Innovative and Interdisciplinary Approaches in Enhancing Learning Outcomes in Biology Education: Integrating Technology, Cognition, and Sociocultural Factors

Addressing the Issues of Online Teaching and Learning: A Review Paper on the Learning Outcome in Biology Education

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ABSTACT

This article integrates the latest and most effective pedagogical approaches for teaching and learning biology with technology, cognitive processes, and sociocultural factors. New technologies such as virtual and augmented reality, digital games, adaptive learning, and artificial intelligence-based tools have shown potential to make students more interested in learning, motivated to learn and engaged while they learn. Cognitive strategies, such as metacognition, self-regulated learning, and scientific reasoning are recognized to be critical for college success. Sociocultural considerations, including culturally responsive education and indigenous knowledge, have also shone a bright light on diversity and inclusion in terms of learning for all. Inquiry-based, flipped-classroom and design thinking are some of the pedagogical approaches that promote creativity and active learning. But equally important to how well their students do is the teachers' knowledge of a subject and how they run a classroom. Assessment of Results —Possible future efforts to maximize technology integration, meet the needs of all learners and promote teacher development could have a great impact on biology learning.

Keywords: Inquiry-based learning, Biology education, educational technology, teacher professional development, self-regulated learning, culturally responsive teaching, interdisciplinary teaching

ABSTRAK

Artikel ini menggabungkan pendekatan canggih dan rentas disiplin yang direka untuk pendidikan dan pembelajaran yang lebih baik dalam konteks biologi, menyepadukan teknologi, proses kognitif dan sosiobudaya. Teknologi baharu seperti realiti maya dan tambahan, permainan digital, pembelajaran adaptif dan alatan berasaskan AI telah menunjukkan janji dalam memacu motivasi, pemahaman dan penglibatan pelajar. Strategi kognitif seperti metakognisi, pembelajaran terkawal kendiri, dan penaakulan saintifik diiktiraf sebagai kunci untuk pencapaian akademik. Dimensi sosiobudaya seperti pengajaran responsif budaya dan pengetahuan orang asli telah membawa kepada penekanan pada kepelbagaian dan keterangkuman ke arah pembelajaran untuk semua. Pendekatan pedagogi seperti berasaskan inkuiri, bilik darjah terbalik dan pemikiran reka bentuk menggalakkan kreativiti dan pembelajaran aktif, manakala pengetahuan kandungan dan amalan bilik darjah guru mempunyai kesan yang ketara terhadap pencapaian pelajar. Ulasan ini menyerlahkan peluang untuk kerja masa depan untuk memaksimumkan pemerbadanan teknologi, memberi perkhidmatan kepada pelajar yang pelbagai, dan membangunkan guru untuk memberi kesan kepada hasil pembelajaran biologi dengan ketara.

Kata kunci: Pembelajaran berasaskan inkuiri, Pendidikan biologi, teknologi pendidikan, pembangunan profesional guru, pembelajaran terkawal kendiri, pengajaran responsif budaya, pengajaran antara disiplin

INTRODUCTION

Biology Teaching in biology is permanently confronted with changing curricula and pedagogic standards, new technologies for doing science, learner heterogeneity and time constraints for taking up the many aspects of teaching content. It is increasingly evident that existing pedagogical practices must be modified or supplemented to incorporate new technologies, circumvent cognitive and metacognitive constraints (Oladipupo et al., 2025; Koukoulidis et al., 2025), as well as social and cultural considerations about how much students engage with learning and do in schools. These diverse requirements require an equilibrium between contemporary teaching strategies, educational technology and frameworks that respect other cultures.

Biotechnology technology development is essential to progress biology education, which has been dominated by immersive, interactive and adaptive learning experiences. Nevertheless, there are several merits in teaching complex cellular structures and physiology in virtual reality (VR) environments since motivation, presence and conceptual understanding may be supported by the immersion into visualizations (Laubscher, Melse et al., 2024; Chuang et al., 2023; Toman & Hubalovska, 2024). AR applications and AR supported e-modules improve the digital literacy, motivation, and cognitive results among elementary to higher education students (Zufahmi et al., 2025; Aldeeb et al., 2024; Li et al., 2024). Furthermore, mobile AR applications enrich customized learning experiences through elevating self-efficacy and engagement (Katyal et al., 2024).

In addition to immersive environments, digital games and simulations have proven useful in promoting biological ‘understanding’ and ‘engagement’. Games based on knowledge organizer have better overall performance than those less-integrated ones, which also emphasizes the importance of peer support and strategic organization of knowledge in game-based learning (Zhao et al., 2025). Punnett Farms and other hard games can teach kids about genetics, and make them learn by doing (Low & Ellefson, d.d.). Virtual labs are now being used in the conceptualization and building of lab skills and using them in an inexpensive and secure digital reproduction, and electronic learning behaviors is one of the factors as a possible strong-unique predictor for successful completion (Bauermeister et al., 2025; Bilici &Yilmaz, 2024; Byukusenge et al., 2022).

