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Developing 21st-Century Skills in Biology Education through Innovative Instructional Practices in Secondary Schools

S. Muhammad[1*], S. Bello[2], and Z. L. Gwandu[3]

[1]Department of Science Education, Kebbi State University of Science and Technology Aliero, Kebbi State, Nigeria

[2] Department of Science Education, Sokoto State University, Sokoto, Nigeria

[3]Department of Science Education, Federal University Birnin Kebbi, Kebbi State, Nigeria

***Corresponding Author**: sagir.muhammad@ksusta.edu.ng

Abstract

This study examines the role of innovative instructional practices in developing 21st-century skills in Biology education among secondary school students. Persistent underachievement in Biology, particularly in Nigeria, has been largely attributed to the continued reliance on traditional teacher-centered pedagogies that emphasize rote memorization rather than meaningful understanding and skill acquisition. Drawing on constructivist learning theory, particularly the works of Ausubel, Novak, and Piaget, the study explores how learner-centered approaches can enhance students' cognitive engagement and knowledge construction. Adopting a qualitative descriptive approach, the study synthesizes evidence from existing literature and instructional practices to analyze the effectiveness of innovative strategies, including concept mapping, 5E learning cycle, inquiry-based learning, project-based learning, collaborative learning, field-based activities, jigsaw strategy, and the integration of classroom technology. Findings from the literature review indicate that these strategies significantly improve students' conceptual understanding, critical thinking, problem-solving abilities, collaboration, communication skills and core competencies required for the 21st century. The study concludes that the integration of innovative instructional practices fosters active learning and meaningful knowledge construction, thereby enhancing students' academic achievement and preparedness for real-world challenges. It recommends sustained teacher professional development, curriculum innovation, and improved access to instructional resources to support effective implementation in secondary school Biology classrooms

Keywords: innovative instructional practices, biology education, 21st-century skills, constructivist learning, secondary education.

1 Introduction

Science, Technology, Engineering, and Mathematics (STEM) education serves as a critical foundation for technological advancement, innovation, and sustainable national development (Akcay, 2024). However, in Nigeria, the persistent underperformance of students in science subjects, particularly Biology, remains a significant educational concern. Empirical studies have consistently linked this problem to the continued reliance on conventional teacher-centered pedagogies that prioritize factual recall over conceptual understanding (Alaagib et al., 2019). As a result, students often memorize scientific information without developing the ability to relate concepts or apply knowledge to solve real-world problems. Learning science is fundamentally an active and constructive process that requires students' engagement in both physical and mental activities. This dual engagement commonly described as "hands-on" and "minds-on" learning supports the development of enduring knowledge through experience and reflection. Given the evolving nature of education and the emergence of interdisciplinary knowledge domains, it is essential to critically evaluate and adopt effective instructional strategies in science classrooms (Reimers & Chung, 2019).

To address the challenges, there has been a growing shift toward constructivist teaching approaches that emphasize learner participation and knowledge construction. Inquiry-based learning, a hallmark of science education, cultivates analytical and critical thinking skills, fostering creativity and innovation. A deep understanding of scientific principles and methodologies lays the groundwork for technological advancements, positioning countries with strong science education systems as leaders in innovation (Ramadani et al., 2021; Coccia, 2017). A well-educated workforce in the sciences contributes significantly to economic growth and enhances national competitiveness. The dominant perspective in contemporary science education is that learning is shaped by prior experiences and must be constructed by the learner (Treagust & Won, 2023; Zidny et al., 2020). This view has led to the adoption of new teaching strategies like concept mapping, collaborative learning, and the learning cycle, which emphasize active student participation. Effective science classrooms involve students being active, aware of instructional objectives, and receiving feedback on their progress (Arthurs & Kreager, 2017). Incorporating constructivist elements allows students to physically interact with materials and engage in various activities, highlighting the importance of active involvement for effective learning. Biology education plays a vital role in developing scientific literacy and equipping learners with the knowledge and skills necessary for understanding life processes and environmental sustainability. In modern educational systems, there is a growing emphasis on equipping students with critical thinking, problem-solving, and collaborative skills required for the 21st century. However, traditional instructional approaches, often characterized by teacher-centered methods and rote memorization, have been found inadequate in achieving these objectives (Cox, 2020).

Despite the importance of biology in national development and technological advancement, many secondary school students exhibit low interest and poor performance in the subject. This challenge has been attributed to ineffective teaching strategies that fail to actively engage learners in the learning process. Townley (2018) study indicates that many science teachers still rely heavily on conventional lecture methods, limiting students' opportunities to explore, inquire, and construct knowledge independently. The need for innovative instructional strategies in biology education is therefore imperative. Innovative teaching methods emphasize student-centered learning, active participation, and the integration of real-life experiences into classroom instruction. These approaches not only enhance understanding but also promote long-term retention of knowledge and development of higher-order thinking skills. This study aims to present innovative instructional strategies and their effectiveness in teaching and learning biology. It highlights practical approaches that can be adopted by teachers to improve classroom practices and student outcomes.

