STATE OF THE ART IN RESEARCH ON SCIENCE TEACHING AND LEARNING IN BIOLOGY

Akinola, Yetunde Falilat
Department of Science, Education Faculty of Education
University of Lagos, Akoka – Lagos
akinolayetundeulws@yahoo.com

Abstract

This paper reviews the state of the art in Biology education, highlighting the shift from teacher-centered, exam-driven practices to innovative, student-centered, and technology-enhanced approaches. Biology plays a vital role in addressing global challenges such as climate change, biodiversity loss, and public health, yet many classrooms still rely on outdated methods that hinder conceptual understanding and application. Research demonstrates the effectiveness of inquiry-based, project-based, collaborative, and experiential strategies, supported by digital tools including virtual laboratories, simulations, and AI-powered platforms. These approaches foster critical thinking, creativity, and problem-solving skills while enhancing student engagement. Strengthening teacher competencies through Pedagogical Content Knowledge (PCK), Technological Pedagogical Content Knowledge (TPACK), and Continuous Professional Development (CPD) is essential for sustainability. However, challenges such as inadequate infrastructure, resistance to change, and curriculum-policy misalignment persist. The review concludes with a call for scalable, inclusive, and culturally responsive innovations that align research with practice and equip learners with 21st-century skills.

Keywords: Biology education; science teaching and learning; innovative instructional strategies; technology integration; teacher professional development; 21st-century skills

Introduction

The teaching and learning of biology are undergoing significant transformation, reflecting wider changes in education and the demands of a rapidly evolving world. No longer is biology education limited to rote memorization and content delivery; it now increasingly aims to develop skills such as critical thinking, creativity, problem solving, and collaboration that are essential for the twenty first century (Trilling and Fadel, 2009). These shifts are fueled by new technologies, innovative pedagogical models, and a growing awareness of the role of science education in addressing pressing global challenges.

Biology, as a discipline, plays a central role in helping learners understand issues such as climate change, public health crises, biodiversity loss, and environmental sustainability. Consequently, there is heightened interest in research that explores how teaching strategies can enhance students' engagement and connect biological concepts with real life applications (Bybee, 2020; Zeidler, 2016; Chukwu et al., 2022).

State of the art research in biology education refers to the most current, evidence based, and innovative strategies that aim to improve how students experience and understand biology. These approaches include student centered learning models, the integration of digital tools, interdisciplinary teaching, and culturally responsive pedagogy. While these developments have shown positive impacts on student achievement and motivation, their successful adoption requires systemic changes in curriculum design, teacher competencies, and resource allocation.

Although biology is uniquely positioned to prepare students for understanding and responding to real world challenges, many classrooms still rely on outdated, teacher centered methods. Such approaches are typically examination driven and prioritize content coverage over meaningful understanding, inquiry, and critical thinking (Akinpelu, Yusuf, and Amadi, 2023). This creates persistent gaps in students' ability to apply biological knowledge to everyday contexts and undermines their preparedness for higher education and the demands of the modern workforce.

The integration of research informed strategies, such as inquiry-based learning, project-based approaches, and the use of digital tools, remains limited. Barriers include insufficient infrastructure, misalignment between curriculum policies and classroom practices, and inadequate professional development for teachers (Ojo and Adebayo, 2022; Akpan and Okoro, 2021). These factors collectively reduce the impact of innovative reforms and contribute to the slow progress in transforming biology education.

Bridging these gaps requires not only adopting state of the art teaching methods but also ensuring that these practices are contextually appropriate, supported by ongoing teacher training, and reinforced by policies that prioritize meaningful science learning.

Literature Review

Innovative Approaches to Teaching Biology

Contemporary research in biology education shows a decisive shift from teacher dominated instruction to approaches that actively involve students in constructing their own knowledge. These approaches are rooted in constructivist principles and emphasize participation, collaboration, and the development of critical thinking skills. Studies suggest that when learners are engaged in exploring concepts, asking questions, and applying knowledge to real world contexts, they achieve a deeper understanding of biological principles (Aydin-Gunbatar, Bozdag, and Yilmaz, 2021; Aslan, Durmuş, and Aydin, 2023).