Realist adaptive learning environments feature simultaneous feedback, game-based approach to final assessment of knowledge acquisition and the development of multimodal resources together with critical thinking have also produced better educational achievement in biology (greater student engagement, retention and academic achievement) (Aleksandrovich et al., 2024). AR AI chatbots (especially useful for online learning such as during the COVID-19 pandemic) empower individuals to selflearn by motivating and understanding them more (Chuang et al., 2023). The use of multimedia technology and digital storytelling is conducive to academic success, problem-solving skills, communication competences and co-regulation (Bilici & Yilmaz, 2024; Sautiére et al., 2019). Methods like these are designed to engage more students and help them learn new skills.

Cognitive and Metacognitive Processes in Biological Concept Learning.

Recent development of multimodal investigation of temporal dynamics in the domain of self-regulated learning (SRL) has shed new light on how regulatory systems support academic achievement (see Sung et al., 2024). “Directed” or “guided systems”, which employ metacognitive intervention, i.e., cognitive scaffolding for guided problem-solving systems have robust effects on motivation and academic performance (Eticha et al. 2025). Metacognitive awareness and enhanced academic performance at different levels of achievement: The role of reflective tools (Ratnayake et al., 2024). In the same vein, self-efficacy in genetics is primarily a potent predictor of genetics success although

science reasoning drives it (Ojo & Ige, 2025). Cognitive evidence for the use of affective attainment-based goals seems to provide a more comprehensive view of students' learning processes (Elmaş et al., 2023). Additionally, academic success is associated to be a mix of cognitive and metacognitive strategies in which study habits and scientific process skills are involved (Glogger-Frey et al., 2012; Thamarasseri & Martin, 2025).

Interdisciplinarity and societal context are now necessities in the biology curriculum. Culturally and linguistically responsive instruction that integrates language development and culture affirmation with biology content and scientific practices improves multilingual student engagement and learning (Koukoulidis et al., 2025). The integration of indigenous approach to teaching has been positively associated with increased academic achievement scores and self-concept among senior biology students (Oladipupo et al., 2025). Biology-literature cross-curricular classes exploring literature and film texts might encourage critically engaging with complex socioscientific themes, enriching appreciation in humanities and STEM (Squires & Affara 2024). Biomimetic practices promote this transdisciplinary attitude of mind and the increased exploration of nature, sense effects and scientific - technical field (Honra, 2024).

Issues of language and diversity also factor into how students will perform in biology. Studies of multilingual and bilingual biology instruction also pointed to matters with linguistic inversions in addition to the pros- pects for inquiry-based learning as a mediator of conceptual en- gagement within this context (David & Venuste, 2022). The interaction between gender-grouping and type of instruction (e-learning) has a very impressed effect in attitudes and achievement; e-learning surroundings could reduce the barriers to which underprivileged females are subjected in mixed-gender grouping enabling them to have equal participation chances (Almasri, 2022). Some studies reported the improved level of achievements, critical thinking and student's engagement by using inquiry-based learning (IBL), project-based collaboration, and flipped classroom method (Manishimwe et al., 2023; Sukmawati et al., 2019; Ridlo et al., 2022; Reinoso-Tapia et al., 2021). Hybrid problem-based programs can be a way for individuals to remember what they learn and solve problems in the future (Carrió et al., 2016). In the case of career-literacy and design thinking pedagogies, SPiix [self-regulation indicator] predicts for construction of an integrated system of biological, technical and professional skills as well as academic resilience and creative problem solving (Honra et al., 2025; Honra, 2024).

We need to invest in helping educators learn and feel competent. Teachers' domain-specific pedagogical content knowledge (PCK) indirectly is related to student success through effective use of physical models, and diagnostic competencies are positively associated with teachers' professional biological knowledge (For tsch et al., 2018, 2016; Kramer et al., 2021). In addition, positive teacher interpersonal behaviors in the classroom are important predictors with respect to student attitudes and achievement within biology (Cakir & Iskar, 2015). In that respect, meaningfulness and autonomy are considered as moderators in the relationships between mastery goal orientation, motivation and performance of students (Soltani et al., 2022). Extended professional learning develops teachers' formative assessment practice, which is associated with positive student learning impacts (Furtak et al., 2016). Additionally, the use of CPR techniques supports the development by students in computer-assisted resarch education and makes up an integral part in deep, active learning approaches (Clase et al., 2010).