2 Literature Review/Theoretical Framework

2.1 Theoretical Framework

The theoretical foundation of this study is rooted in constructivist learning theory, which posits that learners actively construct knowledge through interaction with their environment rather than passively receiving information. Constructivism emphasizes learner-centered instruction, inquiry, and experiential learning. Constructivism represents a comprehensive pedagogical framework widely utilized in science education, shifting the emphasis from traditional teaching to a focus on active learning and knowledge construction (Brau, 2020).

2.1.1 Ausubel's Assimilation Theory of Cognitive Learning (1963, 1968), Novak's Human Constructivist Epistemology (1993) and Piaget's Cognitive Constructivism Theory (1952; 1969; 1976)

Ausubel's Assimilation Theory (1963), posits that meaningful learning occurs when new information is related to relevant concepts already known by the learner. In contrast to rote learning, where information is memorized without connections to existing knowledge, meaningful learning requires the learner to integrate new concepts with prior knowledge in a structured, meaningful way. Furthermore, Joseph Novak (1993) expanded on Ausubel's ideas by developing the concept of Human Constructivist Epistemology, which views knowledge as a human creation. According to this view, learning is not a passive process but involves the active construction of knowledge by the learner. Novak proposed that meaningful learning requires a high level of cognitive engagement, where learners actively construct new concepts and propositions through a process of inquiry, reflection, and synthesis.

However, Piaget's Cognitive Constructivism Theory (1952; 1969; 1976) theory emphasizes how learners construct knowledge through interaction with the environment and cognitive processes. Piaget argued that learning is an active, internal process where students build new knowledge based on prior knowledge through assimilation and accommodation. He views cognitive development as a process driven by biological maturation and interaction with the environment. Therefore, the integration of innovative instructional strategies in the teaching and learning of Biology in secondary schools is firmly grounded in constructivist learning theory and its associated frameworks. Constructivism advocates for active, learner-centered engagement, which is essential for meaningful knowledge construction in science education (Yusuf, & Afolabi, 2020). Ausubel's Assimilation Theory provides a basis for understanding how learners integrate new biological concepts with prior knowledge, thereby promoting meaningful rather than rote learning. Building on this, Novak's Human Constructivist Epistemology emphasizes that knowledge is actively constructed through cognitive engagement, inquiry, and reflective thinking. Furthermore, Piaget's Cognitive Constructivism highlights the dynamic processes of assimilation and accommodation through which learners develop and restructure their understanding.

Collectively, these theoretical perspectives validate the use of innovative instructional strategies such as concept mapping, inquiry-based learning, and experiential activities, which foster deeper understanding, critical thinking, and long-term retention. Therefore, aligning instructional practices with these constructivist principles is essential for improving students' academic achievement and promoting effective Biology education in secondary schools.

2.2 Literature Review

2.2.1 Concept of Innovative Instructional Strategies in Biology Education

Innovative instructional strategies in science education refer to pedagogical approaches that move beyond traditional lecture-based teaching to promote active learning, critical thinking, and student engagement (Kayode et al., 2020). In recent years, there has been a growing emphasis on learner-centered approaches in Biology education due to persistent concerns about students' poor academic performance and limited conceptual understanding. Oyelekan, Igbokwe, and Olorundare, (2018) studies have shown that conventional teaching methods, which prioritize rote memorization, often fail to equip students with the ability to apply biological knowledge in real-life contexts.

Contemporary research highlights the effectiveness of strategies such as inquiry-based learning, concept mapping, and collaborative learning in enhancing students' engagement and achievement. For instance, Akinbobola and Afolabi (2021) found that students exposed to innovative teaching approaches demonstrated significantly higher achievement and retention in Biology compared to those taught using traditional methods. These findings reinforce the need to adopt pedagogical practices that foster active participation and meaningful learning.

2.2.2 Concept Mapping and Meaningful Learning in Biology

Concept mapping has gained considerable attention as an innovative instructional strategy in science education. Developed by Novak and Gowin (1984), concept mapping enables learners to visually represent relationships among concepts, thereby facilitating meaningful learning. Recent studies have demonstrated the effectiveness of concept mapping in improving students' understanding of complex biological processes. For instance, Okebukola (2020) found that students who used concept maps performed better in topics such as genetics and ecology compared to those taught using conventional methods. Similarly, Adesoji and Idika (2022) reported that concept mapping enhances knowledge retention and helps students identify misconceptions.

