MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2025, 21(3), em2598
ISSN:1305-8223 (online)
OPEN ACCESS Review Article https://doi.org/10.29333/ejmste/16044

Technology-supported differentiated biology education: Trends, methods, content, and impacts

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Received 03 June 2024 ▪ Accepted 26 January 2025

Abstract

This study aims to fill the gap in understanding the trends, methods, content, and impacts of technology implementation in differentiated biology education at the secondary and higher education levels. The methodology employed is a systematic literature review on the use of technology in differentiated biology education. The search was conducted using the terms 'technology' AND ('differentiated instruction' OR 'personalized learning' OR 'adaptive teaching' OR 'learning style') AND 'biology education' in the Scopus database, yielding 922 articles, of which only 18 met the criteria for further analysis. The findings indicate a rapid increase in publications, with 61% of the articles published between 2022 and 2024. The majority of publications come from journals in the fields of *social sciences/education*, while contributions from journals in biochemistry, genetics, and molecular biology remain limited, suggesting the need for cross-disciplinary collaboration. Most of the studies (78%) used quantitative and mixed methods, with 72% focusing on higher education. The most commonly used technologies include hands-on tools, data analysis tools, and collaborative tools, with animal anatomy and physiology as the dominant topics. These technologies support learning by enhancing understanding, engagement, and learning outcomes, as well as observation and scientific explanation skills at the secondary school level, and research and bioinformatics skills at the higher education level.

Keywords: technology, digital learning, biology education, differentiated instruction

INTRODUCTION

Biology education at the secondary school level faces a range of multifaceted challenges that hinder students' academic success and their development of essential scientific competencies. Many students struggle with abstract concepts, such as the cell cycle and biochemical processes, which require innovative pedagogical approaches to enhance comprehension (Aghasafari, 2023). Furthermore, cultivating fundamental scientific skills, including hypothesis formulation and experimental design, remains a persistent barrier to achieving academic excellence (Fernández et al., 2022). Additionally, scientific literacy, especially in areas like data analysis and scientific interpretation, is alarmingly low, even among high-achieving students (Fausan et al., 2021). The inherent complexity of biological content increases cognitive load, which impedes students' ability to effectively absorb and retain information (Toh & Tasir, 2024). Moreover, limited access to technology, exacerbated by poor internet infrastructure in certain regions, further widens the learning gap and deepens educational inequalities (Nedzinskaite-Maciuniene et al., 2022). These challenges highlight the critical need for adaptive, technology-enhanced, and personalized learning solutions to address the diverse needs of students and improve outcomes in biology education.

At the university level, many of the challenges faced at the secondary level persist, compounded by issues of equity and inclusion within STEM fields. The diversity of students' backgrounds often limits participation, leading to disparities in learning outcomes and engagement (Fink et al., 2024). Traditional teaching methods, which often lack active learning strategies, further contribute to low motivation and academic performance (Adeika et al., 2024). For example, students

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Contribution to the literature

- This review contributes to the literature by focusing on key publications related to the implementation of technology in differentiated biology education at the secondary and higher education levels, examining its implications for trends, methods, content, and impacts. By exploring less-discussed aspects, the review provides new insights and lays a foundation for future research.
- Additionally, it offers a comprehensive overview of technological tools, such as hands-on tools, data analysis tools, and collaborative tools, while assessing their effectiveness in supporting content adaptation and addressing diverse learning needs.
- Moreover, this study evaluates the application of technology in dominant topics, including animal anatomy and physiology, genetics, and environmental biology and conservation, and highlights its impact on student learning.

frequently struggle with complex topics such as DNA transcription through conventional approaches (Liang et al., 2023; Norizan et al., 2025). Given the interdisciplinary nature of biology and the advanced concepts explored at the university level, innovative approaches are needed to foster deeper comprehension and holistic academic development. Interdisciplinary integration, such as linking biology with mathematics, health education, and environmental studies, is one promising strategy to address these challenges (Athanasiou, 2021; Fink et al., 2024).

The application of adaptive learning technologies, integrated with a differentiated instruction (DI) approach, provides an effective solution for addressing challenges in biology education. DI allows for the customization of content to meet individual students' needs, which can be enhanced through various technologies. These technologies help teachers design more creative and relevant materials, ensuring each student receives a learning experience tailored to their learning style (Hidayat et al., 2024). Technologies such as virtual laboratories and practical simulations not only overcome physical limitations but also increase student engagement in hands-on experiments, allowing them to be more active in understanding complex biological concepts (Makolo et al., 2022). For instance, predator-prey simulations are used to teach the theory of natural selection interactively, providing students with an opportunity to engage directly in deeper learning (Unger et al., 2023). Additionally, learning platforms like Canvas and Moodle play a crucial role in fostering more personalized interactions between students and instructors, which is essential for differentiated learning (Dixon & Packwood, 2023).

Artificial intelligence (AI)-based technologies hold significant potential in creating more interactive simulations and learning environments. AI enhances student engagement in biology education by offering deeper and more personalized learning experiences (Usak, 2024). The use of AI to design exam questions tailored to individual students' needs further improves evaluation effectiveness in higher education (Nasution, 2023). At the higher education level, machine learning (ML) and natural language processing (NLP) technologies enable deeper analysis of biological data and provide more specific feedback, aligned with each student's needs (Aleksandrovich et al., 2024; Ariely et al., 2024). Overall, the implementation of these technologies not only creates more interactive learning experiences but also supports an inclusive and adaptive learning environment.