LITERATURE REVIEW

The way biology is taught has evolved a great deal over the last few decades, due to new technologies and discoveries in cognitive science, as well as an understanding that different cultures learn differently. Despite success of teacher-centered approaches in knowledge transfer, such have been criticized for not adequately engaging learning through activeness and reflection on culturally

relevant situations (Oladipupo et al., 2025). To address these gaps, scholars have explored increasingly multidisciplinary approaches that blend educational technology, cognitive and metacognitive processes, and culturally responsive teaching.

New Technologies in Biology Education.

The advent of new technologies has enabled us to transform students' motivation, engagement and comprehension of challenging biological concepts. For instance, applications like virtual reality (VR) and augmented reality (AR) give learners experiential access to the type of cellular structures, genetic mechanisms, and ecological systems that books alone just can't. The literature shows VR fosters conceptual understanding, learner engagement and intrinsic motivation (Laubscher et al., 2024; Toman & Hubalovska, 2024), while AR tools improve digital literacy, self-efficacy and academic achievement in biology education (Zufahmi et al., 2025; Aldeeb et al., 2016). Gamified learning platforms like Punnett Farms have been successful in making abstract topics like Mendelian genetics more accessible and engaging (Low & Ellefson, 2024). Similarly, simulations in virtual and AI-supported adaptive agents provide flexible, cost-effective environments for the development of applied skills and maintenance of content-related knowledge (Bauermeister et al., 2025; Chuang et al., 2023).

Cognitive and Metacognitive Approaches.

In addition to technology, students' cognitive and metacognitive factors are also an influence on their biology learning. Self-regulated learning (SRL) contributes to academic achievement as students that monitor and regulate their learning experiences more, outperform others in multiple scientific domains (Sung et al., 2024). Because metacognitive scaffolding particularly in problem-solving scenarios enhances motivation as well as academic performance (Eticha et al., 2025). Reflection-based techniques such as blogging and structured self-assessment have been found effective in developing metacognitive awareness and sustaining the learning gains over time (Ratnayake et al., 2024). Importantly, scientific reasoning is a more reliable predictor of genetics success than self-efficacy, demonstrating the need for instruction that lead to higher levels of thinking rather than confidence alone (Ojo & Ige, 2025). Taken together, these results provide evidence that developing the students' ability to reflect on how they learn is as important as learning subject knowledge in biology education. Interdisciplinary and sociocultural approaches.

Sociocultural factors and transdiscipline connections enrich biology education.

Culturally relevant pedagogy, which honors students' linguistic and cultural backgrounds, has been found to enable more equitable and engaging scientific classrooms (Koukoulidis et al., 2025). The integration of indigenous knowledge systems makes it more relevant and develops a stronger academic self-concept among students (Oladipupo et al, 2025). Interdisciplinary approaches, for example using literature and film in biology lessons encourage critical thought about social and scientific issues, but also promote creativity and empathy (Squires & Affara, 2024). Both biomimetic and DTC projects allow the future engineers to exercise problem solving through emulating nature, in different disciplines, thus preparing them for a career in no strongly related STEM occupations (Honra, 2024.) When it comes application, within the classroom setting, inquiry-based learning, flipped classrooms and group projects always improve engagement, science literacy, and long-term memory of what you have learnt (Manishimwe et al., 2023; Ridlo et al., 2022).

Teacher Knowledge and Professional Growth.

Lastly, the literature consistently highlights teacher expertise and professional development as drivers of the success of new ideas. PCKurricular has been linked with student learning when combined with diagnostic tools and interactive models (Förtsch et al., 2016; Kramer et al., 2021). Furthermore, positive teacher-students interactions play in creating motivation and success-friendly class-rooms (Cakir & Iskar, 2015). Furtak et al. (2016) stated that teachers are better in engaging in formative practices when they have had ongoing professional development, and students do better when their teachers routinely use formative assessments to guide instruction over time. The results of the study

also showed that benefits of technological and pedagogical innovation can largely be experienced if educators are well-skilled, well-resourced, and supported professionally.

Theoretical Framework

Drawing from a conceptual framework that merges the Cognitive Theory of Multimedia Learning (CTML), Self-Regulated Learning (SRL) theory and Constructivist Learning theories, this article shows how new technologies, ways of thinking and ways of teaching have converged to make learning biology better. Taken together, these theories offer an integrated explanation of how learners engage with information, manage their learning activities and construct conceptual understanding in digital environments and across disciplines.

Cognitive Theory Multimedia Learning (CTML)

Mayer, (2021) recommended CTML as a cognitive framework to unpack how students learn to acquire and integrate biological concepts through digital environments, such as multimedia technologies (e.g., VR, AR, digital games and adaptive learning systems). The reviewed studies have shown that VR and AR enhance understanding, motivation, and engagement by exposing complex cellular and physiological structures in dual-channel visual-auditory modalities leading to lowered cognitive load that supports the formation of mental model (Laubscher et al., 2024; Toman & Hubalovska, 2024). Multimedia-rich AR e-modules and games based off game-based platforms also support with digital literacy, attention, and comprehension (Zufahmi et al., 2025; Low & Ellefson, 2024). CTML also provides an explanation of why multimedia-based tools are effective for supporting people in seeing and making sense of abstract biological phenomena.