Despite these advantages, some scholars argue that the effectiveness of concept mapping depends on proper implementation and teacher competence. Without adequate guidance, students may struggle to construct accurate concept maps, limiting the strategy's impact. This highlights a gap in teacher training and professional development in the use of innovative instructional tools.

2.2.3 Inquiry-Based and Experiential Learning Approaches

Inquiry-based learning (IBL) is widely recognized as a key component of innovative science instruction. It encourages students to ask questions, investigate phenomena, and construct knowledge through exploration. A study by Hmelo-Silver, (2019) indicates that IBL promotes deeper understanding and enhances students' scientific reasoning skills. Similarly, experiential learning approaches, including project-based learning and field-based activities, provide students with opportunities to connect theoretical knowledge with real-world applications. Kolodner et al. (2021) study revealed that students engaged in project-based learning demonstrated improved problem-solving abilities and higher levels of motivation.

However, there is ongoing discussion regarding the feasibility of these approaches in resource-constrained environments. While some researchers argue that inquiry-based methods require significant time and resources, others contend that even low-cost adaptations can yield meaningful outcomes. This debate underscores the need for context-specific strategies in implementing innovative instruction.

2.2.4 Technology Integration in Biology Education

The integration of technology in education has transformed teaching and learning processes, particularly in science subjects. Digital tools such as simulations, virtual laboratories, and multimedia resources have been shown to enhance students' understanding of abstract biological concepts (Mayer, 2021). Recent studies indicate that technology-supported instruction improves student engagement and academic performance. For example, Ibrahim and Lawal (2023) found that the use of multimedia tools in Biology classrooms significantly increased students' interest and achievement. However, challenges such as limited access to technological resources and inadequate teacher training continue to hinder effective implementation in many developing countries.

2.3 Gaps in Literature

A critical analysis of existing literature reveals several key trends. First, there is a clear shift from teacher-centered to learner-centered instructional approaches in science education. Second, there is growing recognition of the importance of integrating multiple strategies such as concept mapping, inquiry-based learning, and technology to achieve optimal learning outcomes. Despite these advancements, several gaps remain. Many studies focus on the effectiveness of individual strategies rather than exploring their combined impact. Additionally, there is limited research on the practical implementation of these strategies in Nigerian secondary schools, particularly in rural and resource-constrained settings. Furthermore, issues related to teacher preparedness and institutional support are often underexplored. Given the identified gaps, this study seeks to bridge the disconnect between theory and practice by synthesizing and contextualizing innovative instructional strategies for Biology education in secondary schools. Unlike previous studies that focus on isolated strategies, this study adopts a comprehensive approach by examining multiple instructional practices within a unified constructivist framework. By integrating theoretical insights with practical applications derived from previous studies of science instructional strategies and supporting scholarly literature, the study contributes to existing literature by providing a contextually relevant framework for improving Biology teaching and learning. It also addresses the need for practical guidance for teachers in implementing innovative strategies effectively.

3 Materials and Methods

This study adopted a qualitative descriptive research design, specifically a theoretical and instructional synthesis approach, aimed at examining how innovative instructional practices can support the development of 21st-century skills in Biology education at the secondary school level. This design was considered appropriate because the study does not involve experimental manipulation but rather focuses on the systematic analysis and integration of instructional strategies and existing scholarly evidence. The approach enabled the researcher to critically explore and present practical teaching strategies that align with constructivist learning principles and contemporary educational demands. Data for the study were derived from secondary sources, including, Published journal articles on Biology education and instructional strategies, Books and scholarly texts on constructivist learning theories, Empirical studies on innovative teaching methods and Instructional models and classroom-based practices

In addition, the study utilized structured instructional content and activity-based teaching procedures embedded within the selected strategies, such as concept mapping, inquiry-based learning, project-based learning, and collaborative learning. The instructional strategies included in this study were purposively selected based on their alignment with constructivist learning theory, relevance to Biology curriculum at the secondary school level, Potential to develop 21st-century skills (critical thinking, collaboration, communication, and creativity) and empirical support in recent science education literature. Data collection involved a systematic review and extraction process, which included: Identification of relevant literature on innovative instructional strategies in science education, review of theoretical frameworks underpinning Biology teaching (constructivism, meaningful learning), extraction of instructional procedures and classroom activity steps from selected strategies and compilation of examples and practical applications for Biology topics The inclusion of structured activities (e.g., concept mapping steps, inquiry tasks, project-based scenarios) ensured that the study integrates both theoretical and practical dimensions of teaching and learning

4 Discussion

This paper discusses eight innovative teaching strategies and their practices that can improve student engagement in biology learning:

1. Concept Mapping
2. 5E Learning Cycle

3. Inquiry-Based Learning
4. Project-Based Learning
5. Collaborative Learning
6. Biological Field-Based Activities
7. Jigsaw Strategy
8. Effective Use of Classroom Technology

These strategies encourage students to, explore ideas deeply, work collaboratively, think critically participate actively in learning instead of passively receiving information, students construct knowledge through active involvement.