This article explores the trends, methods, and impacts of technology in fostering more inclusive and personalized biology education, with a focus on the application of adaptive technologies and DI at both secondary and higher education levels. This systematic literature review (SLR) critically evaluates previous studies and evidence-based best practices to bridge gaps in biology education. By examining technology's role across these educational levels, the article aims to offer insights into how technology can promote adaptive and effective learning environments, ultimately improving the quality of biology education across all levels.

METHOD

Research Framework

This study is an SLR, a method aimed at identifying, evaluating, and synthesizing research findings from various relevant sources in a structured and planned manner (Lasserson et al., 2019; Purssell & McCrae, 2020). SLRs improve the quality, reliability, and validity of the information collected to answer research questions (RQs) (Xiao & Watson, 2019). In conducting this SLR, we employed a qualitative synthesis approach, which involves reviewing relevant works on a specific subject and gathering data from those studies (Seers, 2015).

Research Questions

The RQs underlying this study are:

RQ1. What technologies are used in differentiated biology education?

RQ2. What content is taught using technology in differentiated biology education?

RQ3. What is the impact of technology use in differentiated biology education at the higher education and secondary school levels?

Search Articles and Inclusion Criteria

In our search in the Scopus database, we used the following keywords: "technology" AND ("differentiated instruction" OR "personalized learning" OR "customized teaching" OR "adaptive teaching" OR "tailored instruction" OR "learning style") AND "biology education." Additionally, we limited the search to include only articles written in English ('LIMIT-TO (LANGUAGE, "English")'), journal articles ('LIMIT-TO (DOCTYPE, "ar")'), and those within the social science subject area ('LIMIT-TO (SUBJAREA, "SOCI")'). We also opted to include only open-access articles ('LIMIT-TO (OA, "all")') to ensure broader accessibility. As a result, we found 922 articles that met the search criteria. Using the PRISMA model, decisions regarding the inclusion and exclusion of articles were made. The PRISMA model applied in this study follows the methodology outlined by Gallagher et al. (2016), who utilized the PRISMA model in their SLR. The following are the inclusion criteria for the articles considered in this SLR:

1. The article is written in English.
2. The article is an original research article.
3. The article falls within the social science subject area.
4. The article is available as open access.
5. The article includes research on the use of technology in differentiated biology education.

Figure 1 illustrates the methodology used in this study for article inclusion and exclusion. We excluded five documents written in languages other than English (Spanish, Turkish, Arabic, and Lithuanian), leaving 917 articles written in English. Next, we identified 658 original research articles and excluded 259 other documents, such as conference papers, reviews, book chapters, books, notes, and editorials. Our selection criteria prioritized original publications to emphasize the originality of completed research findings. This study specifically focuses on social sciences in education, which led to the exclusion of 147 articles deemed irrelevant to social sciences. As a result, 511 articles were retained. We did not limit the publication year range, allowing articles published between 2005 and 2024 to be included. A total of 215 non-open-access articles were excluded, as accessing full-text articles was required, leaving 296 articles.

A meticulous review of titles and abstracts yielded 30 original articles relevant to the research topic. A thorough review of the full text of these articles was then conducted, resulting in 18 relevant studies being identified as aligned with the research topic. To minimize bias in article selection, we employed several techniques, including translating articles into Indonesian, our native language, to enhance scientific comprehension and accuracy, and conducting the inclusion and exclusion process collaboratively with the team.

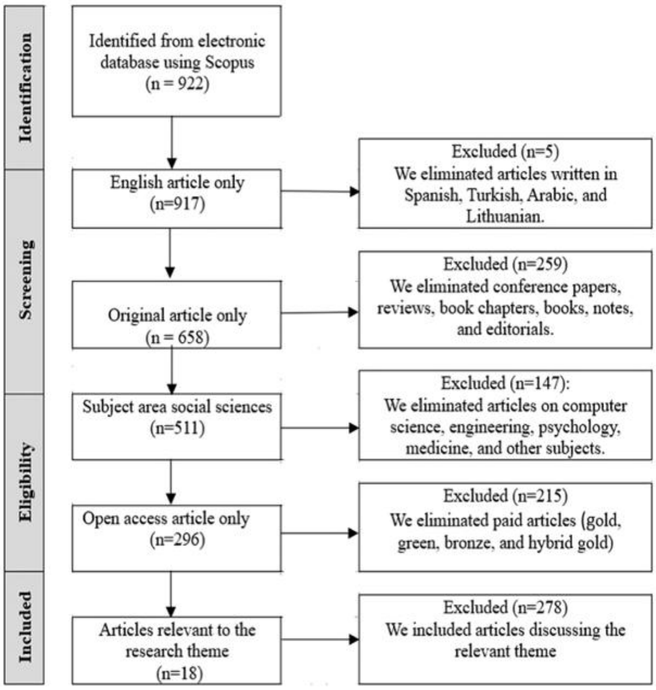

Figure 1. PRISMA diagram (Source: Authors' own elaboration)

RESULTS

Distribution of Articles by Year, Journal, and Country

This study identified and analyzed 18 relevant articles on the use of technology in differentiated biology education. The distribution of these articles spans from 2006 to 2024, with a notable increase in publications between 2022 and 2024. The number of articles surged in 2022, with five published, followed by an even greater increase in 2024, with six articles. This upward trend reflects the growing interest in the use of technology in differentiated biology education. These articles were published across 14 different academic journals, with the highest number of articles coming from *CBE–Life Sciences Education* (3 articles), *Education Sciences* (3 articles), and *Journal of Science Education and Technology* (2 articles).

The line graph in **Figure 2** illustrates the distribution of articles by year, spanning publications from 2006 to 2024, with a significant increase in recent years. Between 2022 and 2024, there was a notable rise in the number of articles, reflecting the growing interest in the use of technology in differentiated biology education.