Self-Regulated Learning (SRL) Theory

Zimmerman's (2000) model was particularly relevant in the context of our study as its proposed SRL theory includes its metacognitive component that clearly articulates how learners select, plan, monitor, and evaluate task engagement while involved in interactive and inquiry tasks in biology. Studies reviewed also reveal that goal-setting and monitoring, reflective journaling, and strategic regulation SRL practices are significant predictors of academic achievement in biology (Sung et al., 2024; Ratnayake et al., 2024). In such cases metacognitive support resulted in an increase on motivation and successful performance due to the fact that learners are given help on how to manage a cognitive load by keeping engaging in problem solving activities (Eticha et al., 2025). Furthermore, in the domain of self-regulated learning, scientific reasoning is a better predictor of genetic achievement than self-efficacy (Ojo & Ige, 2025). SRL theory informs how students' internal regulations influence the manner in which technology tools and instructional decisions impact learning outcomes.

Constructivist Learning Theory

Building on the constructivist theory of learning, which views learners as actively involved in knowledge construction through interaction, questioning, reflection and problem-solving (Vygotsky, 1978), the pedagogical framework for this review is established. This can be viewed in the findings that researches provide evidence of inquiry-based learning, flipped classrooms, team based projects and interdisciplinary approach to teaching as successful applications when increasing attainment, critical thinking and students' involvement are concerned (Squires & Affara 2024; Ridlo et al. The pedagogical tasks are made to be contextually authentic, so that learners can develop their biological knowledge through engagement in real-life design problems (biomimetics projects or problem-based design-thinking tasks) and work with peers on investigative assignments. This concept states that student-centered instruction has been shown to result in the retention of information over time.

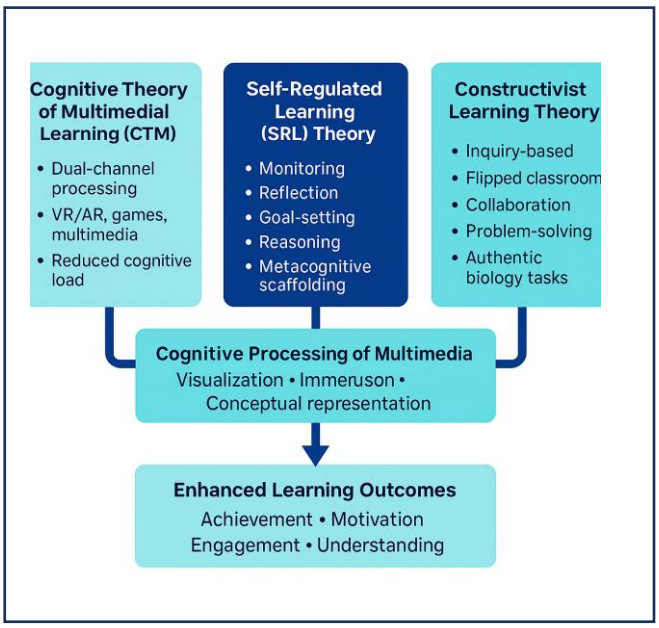

Figure 1: Theoretical Framework Integrating CTML, SRL, and Constructivist Theory
Source: *Adapted from theoretical principles described in Mayer (CTML), Zimmerman (SRL), and Piaget/Vygotsky (Constructivism). Figure created by the authors.*

METHODOLOGY

This study utilized a qualitative synthesis approach to gather insight into recent trends and cross-disciplinary initiatives related with biology education. The eligible articles were peer-reviewed and published from 2015 to 2025, most of which were found through Scopus, Web of Science, and Education Source. Search terms used were biology teaching methods with technology, integrating technology in the classroom, cognitive and metacognitive strategies with sociocultural or interdisciplinary practices. Only articles published in English were included for biology education. Additionally, the articles were supposed to be related to integrated technology (e.g., virtual reality, Gamification, augmented reality, AIbased tools), cognitive process (e.g., self-regulated learning, metacognition, scientific reasoning) and socio-cultural perspective such as culturally responsive teaching (CRT), indigenous knowledge and interdisciplinary pedagogical approaches and they should have reported empirical or review-based evidence. Excluded were non-peer-reviewed contributions, irrelevant discipline studies and theoretical papers without empirical foundation. A thematic analysis was performed, based on the principles of Braun and Clarke's (2006) thematic synthesis. This process required an understanding of the data, coding inferences, identity of patterns among studies within and between articles. Three mainline themes were discovered: (a) technology innovations in biology education, (b) cognitive/metacognitive strategies and (c) social/cultural/interdisciplinary approaches. These are discussed in the results and discussion that follow.