4.1 Concept Mapping

Concept mapping is a visual method used to show the relationships between ideas. A concept map looks similar to a flowchart where key concepts are placed in boxes and connected with arrows to show relationships. Concept maps are usually arranged hierarchically, with General ideas at the top More specific ideas below. According to Novak and Gowin (1984), constructing a concept map involves the following steps:

a. Identify the topic.
b. List the important concepts.
c. Arrange the concepts in hierarchical order.
d. Connect the concepts to form a preliminary map.
e. Add linking phrases to explain relationships.
f. Include cross-links where necessary.
g. Review and refine the map.

Concept maps help students understand how ideas are related. Research shows that concept mapping improves: Academic performance, understanding of concepts, knowledge retention and critical thinking skills. Ajaja (2011) found that students who used concept mapping performed better in biology and retained knowledge longer than students who used other study methods.

Activity:1 Concept Mapping Steps for Teachers

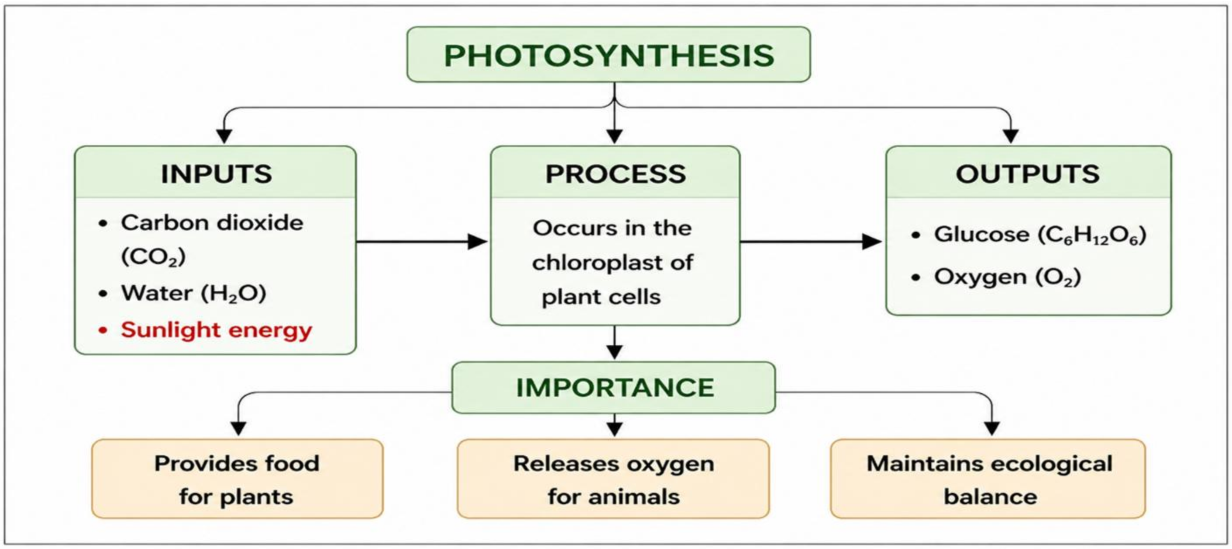
Example Topic: Photosynthesis

a. Introduce the topic Photosynthesis.
b. Ask students to list important terms:
  i. Sunlight
  ii. Chlorophyll
  iii. Carbon dioxide
  iv. Oxygen
  v. Glucose
c. Place the main concept Photosynthesis at the top.
d. Arrange related concepts under it.
e. Draw arrows showing relationships.
f. Add linking phrases such as **"uses," "produces," "occurs in."**

Review the concept map with students.

Figure **1**

Concept Map showing relationship in Photosynthesis



Source: Adapted from Novak & Gowin, 1984

4.2 The 5E Learning Cycle

The learning cycle is a teaching model that helps students develop their understanding of scientific concepts through exploration and application. The most widely used version is the 5E Model, created in 1987 by the Biological Science Curriculum Study (BSCS) (Bybee, Taylor, Gardner, Van Scotter, Powell, Westbrook, & Landes, 2006).The five stages are:

i. **Engage** : Capture students' interest and connect with prior knowledge.

ii. **Explore** : Students investigate and gather information through activities.

iii. **Explain**: Students and teachers discuss and clarify concepts.

iv. **Elaborate** : Students apply the knowledge to new situations.

v. **Evaluate**: Teachers assess students' understanding.

