

Digital and Simulation-Based Learning in Biology Education: A Systematic Review Using the PRISMA 2020 Framework

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ABSTRACT

This systematic literature review examined digital and simulation-based learning in biology education in accordance with the PRISMA 2020 reporting guidelines. Forty-eight studies published between 2017 and 2026 were included in the final synthesis. The review focused on virtual reality, augmented reality, virtual laboratories, digital simulations, and related interactive tools used in secondary and higher education biology contexts. Findings revealed four major themes: enhanced visualization of abstract biological concepts; improved engagement and motivation; support for laboratory learning and flexible instruction; and emerging value for scientific reasoning, collaboration, and inclusion. The strongest evidence showed that simulation-based technologies were useful for topics involving microscopic, molecular, dynamic, and three-dimensional biological processes, including genetics, cell biology, osmosis, microbiology, molecular biology, and biomolecular structures. However, the effectiveness of these technologies depended on instructional design, teacher guidance, accessibility, curriculum alignment, and integration with hands-on learning. Although most studies reported positive outcomes, the evidence varied in methodological rigor, sample size, intervention duration, and outcome measures. This review concludes that digital and simulation-based learning can meaningfully support biology education when used as part of a pedagogically guided and blended instructional approach.

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INTRODUCTION

The integration of digital and simulated learning tools has become increasingly vital in biology education, as many core biological concepts are abstract, microscopic, dynamic, or otherwise inaccessible within traditional classroom settings. Over recent years, research in biology and science education has demonstrated that virtual reality (VR), augmented reality (AR), virtual laboratories, digital twins, and interactive simulations enable students to visualize complex biological structures, conduct simulated investigations, and observe scientific processes—experiences that are often difficult to facilitate due to safety constraints, time limitations, or resource costs (Ayer & Miller et al., 2025; Christopoulos et al., 2023; Majewska & Vereen, 2023; Staněk & Špeník, 2025). These technologies are particularly well-suited to topics including cell biology, molecular biology, genetics, physiology, ecology, and microbiology, where learners must frequently interpret invisible mechanisms and three-dimensional relationships.

In biology instruction, simulation-based technologies do not replace traditional teaching materials; rather, they create interactive learning environments that support visualization, experimentation, repeated practice, and timely feedback. For instance, VR-enhanced biology instruction has been shown to deepen student understanding and improve learning outcomes by presenting abstract biological concepts through immersive, interactive experiences (Archibald et al., 2026; Chuang et al., 2023; Majewska & Vereen, 2023). Similarly, virtual laboratories are highly valued by learners, who report that simulations allow them to practice, analyze, and test procedures that may be unsafe or unavailable in physical laboratory settings (Ayer & Miller et al., 2025; Navarro et al., 2024). These findings demonstrate how simulation extends biology instruction beyond the physical boundaries of the classroom and laboratory.

The growing significance of augmented reality (AR) in biology education is also well-documented in recent literature. When deployed in instruction, AR overlays digital biological models onto physical or classroom environments, making it particularly valuable for topics requiring spatial comprehension—such as floral anatomy, cell membrane architecture, and biomolecular structure–function relationships (Panžera-Gonçalves & Oliveira, 2025; Sulisetijono et al., 2023; Vardar-Ulu et al., 2024). A comprehensive literature review further confirms that AR has been applied across all educational levels and is consistently reported to strengthen visualization, motivation, learner engagement, and conceptual mastery (Stanić & Špernjak, 2025). Empirical evidence additionally demonstrates that collaborative inquiry supported by AR can

improve learning outcomes, reduce cognitive load, and foster inclusive participation among students in secondary biology classrooms (Cai et al., 2026).

The global shift toward online, hybrid, and flexible learning accelerated by the COVID-19 pandemic has further elevated the role of virtual laboratories and simulation-based tools in science education. Biology courses inherently rely on laboratory work, yet in-person practical sessions are frequently constrained by limited institutional resources, safety protocols, large class sizes, or disruptions to on-campus instruction. Research confirms that virtual laboratories help sustain continuity in hands-on learning, serve as effective preparatory environments before students undertake physical experiments, and strengthen learner confidence in executing scientific procedures (Ayer & Miller et al., 2025; Jiang & Ning, 2026; Navarro et al., 2024; Sun et al., 2023). Hybrid laboratory models that integrate both simulated and in-person experiences offer a balanced approach, allowing students to develop conceptual understanding and procedural competence prior to engaging in actual laboratory tasks (Ayer & Miller et al., 2025; Navarro et al., 2024).

Despite these advantages, the empirical evidence regarding digital and simulation-based learning in biology education remains limited and inconsistent. Existing studies diverge across educational levels, biological topics, technological modalities, intervention designs, assessment tools, and measured outcomes—spanning academic performance, conceptual mastery, knowledge retention, learner engagement, scientific reasoning, collaborative skills, critical thinking, scientific literacy, accessibility, and student perceptions (Cai et al., 2026; Husna et al., 2026; Neiroukh & Ayoub, 2025; Rannastu-Avalos et al., 2025; Sulisetijono et al., 2023). Furthermore, widespread implementation faces notable barriers, including technical constraints, device limitations, accessibility gaps, language disparities, varying levels of teacher readiness, and the ongoing challenge of balancing virtual experiences with hands-on laboratory skill development (Havlíčková et al., 2023; Husna et al., 2026; Navarro et al., 2024; Stanić & Špernjak, 2025).