RESULT

This review compiles 45 studies that try to give a more comprehensive picture of innovation in biology education. As for technology innovation domain, the benefits of VR tools over motivation, conceptual understanding and learners' engagement (i.e., means, perceived ease of use) is constantly reported (Laubscher et al., 2024; Zufahmi et al., 2025). For instance, one such context, the genetics-based Punnett Farms was found to increase comprehension and engagement in students (Low & Ellefson, 2024). Similarly, to the aforementioned, adaptive courses and AI-based modules enhanced

students' self-decision learning, autonomy and academic success (Aleksandrovich et al., 2024; Chuang et al., 2023).

The second focuses on cognitive and metacognitive approaches. SRL and Reflective Learning having strong predictive impact on academic performance have been reported in the literature (Sung et al., 2024; Ratnayake et al. Metacognitive scaffolding and problem-solving model to combined students' motivation and performance (Eticha et al., 2025). Importantly, science reasoning was a stronger predictor of genetics achievement when compared to general genetics self-efficacy (Ojo & Ige, 2025), suggesting that reason-focused interventions result in more lasting gains.

There is another aspect of which, culturally and intercultural (that's a third area). Culturally responsive teaching and indigenous knowledge use were found to lead to improved engagement, self-concept, and achievement amongst students (Oladipupo et al., 2025; Koukoulidis et al., 2025). STEM field bridges (biology and here: film, or literature, or biomimetics) developed critical thinking skills and attitudes to persevere and think creatively (Squires & Affara, 2024; Honra, 2024). Related pedagogical practices (see for example inquiry-based learning, flipped classrooms, project based collaboration) showed to have contributed a positive effect on participation and longer lasting memorization Manishimwe et al., 2023; Ridlo et al., 2022; Reinoso-Tapia et al., 2021. Teacher professional knowledge, classroom interactions as mediators: An overarching framework across these foci is the role of teacher professional knowledge and classroom interaction as mediators of student learning (Förtsch et al., 2016; Cakir & Iskar, 2015).

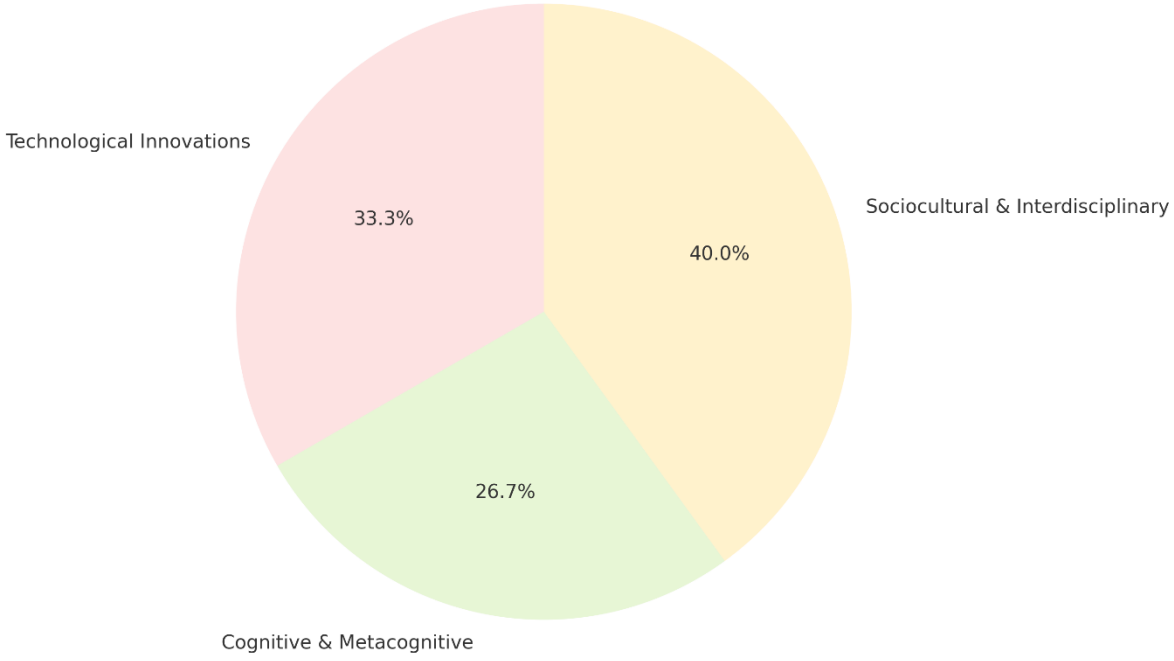

Figure 2 : Distribution of Studies by Thematic Domain in Biology Education Review
Source**:** *Derived from thematic coding of studies in the review.*