Research shows that the 5E learning cycle improves, academic achievement, knowledge retention, students' attitudes toward science and correction of misconceptions. Balta and Sarac (2016) emphasize that teachers should be encouraged to integrate this model into their teaching practices. While instructional models are not a new concept, their application has seen a significant rise in recent years (Bybee, 2006).

Activity:2 Steps for 5E Learning Cycle

Example Topic: Human Digestive System

1. Engage

Teacher would ask: "What happens to food after it is swallowed?"

2. Explore

The students would be examining diagrams of the digestive system and identifying organs.

3. Explain

The Teacher further explains the functions of mouth, stomach, small intestine, and large intestine

4. Elaborate

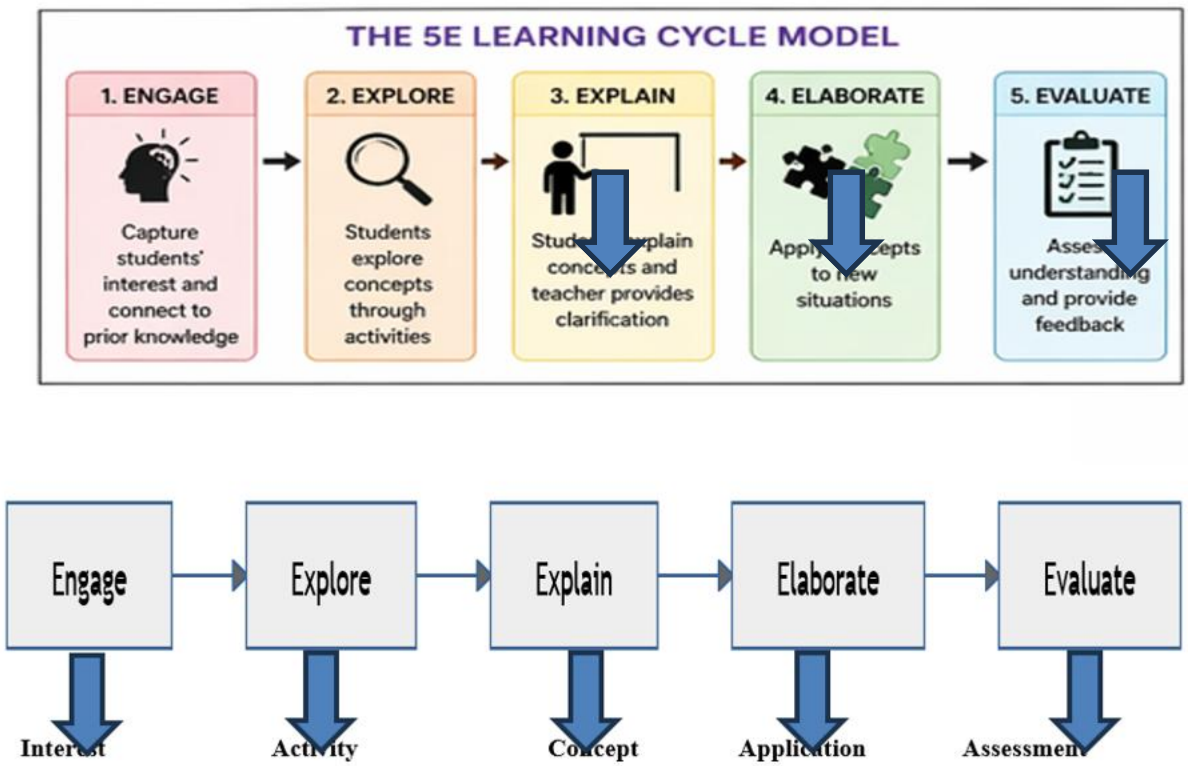
The students would further explain how digestion would be affected if the stomach stopped producing acid.

5. Evaluate

The teacher would assigned students to label a diagram of the digestive system.

Figure **2**

5E Learning Cycle Strategy on Human Digestive System



4.3 Inquiry-Based Learning

Inquiry-based learning encourages students to learn by asking questions and investigating answers. In this approach, the teacher acts mainly as a facilitator of learning rather than a lecturer.

The process usually involves four steps:

- **i.** Students develop questions they want to investigate.
- **ii.** Students research the topic.
- **iii.** Students present their findings.
- **iv.** Students reflect on the learning process.

Inquiry-based learning is an educational approach that emphasizes the student's role in the learning process, allowing them to explore, ask questions, and discover new knowledge. Inquiry-based learning promotes deeper understanding because students actively construct knowledge rather than simply receiving information from the teacher. Gillies, (2020). notes that inquiry-based science education promotes curiosity, critical thinking, and a deeper understanding of scientific principles.