Although recent years have seen growing research on virtual reality, augmented reality, and virtual laboratories in science and biology education, a comprehensive synthesis of empirical evidence across these digital and simulation-based tools remains lacking. Most prior studies and reviews focus on individual technologies or narrow instructional contexts, leaving critical gaps in our understanding of broader patterns in technology adoption, learner outcomes, and implementation challenges across diverse biology learning environments. No systematic review to date has consolidated findings across VR, AR, virtual laboratories, and interactive simulations to compare their relative effectiveness, identify consistent benefits, and highlight unresolved limitations in biology instruction. Accordingly, this study addresses this gap by presenting a

systematic literature review that integrates empirical evidence across all these modalities, offering a unified analysis that extends beyond the scope of existing single-technology or narrative reviews.

The primary aim of this study is to systematically review and synthesize empirical studies on the use and impact of digital and simulation-based learning tools in biology education. Specifically, this review characterizes the range of technologies employed, the biology topics addressed, the educational levels examined, the student outcomes measured, and the reported benefits and challenges during implementation. This review aimed to deepen understanding of the impact of VR, AR, virtual laboratories, and simulation-based tools on biology education by synthesizing empirical evidence drawn from 48 included studies.

RESEARCH METHODS

The approach used in this study was a systematic literature review (SLR) to synthesize empirical evidence on digital and simulation-based learning in biology education. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework guided the transparent, systematic, and reproducible review process (Page et al., 2021). Before conducting searches, clear inclusion and exclusion criteria are defined to minimize selection bias, covering study types, publication period, and relevance to biology education. Searches are conducted across multiple academic databases and scholarly search engines to reduce publication bias and ensure broad coverage. Records are screened in two stages – first by title and abstract, then by full text – with documented reasons for exclusion at each step. The methodological quality of included studies is also evaluated by assessing design appropriateness, sample characteristics, intervention duration, and alignment with the review objectives. The PRISMA 2020 guidelines provide updated guidance on searching, locating, assessing, and compiling literature for systematic reviews. In this way, this study sought to explore the use of virtual reality (VR), augmented reality (AR), virtual laboratories, and other simulation-based technologies in biological education, the role these technologies play in improving student learning, and the benefits and challenges they present.

Several academic databases and scholarly search engines were used in a comprehensive literature search. The major databases used for this review were Google Scholar, Scopus, ERIC, and other accessible databases in biology and science education. Further records were identified by manually searching for relevant articles and by following references (Figure 1).

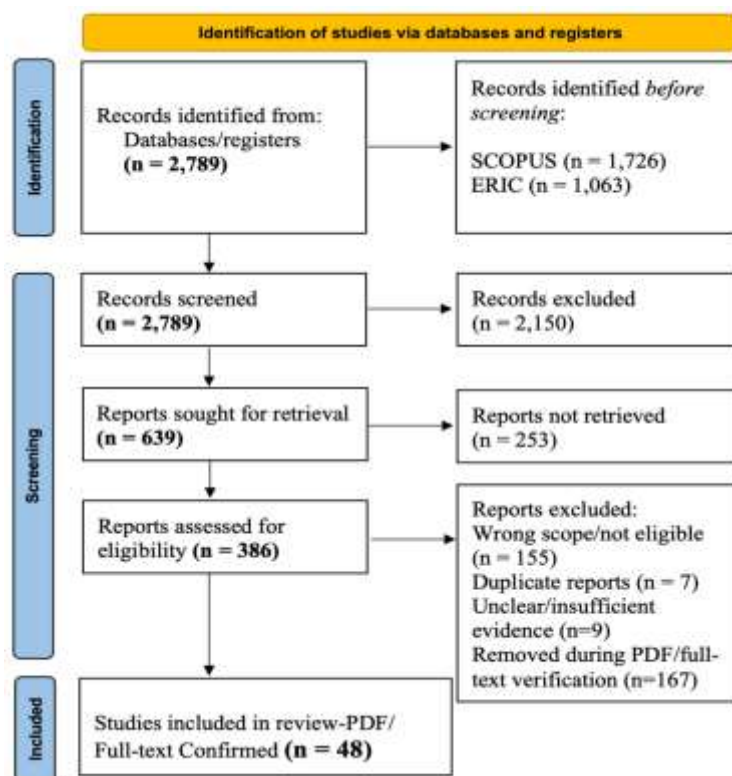


Figure 1. PRISMA (2020) Flow Diagram

The literature search was conducted covering the period 2017–2026 to reflect the latest advances in digital and simulation-based learning technologies in biology education. A combination of keywords and Boolean operators was used to maximize the retrieval of relevant studies, with terms deliberately selected to capture the full scope of the review — the technology, the educational context, and the learner outcomes. These search terms were: “virtual reality” AND biology education, “augmented reality” AND biology learning, “virtual laboratory” AND biology students, “simulation-based learning” AND science education, “immersive learning” AND biology, and “digital simulation” AND biology instruction. Each term was chosen for its established use in the field, its alignment with the review’s objectives, and its proven efficacy in identifying empirical work examining digital and simulation tools within biology teaching and learning contexts. Searches were limited to empirical studies published between 2017 and 2026.

The inclusion and exclusion criteria were established before full-text screening to ensure consistent and transparent selection of studies for the review (Table 1).