The bar graph in **Figure 3** illustrates the contributions of 14 journals, with *CBE–Life Sciences Education* and *Education Sciences* publishing the highest number of articles (three each).

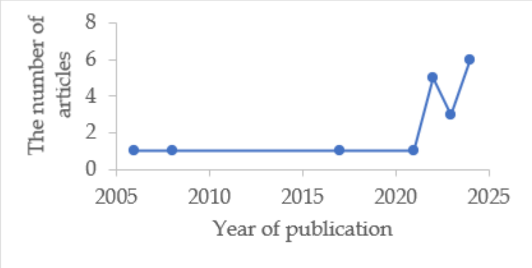

Figure 2. Distribution of articles by year (Source: Authors' own elaboration)

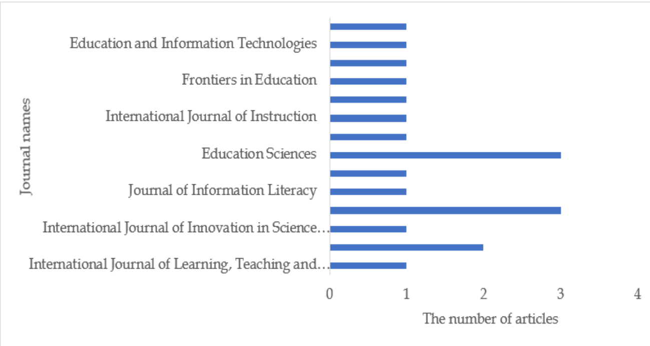

Figure 3. Distribution of articles by source (Source: Authors' own elaboration)

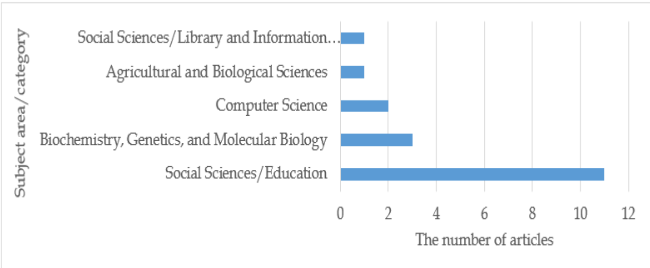

Figure 4. Distribution of articles by subject area/category (Source: Authors' own elaboration)

Other journals, such as the *Journal of Science Education and Technology*, contributed two articles, while additional journals, including *Advances in Physiology Education*, each published one article. The variety of sources reflects the broad scope of the research and underscores the significant role of several key journals in advancing studies related to technology in differentiated biology education.

The bar graph in **Figure 4** illustrates the research areas most frequently published about the use of technology in differentiated biology education. Most articles were published in journals within the *social sciences/education* category, with a significantly higher number than in other categories. Journals in *biochemistry, genetics and molecular biology*, and *computer science* also contributed, although in smaller numbers. In addition to considering journal types, the distribution of articles by the country of origin of the journals plays an important role in reflecting the global contribution to the studied topic.

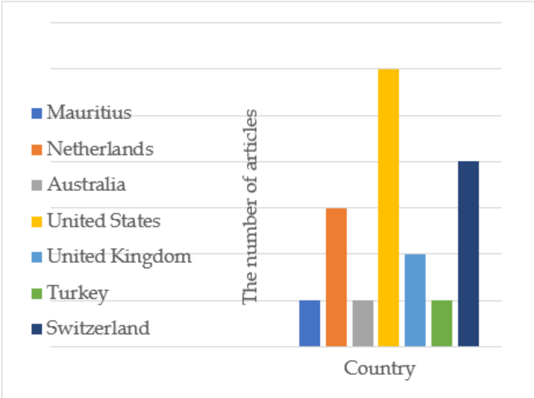

Figure 5. Distribution of articles by country of origin (Source: Authors' own elaboration)

The majority of the articles originated from journals published in the United States, reflecting the dominance of this country in contributing to research on the use of technology in differentiated biology education (**Figure 5**). Switzerland and the Netherlands also made substantial contributions, reflecting the involvement of European countries in supporting relevant research. Other countries, such as the United Kingdom, Mauritius, Australia, and Turkey, contributed fewer articles, suggesting that while the topic has attracted attention from various regions, it is not yet evenly distributed across the globe.

Characteristics of Included Studies

The included studies varied in research methods, settings, and sample sizes (**Table 1**). Most studies used quantitative (39%) and mixed methods (39%), focusing on comprehensive data collection. The majority were conducted in higher education (72%), with fewer in secondary schools (28%). Sample sizes ranged from 8 to 2,398 participants, reflecting variation in research scale.

Main Findings

Types of technology used

The technologies utilized in differentiated biology education across the studies included in this research have been categorized based on their functions, which include hands-on tools, virtual tools, data analysis tools, collaborative tools, assessment tools, and multimedia tools, as shown in **Table 2**. **Table 2** provides an overview of the types of technology utilized in differentiated biology education, categorized by function and their role in enhancing student engagement. Among the various technologies employed, tools designed for hands-on interaction, data analysis, and student collaboration are the most widely used. Virtual tools such as VR and AR provide immersive experiences, while assessment tools like online quizzes support personalized learning. These technologies collectively enhance the flexibility and effectiveness of biology education.

