students with different levels of executive functioning and self-regulation navigate UDL environments, especially in cognitively demanding subjects like Biology.

CONCLUSION

The findings from this systematic literature review highlight the transformative capabilities of the Universal Design for Learning (UDL) framework in promoting inclusive and differentiated STEM education, particularly in Biology. By emphasizing choice, variety, and technology, UDL allows diverse learners to engage with content in ways that best align with their strengths, promoting autonomy and accessibility. However, challenges remain in bridging research and practice, ensuring equitable access to digital tools, and determining the best degree of flexibility in instructional planning. Future studies should focus on developing implementation models, evaluating long-term learning outcomes, and addressing barriers to UDL adoption in different educational contexts. To fully realize the benefits of UDL, sustained efforts in teacher training, policy reform, and institutional support are essential, ensuring that inclusive and differentiated learning becomes the standard instead of the exception.

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