Table 1. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Population	Students enrolled in biology, life science, biochemistry, microbiology, or related science courses	Studies focused only on teachers, developers, or general technology users without student learning data
Focus	Digital and simulation-based learning in biology education	Studies unrelated to biology or science learning
Intervention/Exposure	VR, AR, virtual laboratories, digital simulations, immersive simulations, digital twins, or interactive simulation tools	Traditional instruction only, non-digital activities, or technology use without simulation features
Study Design	Empirical quantitative, qualitative, or mixed-methods studies	Conceptual papers, editorials, opinion papers, protocols, or purely technical development papers without educational evaluation
Outcomes	Achievement, conceptual understanding, engagement, motivation, scientific reasoning, science literacy, collaboration, skills, perceptions, or attitudes	Studies with no student-related learning outcome
Publication Type	Peer-reviewed journal articles with accessible full text	Conference abstracts, theses, dissertations, reports, inaccessible papers, or incomplete records
Language	English	Non-English publications
Publication Year	2017–2026	Publications before 2017

This preliminary search provided records from the chosen databases and scholarly search engines. The duplicate records were removed, and the titles and abstracts were screened for relevance to digital and simulation-based learning in biology education. Studies excluded during screening of titles, abstracts, and full texts were not included in the study. Then, the full-text articles were evaluated against the established inclusion criteria. The 48 studies were selected for the synthesis based on the inclusion criteria.

Each article was assessed for methodological clarity, research design, data collection, relevance to biology teaching, and reporting of results to ensure the quality and credibility of the included studies. Information included in the final synthesis was based on studies with clear educational implementation, appropriate research methodology, and relevant outcome measures.

A narrative and thematic synthesis approach was used to analyze and interpret the findings of the included studies. Because of differences in educational contexts, the technologies employed, research methods, and outcome measures, a meta-analysis was not conducted. Rather, the studies were organized and collated into themes and categories that appeared repeatedly across the studies.

The synthesis focused on the types of simulation-based technologies used in biology education, the biology topics and educational levels represented, the student outcomes associated

with simulation-based learning, the reported benefits of digital and simulation-based technologies, and the challenges and limitations associated with implementation.

Patterns, trends, and emerging themes across studies were identified and discussed to provide a comprehensive understanding of digital and simulation-based learning in biology education.

Secondary data were used in this study; thus, no direct interaction with human subjects was needed. Ethics was addressed through transparency, accuracy, and the citation of all sources reviewed. The review process was conducted in accordance with the principles of academic integrity and the ethical standards for systematic literature reviews. The studies cited in the papers were appropriately referenced in accordance with APA 7th edition standards.

RESULTS

The final synthesis included 48 studies. The publication years range from 2017 to 2026; most were published since 2020 and reveal the increasing presence of digital and simulation-based technologies in biology education. The highest number of studies appeared in 2020, 2023, and 2025, with eight studies each.

The majority of studies took place in higher education ($n=30$) and secondary education ($n=16$). Few were of the type relating to elementary or middle school. This indicates that the field of digital and simulation-based biology learning has been studied more than basic education in biology, microbiology, molecular biology, biochemistry, and related courses in universities.

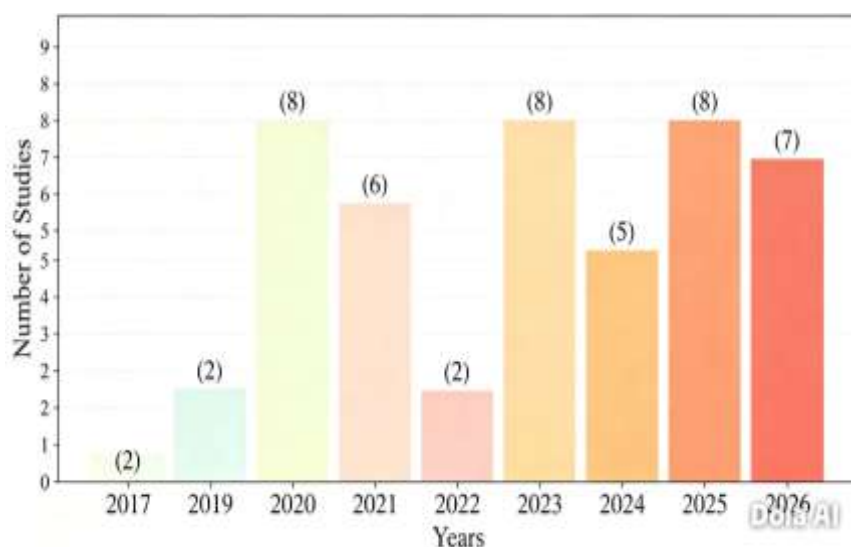


Figure 2. Number of Papers Based on Years

Types of Digital and Simulation-Based Technologies Used

Several types of digital and simulation-based learning technologies were implemented across the included studies. The most popular were virtual reality and 360° VR ($n = 17$), virtual laboratories ($n = 11$), digital simulations or modeling tools ($n = 11$), and augmented reality ($n = 8$).