Table 1. Characteristics of studies

No	Study	Method	Setting	Sample
1	Ndikumana et al. (2024)	Mixed	Higher education	2 lecturers and 109 students
2	Dunbar-Wallis et al. (2024)	Qualitative	Higher education	15 students
3	Chapple et al. (2022)	Mixed	Higher education	116 students
4	Goff et al. (2017)	Quantitative	Higher education	534 students
5	Dixon and Packwood (2023)	Qualitative	Higher education	11 students and 2 module leaders
6	Robledo et al. (2023)	Mixed	Secondary school	839 students
7	Cooper and Tang (2024)	Qualitative	Secondary school	Not specified
8	Abel and Ziman R. (2024)	Mixed	Higher education	19 students (chondrocranium) & 16 students (brain)
9	Ntaila and Mbaraka (2023)	Quantitative	High school	189 students
10	Zulfiani et al. (2021)	Mixed	Junior high school	153 students (learning style identification) & 50 students (summative evaluation)
11	Knight et al. (2008)	Qualitative	Higher education	8 students
12	Ariely et al. (2024)	Quantitative	High school	607 students
13	Ben et al. (2024)	Quantitative	Higher education	85 students
14	Makolo et al. (2024)	Quantitative	Higher education	Not specified
15	Barnes (2022)	Quantitative	Higher education	139 respondents (2017) & 53 respondents (2019)
16	Holtzclaw et al. (2006)	Quantitative	Higher education	28 students
17	Almasri (2022)	Mixed	Higher education	26 students
18	Pollock (2022)	Quantitative	Higher education	2,398 students

Table 2. Types of technology in differentiated biology learning

Types of technology	Examples of tools	Quantity
Hands-on tools	Fluorescence microscopy, gel electrophoresis, Western blotting, microarrays, PCR, DNA sequencing, 3D printing, anatomical models, histology slides, and Cadavers	10
Virtual tools	Virtual cell animation collection, VR and AR, virtual anatomical models, virtual experiments via Pearson mastering A&P, JMR website	6
Data analysis tools	DNA analysis software and online applications, data collection and analysis software, data visualization software, visual analytics, desktop computers with high-speed internet access, wireless laptops, graphics software like Cn3D, NCBI website and tools such as BLAST, GenBank, and Map Viewer, ML and NLP	9
Collaborative tools	Online learning platforms, Moodle course management system, Microsoft Teams, Canvas learning platform, Zoom, Google Drive, Gmail, Android-based applications	9
Assessment tools	Online quizzes and practical using Pearson mastering A&P, practice questions, LockDown browser, Google Forms, and Autoproctor	5
Multimedia tools	PowerPoint, audio-visual tools, instructional videos, multimedia equipment and LCD projectors, interactive multimedia, lecture video recordings, cameras, and microphones	8
Total		47

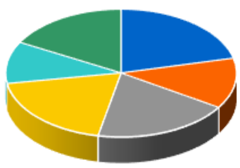

Figure 6. Pie chart of technology types (Source: Authors' own elaboration)

The pie chart in **Figure 6** illustrates that hands-on tools represent the most frequently used technology type in these studies (21%), followed by data analysis Tools and collaborative tools, each accounting for 19%. This suggests that technologies designed to facilitate practical and collaborative learning are more prevalent in differentiated biology education.

Biology topics taught using technology

The topics were identified and classified based on their scope into seven main categories: biotechnology, bioinformatics, environmental and conservation biology, cellular and molecular biology, biochemistry, genetics, and anatomy and physiology, reflecting the comprehensive scope of technology-assisted biology education. **Table 3** shows the distribution and frequency of biology topics in the studies included in this SLR. The graph in **Figure 5** illustrates the percentage comparison of these topics, with animal anatomy and physiology being the most frequently discussed (31%), followed by genetics (17%) and environmental biology and conservation (14%). The pie chart in **Figure 7** shows that animal anatomy and physiology are the most prominent topics for technology use in biology education closely related to the deep need to understand the structure and function of living organisms.

Table 3. Topics and examples of biology content

Biology topics	Examples of content	Quantity
Biotechnology	Biotechnology and recombinant plasmid technology	2
Bioinformatics	Bioinformatics	2
Environmental and conservation biology	Environmental biology, conservation biology, sampling and environmental monitoring, and backyard biodiversity experiments	4
Cellular and molecular biology	Meiosis concepts, animal cell culture, yeast respiration experiments (yeast balloon models), and foldable biological levels of organization	4
Biochemistry	Protein purification techniques, photosynthesis	3
Genetics	Sickle cell anemia, diabetes, breast cancer, pedigree construction activities, genetic inheritance simulations, edible DNA models, and DNA structure	5
Anatomy and physiology	Comparative chordate anatomy, animal anatomy, and physiology, human anatomy, the neuroanatomy of the dogfish shark (*squalus acanthias*), including chondrocranium and brain focus, human nervous system, musculoskeletal system, respiratory and circulatory systems, 3D model of the human reproductive system, chicken wing dissection activities	9
Total		47

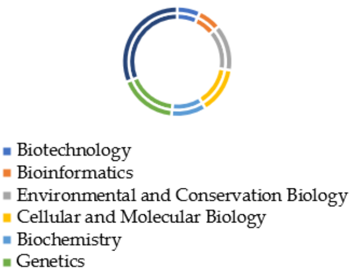

Figure 7. Biology topics (Source: Authors' own elaboration)

Impact of technology use in differentiated biology education

Table 4 and **Table 5** detail the role of technology in differentiated biology education at secondary and higher education levels. Various studies indicate that the use of technology significantly impacts student learning outcomes, particularly in the context of differentiated biology education.

DISCUSSION

Technology adoption in biology education experienced a significant surge during 2022-2024, driven by the rapid digital transformation prompted by the COVID-19 pandemic. Platforms such as Google Meet and Zoom (Alhussain, 2020; Al-Maroof et al., 2021) have been widely adopted in flipped classroom models (Lei et al., 2022).