Inquiry based learning is one of the most widely discussed of these approaches. It encourages students to investigate questions, gather evidence, and build their own explanations, thereby reflecting the authentic practices of scientists (Krajcik and Delen, 2017). Project based learning builds on this by allowing students to work on extended tasks that link classroom theory with practical application, while problem based and collaborative learning promote teamwork and peer-to-peer knowledge exchange (Matongo and Goronga, 2024). These approaches do more than enhance academic performance; they also nurture communication, creativity, and problem-solving abilities, which are essential for lifelong learning.

The flipped classroom model further extends this reform by enabling students to access instructional content outside class time through recorded lectures or online resources. Classroom time is then repurposed for discussions, experiments, and applied tasks, making learning more interactive and personalized (Pal, 2025). Similarly, experiential learning and choice-based learning provide students with agency, allowing them to make decisions about what and how they learn. Collectively, these strategies represent a paradigm shift in biology education, transforming classrooms into spaces for inquiry, dialogue, and active knowledge creation.

Integration of Digital Tools in Biology Education

The integration of digital tools has become a central feature of modern biology education. From the teaching perspective, technology enhances lesson delivery by providing interactive and visual means of presenting complex content. Tools such as interactive whiteboards, multimedia platforms, and virtual laboratories help simplify abstract concepts and make lessons more engaging (Rutten, van Joolingen, and van der Veen, 2012). Artificial intelligence driven applications go further by analyzing students' progress and offering personalized feedback, allowing teachers to address individual learning needs more effectively (Holmes, Bialik, and Fadel, 2019).

For learners, technology creates opportunities for exploration and personalized learning. Virtual laboratories allow students to conduct experiments in safe, simulated environments, which is particularly valuable where physical laboratory resources are limited. Simulations provide dynamic representations of biological systems, enabling learners to visualize processes such as photosynthesis or cell division that are otherwise difficult to observe. Educational applications also provide adaptive, self-paced activities that help students consolidate their understanding and track their progress. Research indicates that such tools can increase motivation, support differentiated learning, and improve academic achievement (Talan and Gulsecen, 2023).

Interdisciplinary Approaches

Biology is increasingly being taught through interdisciplinary frameworks that draw on knowledge and methods from multiple fields. The integration of science, technology, engineering, and mathematics (STEM) has been particularly significant in fostering innovation and preparing students for real world problem solving. By situating biology within these broader contexts, learners gain a holistic understanding of complex phenomena and develop skills that are transferable across disciplines.

Culturally Responsive Pedagogy

Culturally responsive pedagogy has also gained prominence as a means of making biology education more inclusive. This approach recognizes the importance of students' cultural backgrounds, languages, and lived experiences in shaping how they learn. By incorporating locally relevant examples, indigenous knowledge systems, and culturally appropriate teaching strategies, educators can make biology more meaningful and accessible to diverse groups of learners (Jegede and Aikenhead, 2021). Such approaches enhance students' sense of belonging and engagement, which are key to improving academic performance and broadening participation in science.

Enhancing Teacher Competence

The successful implementation of these approaches depends heavily on the competence of biology educators. Pedagogical content knowledge, first articulated by Shulman (1986), remains a core requirement, enabling teachers to present complex biological content in ways that are understandable and meaningful to students. In the current educational context, this is complemented by technological pedagogical content knowledge (TPACK), which integrates the effective use of digital tools into teaching practice.

Continuous professional development is essential for building these competencies. Regular training, mentoring, and collaborative learning opportunities help teachers stay updated on emerging pedagogical and technological trends. Research shows that when educators are confident in their skills and supported in their professional growth, they are more willing to adopt innovative practices and create learning environments that are both engaging and effective (Fisser, Voogt, and van Braak, 2022).