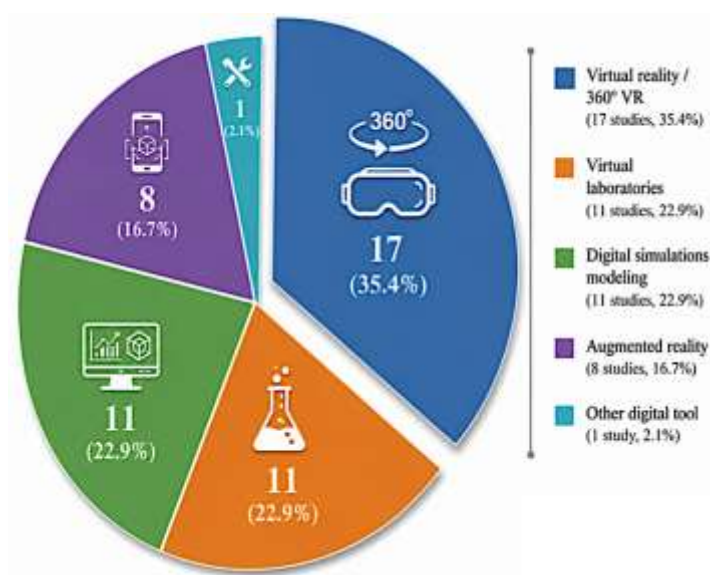


Figure 3. Distribution of Included Studies by Technology Type

Commonly studied subjects with VR were immersive visualization, genetics, cell biology, osmosis, biology labs, and student engagement (Archibald et al., 2026; Majewska & Vereen, 2023; Reinke et al., 2021). For instance, studies on immersive VR reported better achievement outcomes in students' understanding, perceptions, and engagement in learning biology; others reported mixed or equivalent achievement outcomes compared with video-based teaching (Christopoulos et al., 2023). AR studies primarily focused on visualizing biological structures and processes, including biomolecular and floral structures, environmental issues, and co-inquiry activities. The general findings of these studies were positive outcomes in science literacy, scientific explanation skills, engagement, and conceptual understanding (Cai et al., 2026; Sulisetijono et al., 2023; Vardar-Ulu et al., 2024).

Virtual lab studies highlighted laboratory preparation, safe experimentation, repetition, achievement, retention, motivation, and students' perceptions. Some studies documented that virtual laboratories facilitated continuity of learning, particularly in contexts where students were learning virtually or in hybrid environments (Ayer Miller et al., 2025; Navarro et al., 2024; Yap et al., 2021).

Student Outcomes Reported

The most commonly examined outcomes were achievement, performance, conceptual understanding, knowledge, and retention. Many studies also measured affective outcomes, including motivation, engagement, satisfaction, attitudes, perceptions, and confidence. A smaller number examined scientific reasoning, collaboration, laboratory skills, spatial ability, and accessibility.

Table 2. Student Outcome Categories and Frequencies in Digital and Simulation-Based Biology Education Studies

Outcome Category	Number of Studies
Affective outcomes / perceptions	35
Cognitive achievement / understanding	30
Skills and process outcomes	14
Accessibility / inclusion	3

Note. Some studies measured more than one outcome.

Overall, the findings suggest that digital and simulation-based tools were generally associated with positive student outcomes. The strongest evidence emerged from studies measuring engagement, perceptions, motivation, and conceptual understanding. However, the evidence for direct achievement gains was more mixed, especially when simulation-based learning was compared with other multimedia or traditional approaches.

Learning Mapping Matrix

The research study has extracted the information from the record sources. It has been compiled into the following table showing the categories and their compatibility for each topic towards the emerging themes from the synthesis (see Table 3). Where studies spanned multiple educational levels, all relevant levels were coded; frequencies and percentages are reported consistently across analyses.

Table 3. Digital and Simulation-Based Biology Learning Mapping Matrix

Authors, Year	Country	Tech	Biology Topic	Educational Level	Research Method	Themes
1 Pande et al. (2021)	Denmark	VR	Env. Biology; photosynthesis	Higher ed	Quant.	T1, T2, T4
2 Christopoulos et al. (2023)	Finland	360° VR	Cells; genetics; evolution	Upper sec	Quant.	T1, T2
3 Reen et al. (2025)	Ireland	VR	Molecular/cellular biology	Higher ed	Mixed methods	T1, T2
4 Archibald et al. (2026)	USA	VR	Genetics; DNA; heredity	Higher ed	Quant.	T1, T2