Table 4. Impact of technology use in differentiated biology education at the higher education level

No	Topic/subtopic	Main technology	Support for DI	Impact	References
1	Biotechnology	PowerPoint & audio-visual software	Adapting to students' learning styles	Increased concept understanding and learning outcomes	Ndikumana et al. (2024)
2	Bioinformatics	DNA analysis software, online platforms, & data visualization tools	Supports visual learning and data analysis interest	Enhanced interaction, retention, career skills, and student engagement	Dunbar-Wallis et al. (2024)
3	Environmental biology & conservation	Interactive learning modules & Canvas	Visual and kinesthetic learning preferences	Improved understanding of concepts and knowledge retention	Chapple et al. (2022)
4	Cell biology (meiosis)	3D printing, Moodle (iLearn), PCR, & electrophoresis	Supports hands-on interaction and customized learning	Better understanding of meiosis compared to traditional methods	Goff et al. (2017)
5	Chordata anatomy (neuroanatomy)	VR/AR & online platforms	Customization of learning experiences	Increased engagement, retention, and information literacy	Dixon and Packwood (2023)
6	Cell & molecular biology	Analytical visual tools, chromatography cards, & Google Forms	Personalized learning formats for diverse learning styles	Higher understanding, engagement, and career skills	Abel and Ziman (2024)
7	Biochemistry	Multimedia equipment & software like Cn3D	Visual and kinesthetic support	Increased research skills, collaboration, and class performance	Knight et al. (2008)
8	Biochemistry (protein purification)	Software analysis & visual data platforms	Facilitates individual learning preferences	Improved learning outcomes and student self-efficacy	Ben et al. (2024)

Table 4 (Continued). Impact of technology use in differentiated biology education at the higher education level

No	Topic/subtopic	Main technology	Support for DI	Impact	References
9	Genetics (anemia, diabetes, & cancer)	Online platforms & Google Forms	Personalized learning through different media formats	Improved knowledge, confidence, and research engagement	Makolo et al. (2022)
10	Genetics	Multimedia tools & video instructions	Facilitating diverse learning styles	Increased engagement and student participation	Barnes (2022)
11	Animal anatomy & physiology	Microsoft Teams, Moodle, camera, & microphone	Blended learning, accessibility, and content personalization	Improved learning outcomes, flexibility, and collaboration	Holtzclaw et al. (2006)
12	Animal anatomy & physiology	Microsoft Teams, Moodle, camera, & microphone	Face-to-face, blended, & online learning	Increased satisfaction and learning outcomes	Almasri (2022)
13	Animal anatomy & physiology	Microsoft Teams, Moodle, camera, & microphone	Flexibility in communication and evaluation	Enhanced learning outcomes, flexibility, and collaboration	Pollock (2022)

Table 5. Impact of technology use in differentiated biology education at the secondary school level

No	Topic/subtopic	Main technology	Support for DI	Impact	References
1	Home-based biology experiments	Zoom, Google Drive, Google Forms, & Autoproctor	Flexibility to meet diverse learning needs	Improved knowledge, perceptions, self-efficacy, and student engagement	Robledo et al. (2023)
2	DNA structure and human anatomy	DALL-E 3 & ChatGPT	Easy access to digital resources supporting various learning styles and active student interaction	Enhanced concept understanding, engagement, active participation, and observation skills	Cooper and Tang (2024)
3	Human nervous system	Interactive multimedia	Facilitates individual needs through various learning formats	Increased engagement, understanding, and academic outcomes, especially for students in urban areas	Ntaila and Mbaraka (2023)
4	Locomotor system	Android-based application (ScEd-ALS)	Distribution of materials and evaluation aligned with students' learning styles	Improved learning outcomes and understanding of the locomotor system	Zulfiani et al. (2021)
5	Respiratory and circulatory systems	ML & NLP	Personalized feedback, knowledge pattern analysis, and support for teachers in understanding student needs	Enhanced content understanding, scientific explanation skills, and learning outcomes	Ariely et al. (2024)

At the same time, virtual laboratories have gained importance in overcoming the physical limitations of remote learning (Aleksandrovich et al., 2024; Huang et al., 2023; Shambare & Jita, 2024). Comprehensive and systematic digital encyclopedias have proven their potential to support self-directed learning by offering quick access to relevant information (Munzil et al., 2021). Developing e-learning materials tailored to accommodate diverse learning styles, such as the VARK framework (Munzil & Perwira, 2021), has emerged as an effective strategy to support personalized learning. However, despite the growing integration of technology, research on its application in differentiated biology education remains scarce, presenting opportunities for further exploration and development.

The analysis of articles in this SLR reveals that 61% of publications related to technology in differentiated biology learning were published within the last three years, underscoring the growing urgency of employing technology for inclusive and adaptive education. Technologies such as virtual reality (VR), augmented reality (AR), and online learning platforms have seen widespread implementation (Ben et al., 2024; Dunbar-Wallis et al., 2024; Pollock, 2022). However, specific innovations, including molecular simulations and virtual ecosystem models, remain underutilized. For example, web-based molecular simulations that adapt task difficulty through self-assessments have yet to support differentiated learning fully (Dahlen et al., 2020). Similarly, while VR effectively enhances student engagement and comprehension of complex concepts like three-dimensional molecular interactions, its implementation predominantly emphasizes technical skills without sufficiently addressing individual learning needs (Jerry Reen et al., 2022; McDonald et al., 2022; Reen et al., 2024). These findings highlight the need to develop more adaptive and inclusive technologies tailored to the requirements of differentiated biology learning.