Activity:3 Steps for Inquiry-Based Learning

Example Topic: Plant Growth

1. **To construct Question**

   Students may ask:

   "Does sunlight affect plant growth?"

2. **For Investigation**

   Students should grow two plants:

   - One in sunlight
   - One in shade

3. **Further Presentation**

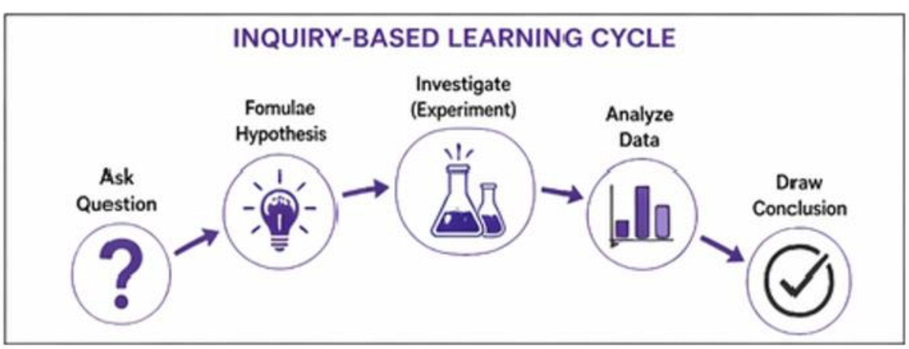
   Students would present results in charts.

4. **Reflection**

   Students would now discuss why the plant in sunlight grew better.

Figure **3**

Inquiry-based learning cycle



Source: Trowbridge, Bybee and Powell (2000)

4.4 Project-Based Learning (PBL)

Project-Based Learning is a teaching approach where students learn by working on real-life problems or projects. Students work individually or in groups to investigate real-world challenges, develop solutions and present their findings. PBL encourages the development of important skills such as: critical thinking, problem solving, collaboration, communication and self-management (Aksela, & Haatainen, 2019).

A study by Gabuardi (2021) shows that project-based learning Makes learning more engaging, improves understanding, encourages the use of technology, connects classroom learning with real-life situations.

Activity:4 Guide Steps for Project-Based Learning

Example Topic: Environmental Pollution

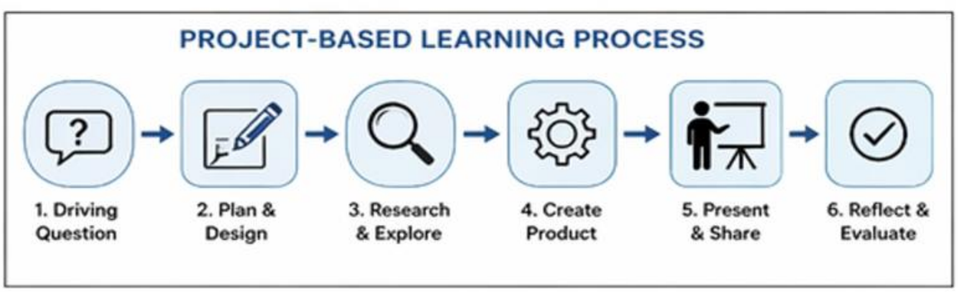
1. Teacher would introduce problem:

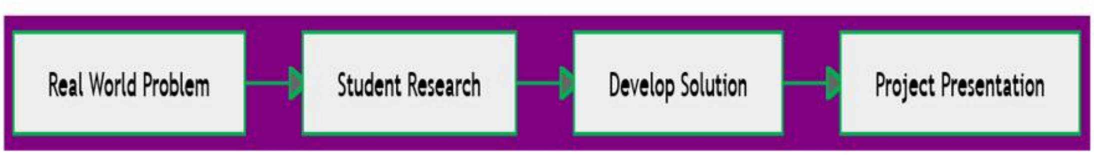
   "Plastic waste in our community."

2. Students would form groups.
3. Groups research would be on:
   - Causes of pollution
   - Effects on Organisms
4. Students would design solutions:
   - Recycling programs
   - Awareness campaigns
5. All the Groups would present projects to the class.

Figure **4**

Project-based learning process





Source: Buck Institute for Education (2019).

4.5 Collaborative Learning

Laal and Laal (2012) study shows that, a collaborative learning involves students working together in groups to achieve a common learning goal. Group activities may include; Researching information, discussing ideas, solving problems together and creating shared presentations. Collaborative learning helps students develop, communication skills, teamwork, critical thinking and social skills. It is especially useful when studying complex topics such as Environmental Issues and Sustainability (O'Donnell, & Hmelo-Silver, 2013).