	Authors, Year	Country	Tech	Biology Topic	Educational Level	Research Method	Themes
5	Kohnke (2026)	USA	360° VR	Cell biology; organelles	Sec (G9)	Quant.	T1, T2
6	Majewska & Vereen (2023)	USA	360° VR	Human biology; anatomy	Higher ed	Survey	T1, T2
7	Peterson et al. (2020)	USA	AR	Protein; DNA; biomolecules	Under	Survey	T1, T2, T3
8	Cakir et al. (2021)	Turkey	AR	Body systems; physiology	Higher ed	Mixed	T1, T2, T3
9	Byeon & Kwon (2023)	South Korea	360° VR	Plant classification; ecology	High sch.	Quant.	T1, T2
10	Cardoso et al. (2020)	Brazil	DS	Evolution theory; natural selection	High sch	Mixed	T4
11	Karaismailoglu & Yildirim (2024)	Turkey	DS	Molecular genetics; DNA	Higher ed	Mixed	T1, T2
12	Çakırlar et al. (2025)	Turkey	AR	Environmental biology; pollution;	Sec (G 10)	Mixed	T1
13	Quan et al. (2026)	China	VR	photosynthesis; ecosystems	Middle sch.	Mixed	T1, T4
14	Costabile (2020)	Australia	DS	Biochemistry enzymes	Undergrad	Survey	T1, T3
15	Ahmed et al. (2023)	Bangladesh	360° VR	Lab skills; microscopy	High sch	Design	T1, T2, T4
16	Turakulova et al. (2025)	Uzbekistan	VL	Lab equipment; cell structure	Elem/Sec	Quant.	T1, T3
17	Widiana et al. (2024)	Indonesia	AR	Circulatory system; heart	Senior High Grade 11	Quant.	T1, T2
18	Reinke et al. (2021)	Australia	VR	Cell transport; osmosis	Undergrad	Quant	T1, T2
19	Vardar-Ulu et al. (2024)	USA	AR	Biomolecules; Biochem.	Undergrad	Intervention	T1, T3
20	Hoog et al. (2020)	USA	AR	Structural biology; lab tech	Undergrad	Survey	T1, T3
21	Zurita (2017)	Argentina	DS	Genetics; evolution	All levels	Design	T1, T4
22	Panzer-Gonçalves et al. (2025)	Brazil	AR	Cell membranes; transport	Undergrad	Quant.	T1, T2
23	Quesada (2020)	Spain	VL	Enzymology; kinetics	Higher ed	Design	T1, T3, T4
24	Havlíčková et al. (2023)	Czech Republic	VR	Dissection; anatomy	Sec/Teacher ed	Quant.	T1, T3
25	King et al. (2019)	USA	DS	Gene regulation; operon	Undergrad	Mixed	T1, T4

	Authors, Year	Country	Tech	Biology Topic	Educational Level	Research Method	Themes
26	Coan et al. (2020)	USA	VR	DNA transcription	Undergrad	Design	T1, T2
27	Wang et al. (2022)	USA	VR	Cellular biology; tissues	K-12/Undergrad	Design	T1, T2, T4
28	Rannastu-Avalos et al. (2025)	Estonia	VR	Genetics; heredity	Sec (G9)	Mixed	T1, T4
29	Booth et al. (2021)	USA	DS	Metabolism; respiration	Undergrad	Quant.	T1
30	Cai et al. (2026)	China	AR	eye; vision; optics	Sec G7	Mixed	T1, T2, T4
31	Sulisetijono et al. (2023)	Indonesia	AR	Flower; plant anatomy	Undergrad	Design	T1, T3, T4
32	Lorusso & Shumskaya (2020)	USA	DS	Phylogenetics; modeling	Undergrad/HS	Design	T1, T3
33	Mavuru et al. (2020)	South Africa	VR	Photosynthesis; plant phys.	Pre-service teachers	Mixed	T1, T4
34	Suwandi et al. (2023)	Indonesia	Dig. Tool	Classification; taxonomy	Jr high Grade VII	Design	T1, T2
35	Odafe et al. (2021)	Nigeria	VL	Animal dissection	Sr. Sec	Quant.	T4
36	Vries & May (2019)	Denmark	VL	DNA tech; restriction digest	Higher ed.	Mixed	T1, T2
37	Rahbek Dyrberg et al. (2017)	Denmark	VR	Microbiology; toxicology	Undergrad	Pilot	T1, T3
38	Ayer Miller et al. (2025)	USA	VR	Microscopy; PCR ID	Undergrad	Mixed	T1, T4
39	Costabile &Turkanovic (2024)	Australia	DS	Immunology; antibodies	Undergrad	Mixed	T2, T4
40	Animashaunet al. (2026)	Nigeria	DS	Reproduction	Sr. Sec	Quant.	T1
41	Navarro et al. (2024)	Chile	VR	Cell transport; solutions	Undergrad	Mixed	T1, T2, T4
42	Soraya et al. (2022)	Indonesia	VL	Biochem.; blood typing	Med students	Quant	T1, T2, T4
43	Yusuf et al.(2025)	Nigeria	VL	Ecology; human phys.	Sr. Sec	Quant	T1, T4
44	Yap et al. (2021)	Malaysia	VL	Animal biotechnology; animal cell culture	Undergrad	Survey	T1, T3
45	Jiang & Ning (2026)	China	VL	Molecular biology; PCR	Med students	Comparative	T1, T3
46	Husna et al. (2026)	Indonesia	VL	Ecosystem; biodiversity	Jr. high G7	Quant	T1, T3, T4

Authors, Year	Country	Tech	Biology Topic	Educational Level	Research Method	Themes
4 Neiroukh et al. 7 (2025)	Palestine / East Jerusalem	VR	Ecosystem; nervous system	High sch G10- 12	Mixed	T1, T2, T4
4 Wang & Li 8 (2023)	China	VR	Metagenomics; DNA; PCR	Undergrad	Survey	T1, T3

Note. VR = Virtual Reality; AR = Augmented Reality; DS = Digital Simulation; VL = Virtual Laboratory; Env. = Environmental; Sec = Secondary; Sch = School; G = Grade; Quant. = Quantitative; T1-T4 = Theme 1-4.