Table 1: Synthesis of Innovative and Interdisciplinary Approaches in Biology Education

Domain	Approach/Tool	Reported Outcomes	Key References
Technological Innovations	Virtual Reality (VR)	Improved motivation, presence, and conceptual understanding of cellular structures and physiology	Laubscher et al. (2024); Chuang et al. (2023); Toman & Hubalovska (2024)
	Augmented Reality (AR) & AR-assisted e-modules	Enhanced digital literacy, motivation, and learning achievements	Zufahmi et al. (2025); Aldeeb et al. (2024); Li et al. (2024)
	Game-based learning (e.g., *Punnett Farms*)	Increased motivation, comprehension, and interest in genetics	Low & Ellefson (2024); Zhao et al. (2025)
	Virtual laboratories	Improved conceptual understanding, lab skills, and positive attitudes toward e-learning	Bauermeister et al. (2025); Bilici & Yilmaz (2024)
	Adaptive/AI systems & Chatbots	Greater engagement, self-directed learning, and academic performance	Aleksandrovich et al. (2024); Chuang et al. (2023)
Cognitive & Metacognitive Strategies	Self-regulated learning (SRL)	Strong predictor of academic achievement; enhanced engagement	Sung et al. (2024)
	Metacognitive scaffolding	Increased motivation and academic achievement in problem-solving	Eticha et al. (2025)
	Reflective practices	Promoted sustained self-regulated learning and awareness	Ratnayake et al. (2024)
	Scientific reasoning	More robust predictor of genetics achievement than self-efficacy	Ojo & Ige (2025)
	Achievement goal integration	Richer learning processes combining cognitive and affective outcomes	Elmas et al. (2023)
Sociocultural & Interdisciplinary Approaches	Culturally responsive teaching	Enhanced engagement and learning for multilingual students	Koukoulidis et al. (2025)
	Indigenous knowledge integration	Improved academic performance and self-concept	Oladipupo et al. (2025)
	Interdisciplinary (biology + literature, film, biomimetic projects)	Fostered creativity, resilience, and critical socio-scientific engagement	Squires & Affara (2024); Honra (2024, 2025)

Domain	Approach/Tool	Reported Outcomes	Key References
	Inquiry-based and flipped classrooms	Improved achievement, critical thinking, and participation	Manishimwe et al. (2023); Ridlo et al. (2022); Reinoso-Tapia et al. (2021)
	Teacher professional development & PCK	Enhanced diagnostic competence, classroom climate, and formative assessment practices	Förtsch et al. (2016); Kramer et al. (2021); Furtak et al. (2016)

Note. PCK = Pedagogical Content Knowledge; AI = Artificial Intelligence.

Based on the results of a meta-analysis of 45 research studies, three main thematic categories of TI—technological innovations, cognitive and metacognitive strategies, and sociocultural and interdisciplinary contexts—emerged to show a combined substantial influence on biology learning gains.

Technological Innovations

There was the positive effect from technology on biology education which was supported by many studies. Both virtual reality and augmented reality were heavily present, allowing for students to have engaging learning experiences – seeing somewhat abstract biological processes such as molecular structures, ecosystem interactions or physiological processes. The resources not only improved conceptual learning but also promoted motivation and engagement by providing a range of multisensory, interactive activities (Laubscher et al., 2020; Zufahmi et al., 2021). AR e-modules and mobile AR apps were also found to be effective in improving students' digital literacy level while according to the student-centred instructional model (Aldeeb et al., 2024; Li et al., 2024).

Game-based learning and computer simulations were also significant predictors for achievement. Strategy and collaboration support in knowledge-organizer games were elevated by collaborative learning, while students learned with the genetic concept literature and got interested through persuasion received from a serious game such as Punnett Farms (Zhao et al., 2025; Low and Ellefson, 2024). In instances where apparatus is simply not available, online ‘laboratories can offer safe, economical and scalable platforms for skills and conceptual development (Bauermeister et al., 2025). On the other hand, adaptive systems and AI technology for example chatbot integrated AR provided instant help, facilitated personalized learning and improved academic performance (Chuang et al., 2023; Aleksandrovich et al., 2024). Overall, this would suggest the potential for technology being a significant disruptor with conscious pedagogical design.

Cognitive and Metacognitive Strategies

The second theme area focused on the contributions of cognitive and metacognitive aspects to sustained learni ng. S self-regulated learning (SRL) emerged as a strong predictor of academic achievement, and multimodal analyses showed that students' SRL via regulation strategies was related to better biology scores in school" (averaged across courses); Sung et al., 2024. Likewise, metacognitive scaffolds enriched denser and coherent problem-solving models and positively influenced motivation and achievement among students; gaining the fact that scaffolding stimulates to think independently (Eticha, et al 2025).