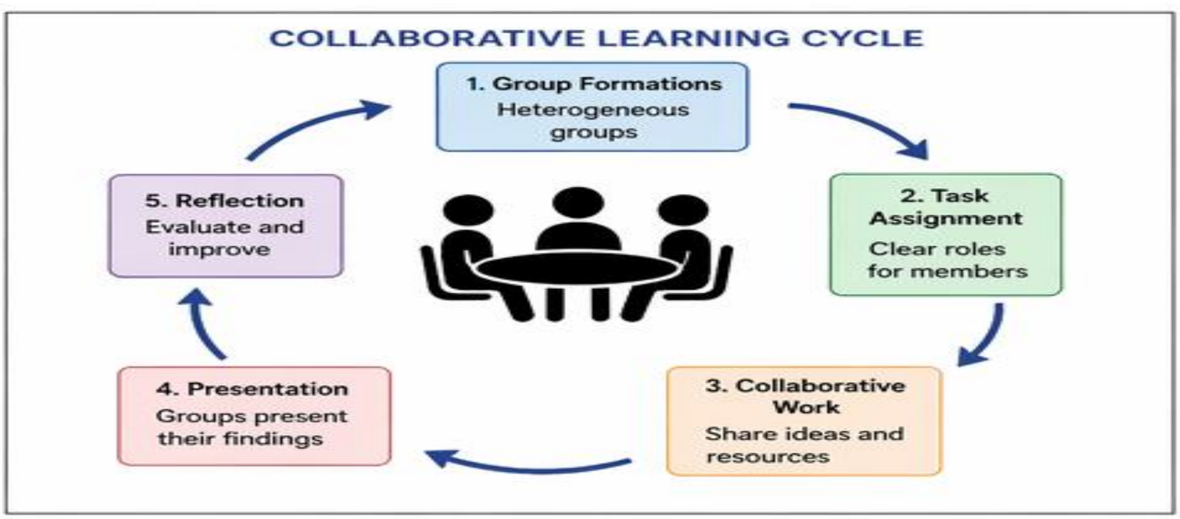
Activity 5: Steps for Collaborative Learning Technique

Example Topic: Food Chains

1. Divide students into groups.
   i. **Group 1** → Producers
   ii. **Group 2** → Herbivores
   iii. **Group 3** → Carnivores
   iv. **Group 4** → Decomposers
2. Assign each group part of a food chain.
3. Groups research their organisms.
4. Each group presents their findings.
5. Class combines all information to build a full food chain

Figure **5**

Collaborating Learning Cycle



Source*: Oyelekan, Igbokwe &Olarundare,2018*

4.6 Biological Field-Based Activities

Field-based activities such as field trips and outdoor investigations provide students with real life learning experiences (Dey, 2024). These activities allow students to; Observe natural environments, study plants and animals in their habitats and apply scientific inquiry skills. Fieldwork increases students' interest in biology and helps them better understand environmental issues (Wallgrun et al., 2024).

Activity 6: Steps for Biological Field-Based Activities

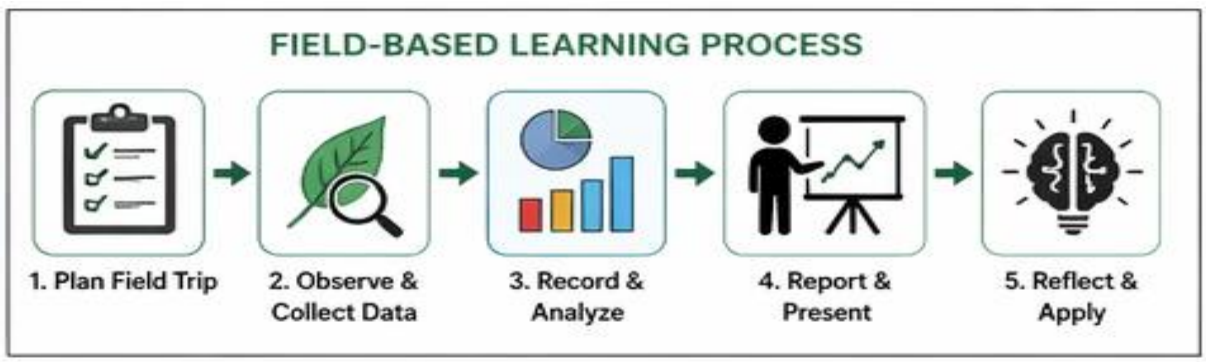
Example Topic: Ecosystem

Steps

1. Take students to a school garden or nearby forest.
2. Students observe:
   - Plants
   - Insects
   - Soil Organisms
3. Record observations and Collect Data.
4. Report back in class, students present and discuss Ecosystem Interactions