Challenges and Gaps in Implementation in Biology Education

While research in biology education has advanced considerably, the translation of these innovations into classroom practice remains inconsistent. Several systemic and contextual challenges continue to hinder the effective adoption of modern teaching approaches, particularly in under-resourced settings.

A critical limitation is the lack of digital infrastructure. In many schools, especially across Sub-Saharan Africa, reliable internet access, stable electricity, and access to digital devices remain inadequate. According to UNESCO (2023), over forty percent of schools in the region still lack the basic tools necessary to support blended or technology-assisted learning environments. This scarcity makes it difficult for teachers to implement strategies that rely on digital platforms, virtual laboratories, or artificial intelligence driven applications, regardless of their documented benefits. The shortage of laboratory facilities and instructional materials also limits the opportunity for hands-on, inquiry-driven learning experiences that are vital to effective biology education.

Overcrowded classrooms add to these constraints, reducing the feasibility of student centered approaches such as project work, group discussions, or practical investigations. In these environments, teachers often default to lecture based instruction to manage large numbers, undermining the benefits of interactive and personalized learning. Teacher resistance to adopting new methods is another barrier. Even when technological tools are available, some educators are reluctant to integrate them due to lack of familiarity, fear of being replaced, or limited confidence in their own digital skills.

As Ojo and Adebayo (2022) note, entrenched teaching habits and insufficient preparation in digital competencies significantly affect educators' willingness to embrace innovation. This resistance is closely linked to the limited professional development opportunities available. Akpan and Okoro (2021) report that less than twenty percent of secondary school biology teachers in Nigeria had received digital training in the two years preceding their study, highlighting a serious gap in capacity building.

Curriculum-policy misalignment further complicates reform efforts. While policies may advocate for the integration of technology and student-centered approaches, actual curriculum guidelines and assessment systems often remain rigid, privileging rote memorization and high-stakes examinations over inquiry and critical thinking (Akinpelu, Yusuf, and Amadi, 2023). This disconnects leaves teachers with little incentive or guidance to adopt innovative practices.

Cultural and linguistic factors also pose challenges. Lessons delivered in languages unfamiliar to students or using examples disconnected from their lived experiences can limit comprehension and engagement. As Jegede and Aikenhead (2021) argue, failing to consider students' cultural and ecological contexts risks alienating them from the subject matter, thereby reducing the effectiveness of instruction. Finally, the persistence of traditional assessment models undermines the implementation of creative, inquiry-based strategies. Examinations that emphasize factual recall rather than application discourage both teachers and students from engaging deeply with scientific ideas.

These challenges highlight the need for a holistic approach to reform. Investments in infrastructure, ongoing professional development, curriculum realignment, and culturally relevant teaching strategies are essential for realizing the potential of state-of-the-art practices in biology education.

Factors Influencing Learning Outcomes in Biology Education

Understanding what influences learning outcomes in biology goes beyond examining teaching strategies or the use of technology. Students' performance in biology is shaped by a complex interaction of cognitive, affective, and contextual factors that determine how they engage with content, process information, and apply knowledge.

Cognitive factors play a central role in biology learning. Beyond memorizing facts, students are expected to develop conceptual understanding, engage in critical thinking, and apply scientific reasoning to explain biological processes. For instance, understanding systems such as ecosystems or cellular functions requires learners to make logical connections between concepts, draw on prior knowledge, and solve problems in novel contexts. As Zeidler (2016) argues, developing socio-scientific reasoning—the ability to evaluate and make decisions about complex, real-world science issues—is an essential outcome of modern biology education. These cognitive skills enable learners to move from surface-level knowledge to deeper, transferable understanding.