The majority of publications (75%) are published in social and education journals, such as *CBE–Life Sciences Education*, while only 10% appear in the fields of *biochemistry* and *genetics and molecular biology*, indicating a lack of cross-disciplinary collaboration. Future research should engage more pure biology journals to bridge this gap and ensure that the technologies developed align with the needs of differentiated biology learning. The dominance of publications from developed countries, such as the United States, Switzerland, and the Netherlands, reflects disparities in research capacity for advancing differentiated biology learning. These nations possess greater resources, including technology, infrastructure, and funding, to support research efforts (Schleicher, 2015). Conversely, developing countries face challenges such as limited infrastructure and inconsistent policies, which hinder technology adoption (Luo et al., 2022; Tsimba et al., 2022). The GEM report 2023 also highlights similar barriers, including low user confidence and inadequate institutional capacity to integrate technology (Global Education Monitoring Report Team, n. d.).

The majority of studies on differentiated biology education employ quantitative (39%) and mixed methods (39%), focusing on numerical data and qualitative analysis. Only 22% use qualitative methods, indicating a lack of in-depth exploration of the experiences of teachers and students. (Heinrich et al., 2020) emphasize the effectiveness of mixed methods in evaluating the use of tablet technology in resource-limited environments, while Daruwala et al. (2021) assess technology-based learning personalization, noting gaps in exploring the subjective experiences of students and teachers. This underscores the need for qualitative research to better understand the challenges of implementing technology in differentiated learning. In line with this, Anderson and Putman (2020) highlight the importance of teacher insights in integrating technology in special education, while Abel et al. (2022) underscore the influence of teachers' perceptions on ICT integration in education.

Seventy-two percent of studies on the application of technology in differentiated biology education are conducted at the higher education level, indicating a significant focus on technology implementation at the tertiary level. This is influenced by better infrastructure availability (Zhang, 2022), curriculum design flexibility (Boustani & Sayegh, 2021), and the cognitive maturity of university students, supported by digital social support (Khan et al., 2023). In contrast, only 28% of studies are conducted in secondary schools, highlighting the need for further exploration of technology implementation at this level. Secondary schools, despite facing infrastructure and resource limitations (Msambwa et al., 2024), play a critical role in laying the foundation for biology understanding. Research at the secondary education level could provide valuable insights to support differentiated learning, particularly if driven by transformational leadership capable of effectively guiding technology utilization (Schmitz et al., 2023).

The sample sizes in studies on the application of technology for differentiated biology education vary widely, ranging from 8 to over 2,000 participants. Large-scale studies, such as Pollock (2022) involving 2,398 students, provide robust generalization of results, while smaller studies, such as Knight et al. (2008) with just 8 participants, offer in-depth insights despite their limited representativeness. Sample size variation is also evident at the secondary school level, for example, Robledo et al. (2023) with 839 students and Zulfiani et al. (2021) with 50 students, reflecting differences in research methodologies and objectives. Lindl et al. (2020) emphasize the importance of methodological consistency to enhance the validity of comparative findings, particularly with complex data. Demakova and Shustova (2021) argue that integrating various research methods whether theoretical, empirical, quantitative, or qualitative represents the most effective approach to leverage the complementarity of these methods. Mixed-methods approaches enable similar studies to explore intervention effectiveness more thoroughly (Ramanujan et al., 2022).

The analysis of the articles indicates that the use of technology in differentiated biology education involves a variety of tools, categorized according to their primary functions. These technologies include hands-on tools, data analysis tools, collaborative tools, multimedia tools, and assessment tools, as summarized in **Table 2** and illustrated in **Figure 6**. Hands-on tools account for the largest share, with 21%, followed by data analysis tools and collaborative tools, each at 19%. These technologies play specific roles in supporting biology education, ranging from developing practical skills to fostering collaboration and enabling more adaptive assessments. The following discussion will further explore the roles and challenges associated with each of these technological categories.

Hands-on tools (21%) dominate differentiated biology education by providing in-depth practical experiences that help develop students' laboratory skills. Tools such as fluorescence microscopes, PCR, and anatomical models facilitate direct interaction with biological specimens, enhancing conceptual understanding. For instance, at San Francisco State University, laboratory techniques like fluorescence microscopy and PCR are employed in case-based learning, bridging theory with real-world experiments and deepening practical skills (Knight et al., 2008). Hands-on learning has been shown to enhance technical skills and promote long-term retention of material (Nischal et al., 2024), while also supporting visual and kinesthetic learning styles through 3D anatomical models that offer tactile experiences (Abel & Ziman, 2024). This approach improves the comprehension of biological concepts and relevant cognitive skills (Lawson et al., 2020; Tokatlidis et al., 2024). Hands-on tools thus support differentiated learning by providing flexible access and activities tailored to students' learning styles.

Data analysis tools (19%) play a crucial role in modern biology education by enhancing students' data analysis skills. Tools such as BLAST, GenBank, and Cn3D assist students in visually interpreting genetics and macromolecules (Holtzclaw et al., 2006). Platforms like H3Africa provide interactive visual representations, supporting personalized learning and boosting students' bioinformatics abilities (Makolo et al., 2022). The use of ML and NLP applications, such as automated short answer scoring (ASAS), enables students to identify patterns in biological data and analyze experimental outcomes (Aleksandrovich et al., 2024). These tools also offer personalized feedback, supporting differentiated learning and improving student performance (Ariely et al., 2024). Furthermore, tools like Galaxy and eBiokits facilitate the visualization and analysis of complex genomic data, strengthening students' analytical capabilities in recognizing patterns and relationships within biological data (Adeika et al., 2024; Kubsch et al., 2023).