Thematic Framework

Four themes were inductively derived from the 48 included studies through iterative thematic analysis. The process involved open coding of study findings, grouping related concepts into provisional categories, and refining these into four coherent themes via constant comparison across all studies. Each theme was assigned an operational definition and clear coding criteria to ensure transparency, replicability, and analytical comparability (see Table 3 for theme prevalence). Theme 1: Enhanced Visualization — tools render invisible biological phenomena visible and interactive; coded when studies report improved understanding of microscopic or abstract structures/processes. Theme 2: Engagement & Motivation — positive affective and behavioral outcomes; coded for evidence of enjoyment, interest, reduced anxiety, or sustained attention. Theme 3: Learning Outcomes — measurable gains in knowledge and comprehension; coded for quantitative or qualitative evidence of improved mastery or performance. Theme 4: Accessibility & Utility — practical and equitable benefits; coded when studies address cost, safety, availability, or inclusive access to lab experiences.

Main Themes Emerging from the Synthesis

Theme 1: Enhanced Visualization of Abstract Biological Concepts

The first major theme concerns the capacity of digital and simulation-based tools to make abstract biological concepts more visible and tangible (Archibald et al., 2026; Panzera-Gonçalves & Oliveira, 2025). Many biological concepts involve microscopic, molecular, or three-dimensional processes that students cannot observe directly. Students could interact with representations of genes, chromosomes, cell membranes, osmosis, protein structure, flower structure, and biomolecular interactions using VR, AR, virtual laboratories, and simulations ((Reinke et al., 2021; Sulisetijono et al., 2023; Vardar-Ulu et al., 2024). This indicates that simulation-based learning is particularly useful in contexts where content representation requires spatial reasoning, visualization, and conceptual modeling in biology.

Theme 2: Improved Engagement, Motivation, and Learning Experience

The second theme focuses on the affective learning outcomes of a simulation-based approach to biology. Across all studies, students frequently reported that VR, AR, virtual laboratories, and interactive simulations were engaging, enjoyable, and helpful for learning (Christopoulos et al., 2023; Majewska & Vereen, 2023). These tools seemed to boost curiosity and engagement, as students not only read and listened but also interacted with biological models and simulated environments (Ayer Miller et al., 2025; Navarro et al., 2024). However, not everyone was automatically engaged. Several studies found that students' positive experiences were linked to usability, clear instructions, teacher guidance, and the meaningful integration of technology into the lesson (Havlíčková et al., 2023; Rannastu-Avalos et al., 2025)

Theme 3: Support for Laboratory Learning and Flexible Instruction

The third theme illustrates how virtual laboratories and simulations facilitated laboratory preparation, online teaching, hybrid learning, and multiple practices (Ayer Miller et al., 2025; Jiang & Ning, 2026). In some studies, students conducted experiments, reviewed them, or practiced them in a simulated environment without high risk before engaging in real experiments. This was particularly applicable to biochemistry, microbiology, molecular biology, cell biology, and biotechnology courses (Navarro et al., 2024; Yap et al., 2021). These tools also helped overcome laboratory limitations in accessibility, safety, cost, and time. However, the research indicates that virtual laboratories can be most effective in complementing physical laboratories rather than replacing them, since there are skills in biology education that cannot be learned through virtual laboratories; hands-on skills and the handling of real equipment remain necessary (Costabile, 2020; Yap et al., 2021).

Theme 4: Emerging Value for Inclusion, Collaboration, and Scientific Reasoning

The fourth theme concerns the broader pedagogical significance of simulation-based technologies beyond content learning. A number of studies indicated that simulations facilitated collaborative inquiry, problem-solving, scientific thinking, and inclusive participation. For instance, AR-supported inquiry activities and smartphone-based simulations enabled students to engage in collaborative discussion of evidence and collaborative problem-solving in biology (Cai et al., 2026; Rannastu-Avalos et al., 2025). The potential to support students with and without disabilities in a biology learning context using a browser-based 360° VR platform was also identified. However, achievement, perception, and engagement outcomes were more common than this theme. This suggests that, for future research, there is a need to further explore the potential of simulation for equity, accessibility, collaboration, and higher-order thinking in biology learning (Kohnke, 2026).

Overall, the 48 studies show that the potential of digital/simulation-based learning in biology is generally positive. The strongest evidence was found in the areas of visualization, engagement, motivation, conceptual understanding, laboratory preparation, and student perceptions. There was some variation in the strength of evidence in the studies, though. Quasi-experimental designs and statistical testing were used in some studies, student perceptions, small samples, design-based evaluation, and descriptive results were used in others. In conclusion, the results showed that simulation-based learning in biology is a promising approach, but it requires designing the learning content, making it available, ensuring teacher readiness, aligning it with learning objectives, and integrating it with practical laboratory learning.

DISCUSSION

The findings from this systematic review suggest that, while digital and simulation-based approaches in biology education can be understood as a specific type of technology, they are best conceptualized as a collection of related instructional approaches rather than technological categories alone. This interpretation is explicitly derived from the synthesis of study findings rather than being introduced solely in the Discussion section. The included studies demonstrate that VR, AR, virtual laboratories, digital simulations, and 3D modeling tools address common learning needs in biology education — especially those involving abstract, microscopic, dynamic, and spatial phenomena — through distinct but complementary pedagogical strategies. These technologies were most educationally relevant when linked to an explicit learning goal, designed to encourage active student exploration, and integrated as interactive learning tools rather than passive visual aids.