Affective factors, including motivation, interest, and attitudes toward science, significantly influence how students engage with biology. Learners who find biology relevant to their lives or who are emotionally invested in the subject are more likely to participate actively, persist with challenging tasks, and achieve higher academic outcomes. Positive classroom environments, where teachers provide encouragement and foster meaningful student-teacher interactions, further enhance students' willingness to learn (Chukwu, Ugwuegbulam, and Ahiakwo, 2022). Such affective dimensions are critical for maintaining long-term interest in science, particularly for students from marginalized or underrepresented groups who may not initially see biology as accessible or valuable.

Contextual factors also shape biology learning. These include the broader cultural, social, and ecological environments in which education takes place. In multicultural classrooms or communities where biology is taught using foreign examples and unfamiliar contexts, students may struggle to relate to the material. Incorporating local knowledge, indigenous practices, and contextually relevant examples can make learning more meaningful and accessible (Jegede and Aikenhead, 2021). This culturally responsive approach not only supports comprehension but also validates students' experiences, fostering inclusion and deeper engagement with the subject.

Together, these factors highlight that improving learning outcomes in biology requires a multi-faceted approach. Cognitive skill development must be supported by strategies that nurture motivation and engagement, while curricula and pedagogy should be aligned with students' cultural and social realities.

Conclusion

Biology education is at a transformative moment, shaped by advances in pedagogy, technology, and a growing recognition of the need for learners to engage critically with real-world issues. This review highlights that innovative approaches such as inquiry-based learning, project-driven tasks, collaborative models, and the integration of digital tools are redefining how biology is taught and learned (Aydin-Gunbatar, Bozdag, and Yilmaz, 2021; Aslan, Durmuş, and Aydin, 2023; Holmes, Bialik, and Fadel, 2019). These approaches not only enhance conceptual understanding but also foster critical thinking, creativity, and problem-solving skills essential for the twenty-first century (Trilling and Fadel, 2009).

Yet, these advances are unevenly applied in practice. Persistent challenges, including inadequate infrastructure, overcrowded classrooms, teacher resistance, and misaligned curricula, continue to undermine reform efforts (UNESCO, 2023; Ojo and Adebayo, 2022; Akinpelu, Yusuf, and Amadi, 2023). Furthermore, the lack of sustained professional development limits teachers' ability to adopt and adapt modern instructional strategies (Akpan and Okoro, 2021). Without addressing these systemic barriers, the full potential of state-of-the-art biology education will remain unrealized.

Implementation and Future Directions

Bridging the gap between research and classroom practice requires a holistic approach. First, investments in infrastructure are critical. Ensuring schools have access to reliable electricity, internet connectivity, and digital devices will create enabling conditions for integrating technology-based tools such as virtual laboratories and adaptive learning platforms (UNESCO, 2023).

Second, continuous professional development should be prioritized. Regular, context-specific training will build teachers' pedagogical and technological capacities, empowering them to adopt student-centered and culturally responsive methods. Teacher preparation programs should also embed competencies in inquiry-based instruction and digital tool use, enabling educators to confidently transition from traditional to modern pedagogies (Fisser, Voogt, and van Braak, 2022).

Third, curriculum reform is needed to align policies, assessment practices, and instructional goals. Examinations that prioritize rote memorization should give way to assessments that measure critical thinking, problem-solving, and application of knowledge. This alignment will incentivize teachers to embrace practices that foster deep, meaningful learning (Akinpelu, Yusuf, and Amadi, 2023).

Finally, culturally responsive approaches should be mainstreamed to ensure that biology instruction reflects learners lived realities. Lessons grounded in local examples, languages, and indigenous knowledge systems will make biology more accessible, inclusive, and relevant (Jegede and Aikenhead, 2021).

Future research should explore sustainable models for integrating digital tools in low-resource settings, the long-term impact of inquiry-based and culturally responsive strategies on student outcomes, and effective policy frameworks for scaling up innovative practices. By addressing these areas, policymakers, educators, and researchers can create a biology education system that equips students with the knowledge and skills to navigate and contribute meaningfully to an increasingly complex world.

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