The integration of ML and NLP in differentiated biology education holds great potential for enhancing large-scale data analysis (Oikonomou et al., 2024), providing personalized feedback, and tailoring content to meet individual student needs (Kochmar et al., 2022; Wabwire, 2024). However, key challenges persist, including the limited quality and availability of data (Good et al., 2014), as well as potential biases in training data that may compromise the accuracy of personalized recommendations (Patino et al., 2024). The complexity of biological texts characterized by ambiguities and specialized terminology further complicates information processing through NLP (Cellier et al., 2015; Cohen & Demner-Fushman, 2014). Additionally, the lack of transparency in ML model decisions can erode educators' trust in these technologies (Patino et al., 2024; Prihoda et al., 2021). Other challenges include difficulties in integrating these technologies with existing curricula, limited faculty training in AI/ML (Rüdian & Pinkwart, 2019), and the substantial computational resources required, along with challenges in scaling learning systems to accommodate large student populations (Sledzieski et al., 2024).

Virtual tools (13%) play a pivotal role in supporting differentiated learning by enhancing the learning experience and improving academic outcomes through digital technology. For instance, the virtual cell animation collection helps students understand meiosis concepts with visual representations that cater to various learning preferences, leading to better comprehension compared to traditional lecture methods (Goff et al., 2017). VR and AR offer immersive learning experiences that increase student engagement and aid in the preparation and review of laboratory materials (Ben et al., 2024). These technologies foster the development of spatial thinking skills through the exploration of 3D anatomical models and the visualization of spatial relationships in complex scientific concepts, such as human anatomy (Mansour et al., 2024; Moro et al., 2021). Mobile-based AR, such as the mobile AR genetics app, has been shown to improve students' mastery of genetics concepts, resulting in higher scores compared to conventional methods (Safitri et al., 2024). Moreover, VR has demonstrated significant improvements in the retention and understanding of complex biological concepts compared to traditional methods (Chuang et al., 2023), while enhancing spatial presence and cognitive abilities (Selivanov & Sorochinsky, 2021; Zaatar et al., 2024). Additionally, VR prepares students for practical experiences, such as dissections, thereby supporting holistic and integrated learning (Rehatschek et al., 2024).

Virtual anatomical models and virtual experiments enhance blended and online learning by providing flexible access and activities tailored to students' diverse learning styles (Pollock, 2022). Generative technologies like ChatGPT and DALL-E 3 create visual representations of biological concepts, boosting student engagement and reinforcing visual understanding (Cooper & Tang, 2024). Digital platforms such as the Jock Marshall Reserve (JMR) website facilitate access to information, support field data analysis, and connect theory with practice in biology education (Chapple et al., 2022). While the cost of VR/AR devices and technical challenges remain obstacles, these technologies have been positively received by both students and instructors, highlighting their significant potential for broader integration into biology education (Chuang et al., 2023).

Collaborative tools (19%) enhance engagement, interaction, collaboration, and learning outcomes in differentiated biology education. For example, MasteryPaths in the Canvas virtual learning environment offers adaptive learning by tailoring content based on formative quiz results, ensuring that students receive materials suited to their individual needs (Dixon & Packwood, 2023). Discussion forums and online collaboration spaces on platforms such as Canvas (Pollock, 2022), Moodle (Knight et al., 2008), and Rain Classroom (Ben et al., 2024) foster rich interactions between students, instructors, and course content. Collaborative simulations, such as plant growth applications, strengthen understanding of biological concepts like ecology (Cen et al., 2014; Sultana et al., 2024). Tools like Microsoft Teams and Zoom support synchronous sessions in remote or blended learning environments, while Google Drive and Gmail facilitate seamless material distribution (Robledo et al., 2023). Google Docs enhances group work on biology assignments by supporting active discussions and real-time feedback (Huang et al., 2020). Applications such as ScEd-ALS extend access to personalized learning through Android devices (Zulfiani et al., 2021). But challenges like managing group dynamics require careful instructional design to ensure effective collaboration (Sampaio-Maia et al., 2014; Sultana et al., 2024).

Assessment tools (11%) are used to evaluate students' knowledge and skills in differentiated biology education. For instance, Google Forms is employed for surveys and post-tests (Barnes, 2022; Robledo et al., 2023), while quizzes and online labs are conducted through Pearson mastering A&P, the Canvas learning platform, and LockDown browser to support online exams (Pollock, 2022). Autoproctor is used to maintain exam integrity (Robledo et al., 2023). Additionally, ASAS, which utilizes models such as deep neural networks and BERT, captures semantic meaning and enables accurate assessment of complex responses. ASAS effectively evaluates students' ability to analyze and synthesize information, as well as their understanding of related concepts in biology. These assessments often require critical thinking and problem-solving skills to address scientific challenges (Amur et al., 2022; Uto & Uchida, 2020).

Multimedia tools (17%) support differentiated biology education by accommodating students' diverse learning styles. PowerPoint allows for structured and interactive material delivery, incorporating animations and videos that support visual learning (Ndikumana et al., 2024). Instructional videos help clarify complex biotechnology concepts (Dunbar-Wallis et al., 2024), while interactive multimedia, such as animations and videos, enhances comprehension of topics like the human nervous system (Ntaila & Mbaraka, 2023). Animations are particularly effective in illustrating dynamic biological processes, such as photosynthesis and cell division, which are difficult to grasp through text alone (Hadie et al., 2024; Lavine, 2011). Additionally, lecture videos and multimedia devices, including cameras and microphones, provide flexible access for students (Almasri, 2022), while LCD projectors and graphic software support data visualization to cater to various learning styles (Holtzclaw et al., 2006). For example, e-modules based on problem-based learning have been shown to effectively enhance students' creative thinking skills and cognitive learning outcomes, such as in the topic of endocrinology (Kusumawati et al., 2021).