Reflective planning was cited to be successful in helping generate metacognitive awareness and maintain performance among mixed learner groups, particularly through structured self-assessment and journaling (Ratnayake et al., 2024). Through these practices in which the learners internalize and embody the ideas (and develop habits of self-monitoring), they acquire biology culture. Most importantly, Scientific Reasoning was found to predict Genetics achievement more than Self-

Efficacy in agreement with students' preference for instructional teaching that promotes reasoning skills and inquirybased learning rather than working based on confidence enhancement (Ojo & Ige, 2025). Such coupling of Cognitive and affective goals facilitated the students learning about both persistence and deep understanding of concepts (Elmas et al., 2023). Collectively, these results illustrate the importance of "balancing" biology instruction—that is, providing conceptual content along with cognitive skills to school going children.

Sociocultural and Interdisciplinary Approaches

All the final keys above are words to do with sociocultural context and multidisciplinarity as transformative of learning. CRB was highly relevant in multilingual and diverse environments where language development, cultural affirmation, were embedded within biology contexts ensuing engagement and equitable diversity (Koukoulidis et al., 2025). In addition, when indigenous knowledge is integrated, senior students demonstrated a greater self-concept and better academic performance because of the relevance of their cultural practices in science curriculum (Oladipupo et al., 2025).

Interdisciplinary discoveries were also instrumental. Biology content linked to literature, film or at design-thinking practices appeared capable of promoting creativity, resilience and critical reflection on socio-scientific problem solving (Squires and Affara, 2024; Honra 2024). Biometry-based projects have shown particular success in supporting cross-curriocular problem solving and, thus, engaging students to apply knowledge in STEM fields and develop skills for critical thinkıng (Honra & Di Paola, 2025). Pedagogical approaches -inquiry-based learning, flipped classroom and projects-oriented-learning- were again successful across all outputs: academic performance, critical thinking and discernment (Manishimwe et al., 2023; Ridlo et al., 2022; ReinosoTapia et al., 2021) becoming themselves active learning practices.

Lastly, teacher knowledge and professional development appeared to be a crucial mediating factor for all (sub-)dimensions. Teaching content and pedagogical knowledge (Pedagogical Content Knowledge, PCK) and diagnostic competences were largest predictors for student learning outcomes among teachers and sustained professional development programs empowered teachers to implement "formative assessment" or create positive classroom climates over time (Förtsch et al., 2016; Furtak et al., 2016). These findings reinforce the argument that sustainable biology educational innovations rely not just on technology and pedagogy integration, but also on sustained investment in teacher knowledge.

Comparative Summary of Findings

The most commonly visited was the sociocultural and interdisciplinary frameworks, which were also the commonness themes in all personal domains. These approaches had strong evidence for improving inclusivity, cultural relevance and student retention in multilingual and diverse contexts (Koukoulidis et al., 2025; Oladipupo et al., 2025). Some technological innovations also evidenced a strong effect, for example students were more inclined to comprehend theories that were fairly complex in nature thanks to digital and adaptive tools (Laubscher et al., 2024; Bauermeister et al., 2025). However, they were all limited in the effectiveness given teachers' professional knowledge and accessibility. Even though cognitive and metacognitive strategies, reported in fewer but more effective studies, did not have most significant effects on achievement and retention from given within the course of studies… reasoning became key predictor of genetics learning outcomes (Ojo & Ige, 2025). Altogether, these results suggest that technology may provide powerful means of engaging students and sociocultural responsiveness ensures inclusiveness but cognitive and metacognitive strategies are what compel deep and sustainable learning in biology.

DISCUSSION

The findings point out that the technological, metacognitive and socio-cultural progress are determining biology education. Close to todayNowadays, Immersive technologies can provide students experiences that are interactive and seem to be designed according to the principles of cognitive theory and neuroplasticity, and facilitate better understanding on concepts such as best practice features (Mayer, 2021; Toman & Hubalovska, 2024). Application of PPE in applications and teacher preparedness is a great concern, though the financial implication for its use has still to be addressed. The findings also support the influence of cognitive and metacognitive strategies on learning. SRL and metacognitive scaffolding not only promote short-term benefits, but also contribute to longer-term academic gains (Ratnayake et al., 2024). This information implies that teacher educating on the meaning of student reflection and regulation as well as how to encourage reflection through teaching should be included in biology teaching. The stronger predictive value of genetics knowledge for scientific reasoning, as opposed to self-efficacy, also implies that instruction that focuses more directly on strategies for reasoning may have a greater contribution to academic growth in genetics.