Visualization and Conceptual Understanding

The two most consistent findings across the 48 studies were that digital and simulation-based technologies help visualize abstract biological concepts and enhance conceptual understanding (see Figure 4). Biology instruction frequently addresses microscopic, molecular, dynamic, and three-dimensional phenomena that students cannot easily observe through traditional teaching methods. Learning in genetics, molecular biology, osmosis, microbiology, biomolecular structures, and cell biology was often supported by VR, AR, virtual simulations, and interactive modeling tools (Archibald et al., 2026; Reinke et al., 2021; Vardar-Ulu et al., 2024). These technologies were particularly useful for helping students connect biological structures, functions, and processes through immersive, interactive experiences that also foster spatial reasoning.

Simulation-based learning further supports conceptual understanding by enabling students to manipulate and observe biological systems otherwise inaccessible in the classroom. For instance, immersive VR allowed students to visualize genes, chromosomes, and cellular processes in 3D, while AR applications enabled interactive exploration of cell membranes, biomolecular interactions, and plant structures (Archibald et al., 2026; Panzera-Gonçalves & Oliveira, 2025; Sulisetijono et al., 2023). Collectively, these findings indicate that visualization technologies enhance science learning by improving students' spatial reasoning and conceptual mastery — though effectiveness depends on instructional quality, as technology itself is only a means, not the end.

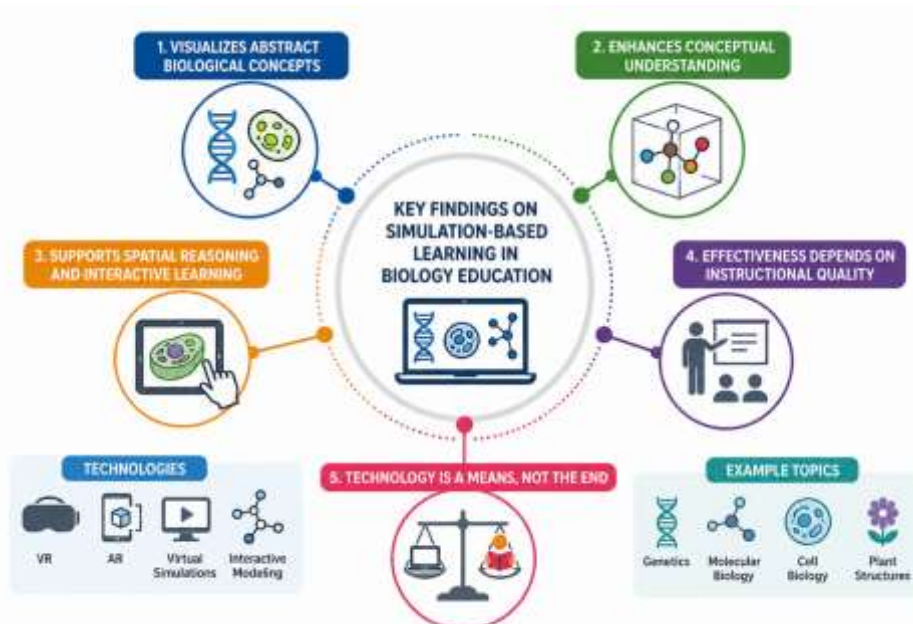


Figure 4. Key Findings on Simulation-Based Learning for Visualizing Abstract Biological Concepts

Engagement, Motivation, and Learning Experience

The second key finding was that simulation-based learning positively affected student engagement and motivation, as well as the overall learning experience. In numerous studies, students reported that VR, AR, virtual laboratories, and digital simulations in biology learning were interactive, entertaining, and supportive, enabling them to be active participants in learning (Ayer Miller et al., 2025; Majewska & Vereen, 2023; Navarro et al., 2024). These technologies seemed more engaging, stimulating learners' curiosity and eagerness to participate in class and lab practice.

The reviewed studies also indicate that engagement is higher when students are actively involved rather than when they receive information passively. The learners interacted with simulations rather than just reading or listening about biological phenomena, explored virtual environments, and manipulated digital biological models. Such modes of engagement can lead to

more effective learning experiences. The results of studies using collaborative inquiry and mobile phone simulations showed similar trends, with students engaging in problem-solving and exploratory learning activities (Rannastu-Avalos et al., 2025).



Figure 5. Simulation-based learning benefits and challenges

However, several studies also highlighted issues of student engagement. The technologies were sometimes less effective in teaching due to technical issues, cognitive overload, device restrictions, and inadequate instruction (Havlíčková et al., 2023). The novelty of VR or AR may initially attract students to the technology, but engagement is likely to be longer if the instruction is of poor quality, the environment is not user-friendly, or it is not a meaningful component of the curriculum. Thus, when it comes to student motivation, the technology itself does not seem sufficient; rather, how effectively it is used in teaching and learning seems to be the factor.

Laboratory Learning and Flexible Instruction

The results also reveal that virtual laboratories and simulations made significant contributions to laboratory teaching, flexible learning, and repeated practice. The majority of the reviewed studies were on biology laboratory activities in microbiology, biotechnology, molecular biology, biochemistry, and cell biology courses (Ayer Miller et al., 2025; Jiang & Ning, 2026; Yap et al., 2021). These studies suggested that simulations can be used to train learners before, review lab procedures, and simulate scientific processes before the lab setting.

The use of simulation-based laboratories was even more important during and after the COVID-19 pandemic, when educational institutions faced disruptions to in-person laboratory

instruction. Students were still able to conduct biology experiments in the virtual laboratory due to limited access to laboratory facilities, safety concerns, and equipment limitations. In this context, simulations helped maintain instructional continuity and offered flexible learning opportunities for online and hybrid learning.