Gamification-based learning tools were not identified in the analysis of the 18 articles in this SLR, despite prior studies highlighting the potential of gamification in differentiated biology education. Platforms such as Kahoot! and BioTourney have been shown to improve test scores and student participation (Latre-Navarro et al., 2024; Schoenenberger et al., 2016), while supporting diverse learning styles, such as through educational board games in cellular biology (Kaimara & Deliyannis, 2019). In the field of genetics, gamification tools like BreakoutEDU and team-based escape rooms foster problem-solving skills and teamwork (Carmona et al., 2024; Martínez-Carmona et al., 2024). In anatomy and physiology education, gamification with digital tools like Kahoot and Quizizz has been found to increase student engagement and academic outcomes (López-Jiménez et al., 2022; Mendoza Rojas, 2024). Advanced technologies such as VR are also being used to create more immersive learning experiences (Hensen et al., 2019; Kumar et al., 2023). These findings suggest that gamification holds significant potential, warranting further exploration, particularly in biology education across various educational levels (Situmorang et al., 2024).

The distribution of articles reveals that the topics of anatomy and physiology dominate the use of technology in differentiated biology education (31%), followed by genetics (17%), and environmental biology and conservation (14%). The prominence of anatomy and physiology is attributed to the need for visualization to understand body structures, with technologies such as 3D models, virtual anatomy simulations, and technology-based dissections providing significant support (Pollock, 2022). In genetics, activities such as "toss your genes" and interactive DNA models help simplify abstract concepts and enhance student understanding (Holtzclaw et al., 2006). In environmental biology and conservation, technologies like environmental sensors, satellite monitoring, and field experiment modeling raise students' ecological awareness regarding global issues (Makolo et al., 2022). Advancements such as the Internet of things and wireless sensor networks enable more accurate real-time monitoring (Sahu et al., 2024), while unmanned aerial vehicles and satellite monitoring provide spatial and temporal data for deeper ecological research (Papazekou et al., 2024; Zhang et al., 2024).

The low application of technology in biotechnology (7%) and bioinformatics (7%) is attributed to the need for specialized software, large-scale data, and more complex analytical skills (Good et al., 2014). However, technologies such as CRISPR simulations, used for gene editing and therapeutic applications (Chawla & Tyagi, 2024), AI-based bioinformatics platforms like Galaxy, which provide flexible workflows for multi-omic analysis (Johnson et al., 2018; Tangaro et al., 2021), and AI-based bioinformatics platforms, such as MetaSpark utilizing Apache Spark, are effective in managing large-scale data for metagenomic analysis (Zhou et al., 2017), show great potential for integration into biotechnology and bioinformatics education.

Biochemistry topics (10%) exhibit limited adoption of technology due to factors such as the reliance on expensive equipment (Ayasrah, 2020; Bećirović, 2023), infrastructure challenges, technical issues such as poor connectivity (Ouanes et al., 2021; Rababa'h et al., 2024), and the requirement for specialized skills and intensive training to address the complexities of data analysis (Howorth et al., 2024; Liang, 2021). The article distribution analysis indicates that technology is more widely applied to topics requiring visualization and real-world applications, such as anatomy and physiology. There is significant potential to expand the use of technology in biotechnology, bioinformatics, and biochemistry. Future research should focus on the development of affordable educational software and technology-based curricula to support differentiated biology education.

CONCLUSION

The adoption of technology in biology education, particularly within the context of differentiated learning, has made significant strides in recent years. The COVID-19 pandemic accelerated this digital transformation, with various technologies such as hands-on tools, data analysis tools, and collaborative tools proving effective in supporting more inclusive and adaptive learning. These technologies contribute to enhanced student understanding, improved learning outcomes, increased engagement, and skill development, particularly in topics like animal anatomy and physiology, where 3D models and virtual anatomy simulations aid in visualizing body structures. Moreover, the integration of technologies like the flipped classroom fosters interactive, collaborative experiences and offers greater flexibility in learning. Despite these advancements, challenges related to personalized learning and equitable access to technology remain, especially in developing countries. Future research should focus on developing affordable, accessible technology-based tools and exploring the integration of technology into curricula for differentiated biology education across various educational levels.

Limitations

This study has several limitations that should be acknowledged. First, the majority of the publications reviewed come from educational and social journals, with limited representation from pure biology fields. This highlights a gap in cross-disciplinary collaboration. Second, while the use of technology in differentiated biology education has grown, research at the secondary school level remains limited, meaning the application of technology at this level has not been thoroughly explored. Furthermore, most studies employ quantitative methods, which restricts a deeper understanding of teachers' and students' experiences in the context of differentiated learning. Lastly, despite the growing body of research, some gamification-based tools were not included in the articles reviewed, even though previous studies have highlighted their potential benefits in differentiated biology education.

Author contributions: AMN, AG, MSS & M: methodology, analysis, writing, review, and editing & **AMN & AG:** conceptualization and writing. All authors have agreed with the results and conclusions.

Funding: This research was funded by the Higher Education Financing Board (BPPT) under the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, and by the Indonesia Endowment Fund for Education (LPDP).

Acknowledgments: The author would like to express sincere gratitude to Prof. Dr. Siti Zubaidah, M.Pd., for her invaluable insights and expertise, which greatly contributed to the completion of this article. Appreciation is also extended to Prof. Dr. Susriyati Mahanal, M.Pd., and Hendra Susanto, S.Pd., M.Kes., Ph.D., for their constructive suggestions and feedback on the article framework.

Ethical statement: The authors stated that the study does not require any ethical approval since it is a review of existing literature.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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