But these sociocultural and cross-disciplinary aspects are also very significant in biology instruction. CR teaching represents and plays a big part the affirmation of students' identity as linguistically diverse, meaning the anchored engagement to academic learning which is made available (Koukoulidis et al., 2038). Integration of indigenous knowledge will enable the trick-at-home close to students and promote positive race relations and learner's achievement (Oladipupo et al., 2025). Interdisciplinary ones, including biomimetic projects and reading-based analysis contribute to extend the scope of biology education; hence a world literate community that can face multimodal complex transdisciplinary challenges of the new millennium (Honra, 2024; Squires & Affara, 2024). And, the most important factor in the effectiveness of new methods is the teacher's place. Teachers' confidence with Pedagogical Content Knowledge (PCK) and the fostering of a positive learning climate are some factors that directly affect student motivation and achievement (Förtsch et al., 2016; Cakir & Iskar, 2015). High-quality professional development programs focused on the development of teachers' diagnostic and formative assessment practices are also likely to be required for consistently collecting and interpreting evidence of learning needed to support sustained innovations in biology instruction (see, for example, Furtak et al., 2016).

In conclusion, from this review, it is evident that the integration of technology, cognition and sociocultural responsiveness supports enhanced biology learning across educational contexts. To ensure long-term change in the teaching of biology more research on the longitudinal effects of technology-enhanced interventions, development of culturally aligned curricula and implementing teachers' education programs is suggested.

SUGGESTIONS

Suggestion for the Policymakers

These review results have far-ranging implications for audiences in biology education. The implications of the results for policy makers, especially the Ministry of Education, are that there is a need to adjust national curricula to reflect changes in technology and work that are increasingly multifaceted. the investments into the u-tainment, adaptive learning systems and other en- rative technologies have been leading to better student increased understanding concepts of et al. (2024), Toman & Hubalovska, 2024). For this, efforts at the national level need to be directed towards creating digital infrastructure, imparting teacher training and ensuring that equality in experiences across schools is achieved to bridge the learning gap. Likewise, cognitive and metacognitive strategies—self-regulated learning skills, reflection and scientific reasoning—are part of any classroom innovation that is shown to have relatively very strong effects (Sung et al., 2024; Ojo & Ige, 2025).

It is urgent for instructors to adopt new teaching approaches like the inquiry-based, flipped classroom and project- based pedagogies as these have a potential to increase participation, promote critical thinking and long-term retention of knowledge in both small-and large-class settings (Manishimwe et al., 2023; Reinoso-Tapia et al., 2021). Teachers should also receive support through a range of PD opportunities aimed at strengthening diagnostic CS competences, pedagogical content knowledge and culturally responsive instructional practices (Förtsch et al., 2016; Koukoulidis et al., 2025). It is critical to prepare teachers who are" adept and proficient in these areas, so that technology and pedagogy can be integrated across diverse classroom environments.

Suggestion for the Parents

Parents and families should encourage learning outside of the classroom, according to the review. Parents can enhance students' work in biology courses by encouraging reflective discussions, validating cultural knowledge and advocating for positive use of digital tools at home. The engagement with novelty as above is aiding self-regulated learning and metacognition development and is conducive to longer-term high academic performance (Ratnayake et al., 2024). Inclusion of parents on the other hand results in culturally responsive learning thus fostering students' motivation and resiliency (Oladipupo et al, 2025). Collectively, these issues increase the demand that there be systemic collaboration among government agencies, schools, and families regarding the promotion of biology in education. If it is tilted towards a direction that includes the use of technology-enhanced approaches, cognitive and cultural dimensions are considered worthwhile, biology education will be more inclusive and stimulating at the same time as providing today's learners with relevant 21st century skills. The results of this review have significant implications for various biology stakeholders

CONCLUSION

This integrative synthesis demonstrates that an integrative inclusion of technological advancements, cognitive approaches, and sociocultural practices in biology education present the past and future of biology education. In particular, the influence of virtual and augmented reality technologies, digital games and AI-based systems can generate strong engagement, motivation and comprehension in learners. Concurrently, attention to self-regulation, metacognition, and argumentation have all been demonstrated to predict academic success. CR teaching and inter-d can deliver holistic & authentic experiences by being more targeted on students' culture, which consequently leads to creativity. Furthermore, teaching methods like problem-based learning and flipped classrooms promote activity while others that emphasize thought, creativity and job application focus on essential future problem-solving skills. In the end, realizing these benefits really does come down to teacher capacity and learning environment but while much of what we discuss in this review has been achieved not just much it has yet been scaled or managed as effectively. finiteElementAssessment\ roleresult: These consist of examining whether the present technologies are scalable, advancing sociocultural values on integration and developing systems to help teacher professional improvement. Future research should involve scaling studies into technologyembedded longitudinal learning, development of culturally responsive education curriculum andarchitecture teachers' training architecture to enact the innovation effectively.

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