However, the results show that virtual laboratories should not be used as a substitute for laboratory experience. While simulations can facilitate conceptual understanding and procedural preparation, practical laboratory experiences remain important for developing equipment-handling skills and for authentic scientific experiences (Costabile, 2020; Yap et al., 2021). It means that a blended teaching model combining virtual and physical laboratories may be a more balanced and educationally appropriate approach for biology.

Scientific Reasoning, Collaboration, and Inclusion

A smaller subset of studies emphasized simulation-based learning to enhance scientific reasoning, group work, question-asking, and an inclusive learning environment. The use of AR-supported inquiry activities and collaborative simulations facilitated discussions of biological concepts, interpretation of evidence, and team problem-solving (Cai et al., 2026; Rannastu-Avalos et al., 2025). Likewise, students were introduced to the processes of explanatory and evaluative reasoning through simulations and modeling activities in which they built and tested a biological model.



Figure 6. Simulation-based learning benefits and challenges

These results indicate that simulation-based learning might help achieve higher-order thinking in situations involving investigation, evaluation, and explanation of biological phenomena, rather than simply depicting images. Simulations seem to be particularly useful when part of inquiry-based and/or collaborative learning.

The review also uncovered some new evidence on accessibility and inclusion. The 360° VR and AR applications in the browser showed promise in helping students with multiple learning styles. Few studies, however, have directly focused on accessibility, disability support, or educational equity (Kohnke, 2026; Panzera-Gonçalves & Oliveira, 2025). Consequently, the study of inclusion remains largely underdeveloped and deserves greater focus in future research.

Implications for Biology Education

The findings of this review have several implications for biology education. First, simulation-based learning technologies appear most beneficial when used to support the understanding of difficult or abstract biological concepts that require visualization and interaction. Second, teachers play a critical role in ensuring that simulations are aligned with curriculum goals, instructional strategies, and assessment practices. Technology alone does not automatically improve learning outcomes; rather, the effectiveness of digital tools depends on thoughtful pedagogical integration.



Figure 7. Key Implications of Simulation-Based Learning in Biology Education

Third, the findings support the use of blended instructional approaches that integrate simulations with traditional classroom and laboratory experiences. Such approaches may help maximize the benefits of digital visualization while preserving the importance of hands-on scientific practice. Finally, biology educators and institutions should consider accessibility, teacher preparation, infrastructure, and technological support when implementing simulation-based learning environments.

CONCLUSION

This systematic literature review aimed to gather and synthesize findings from 48 studies on digital and simulation-based learning in biology education published between 2017 and 2026. VR, AR, virtual laboratories, digital simulations, and related technologies show promising potential to support biology teaching and learning in secondary and higher education settings, though findings are not yet universal or definitively established. Across the reviewed studies, the most consistent contributions include facilitating the visualization of abstract biological concepts, improving student engagement and motivation, supporting skill development in laboratory settings, and fostering inquiry and scientific reasoning — outcomes directly tied to the technologies' capacity to render microscopic, molecular, and dynamic phenomena visible and interactive.

The results indicate that simulation-based learning technology can be beneficial for learning biology topics difficult to grasp through conventional methods, particularly those involving microscale, molecular, dynamic, and three-dimensional processes. Virtual and immersive technologies enabled students to interact with biological structures and processes more effectively and accessibly, especially in genetics, cell biology, microbiology, molecular biology, and biomolecular studies. Virtual laboratories and simulations further offered flexible alternatives for laboratory preparation, repeated practice, and blended or remote learning.

The review also suggests, however, that technology alone does not ensure improved learning outcomes. Effectiveness depends on instructional design, pedagogical alignment, instructor guidance, and the extent to which tools are integrated into meaningful learning experiences — rather than being adopted for their novelty alone. While most studies reported positive results, variability existed in study quality, sample sizes, and outcome measures. Many investigations focused primarily on student perceptions and short-term knowledge gains, with comparatively limited evidence for sustained conceptual change, higher-order scientific thinking, or long-term retention. These gaps highlight important directions for future research.

Overall, this review supports the growing educational potential of digital and simulation-based learning in biology education. The findings underscore that technology is a pedagogical tool rather than an end in itself, and that its greatest value emerges when paired with sound instructional design. Future research should further examine long-term learning outcomes, inclusive and accessible design, comparative effectiveness across technologies, and the balance between virtual

and physical laboratory instruction to establish evidence-based guidelines for integration into biology curricula.

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The authors declare that there is no conflict of interest regarding the publication of this paper.

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Labajo, C. M.: conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing – original draft, writing – review & editing, project administration, and supervision; **Nacianceno, M. N. V.:** methodology, validation, formal analysis, investigation, data curation, resources, visualization, writing – original draft, and writing – review & editing.

DECLARATION OF THE USE OF AI

This paper used generative AI tools, including ChatGPT-4 by OpenAI for article review and Grammarly for language refinement and textual consistency. Figures 3–7 were created using the ChatGPT-4 image generator. After using these tools, the authors reviewed and edited the content as necessary and took full responsibility for the final publication.

DATA AVAILABILITY STATEMENT

The secondary data used in this study are presented in Table 3. Digital and Simulation-Based Biology Learning Mapping Matrix.

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