Figure **6**

Field Based Learning Process



Sources*; Palmerg et al.,2015*

4.7 Jigsaw Strategy

The jigsaw technique is a cooperative learning strategy. Students are divided into groups, and each group is assigned a different part of the topic (Nusrath et al., 2019). Each group becomes experts in their assigned section. After learning their section, students reorganize into new groups where each member teaches their part to others. This method encourages active participation, peer teaching, knowledge sharing and responsibility for learning

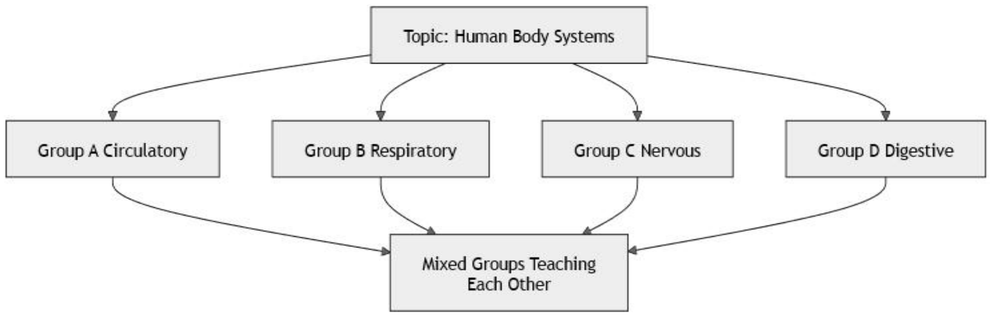
Activity 7: Steps For Jigsaw Technique

Example Topic: Human Body Systems

1. Divide class into groups.
2. Assign each group a system.
3. Students learn their system well.
4. Create new mixed groups.
5. Each student teaches their system to others.

Figure **7**

Jigsaw Technique Strategy on Human Body Systems



Sources: *Arends, 2012*

4.8 Effective Use of Classroom Technology

Many schools now provide students with digital devices such as tablets or laptops. When used properly, technology can improve student engagement (Hamilton, 2018). . However, teachers must ensure that technology is carefully managed and purposefully used. Examples of useful digital tools include: Google Docs for collaboration, YouTube for visual learning, Quizlet for revision, Kahoot for interactive quizzes and Remind for communication with students. These tools help teachers; organize learning, support collaboration, monitor students' progress, make lessons more engaging (Dias, & Victor, 2017).

Activity 8: Steps for Wisely Managed Classroom Technology

Example Topic: Genetics

1. Show a YouTube video on Mendelian genetics.
2. Students collaborate on Google Docs to summarize concepts.
3. Conduct a Kahoot quiz to test understanding

5 Conclusion

This study demonstrates that innovative instructional strategies can improve biology teaching and learning in secondary schools. These approaches promote active learning, enhance student engagement, and develop essential 21st-century skills such as critical thinking, collaboration, and problem-solving. Furthermore, adopting innovative instructional practices in Biology education is crucial for bridging the gap between theoretical knowledge and practical application. Strengthening teacher capacity and instructional support systems will ensure effective implementation and improved student learning outcomes.

6 Recommendations

This study proposes the following recommendations to enhance the effective implementation of innovative instructional practices in Biology education and to foster the development of 21st-century skills among secondary school students:

Teacher Professional Development and Capacity Building

Teachers should be provided with continuous professional development programs focused on innovative instructional strategies such as concept mapping, inquiry-based learning, and project-based learning. Training should emphasize practical classroom application, lesson planning, and assessment techniques aligned with constructivist principles. This will enhance teachers' competence, confidence, and willingness to adopt learner-centered approaches.

Curriculum Review and Integration: Educational authorities should revise the biology curriculum to explicitly incorporate innovative instructional strategies and 21st-century skills development. The curriculum should promote active learning, problem-solving, critical thinking, and collaboration, ensuring alignment with global educational standards and workforce demands.

Provision of Instructional Resources and Infrastructure: Schools should be equipped with adequate instructional materials, including laboratory equipment, teaching aids, and digital technologies such as multimedia tools, simulations, and virtual laboratories. Access to these resources will support the effective implementation of innovative teaching practices and improve students' engagement and understanding.

Integration of Technology in Teaching and Learning: Teachers should be encouraged to integrate appropriate educational technologies into Biology instruction. Tools such as interactive simulations, online collaboration platforms, and digital assessment systems can enhance visualization, engagement, and personalized learning. Government and school administrators should ensure equitable access to these technologies.

Strengthening Assessment Practices: Assessment methods should move beyond rote memorization to include performance-based and formative assessments that evaluate students' understanding, creativity, and problem-solving abilities. Continuous assessment techniques such as project work, presentations, and concept mapping should be integrated into evaluation systems.

7 Further Research

Future studies should explore the combined impact of multiple innovative instructional strategies on students' learning outcomes in Biology. There is also a need for empirical research focusing on rural and resource-constrained settings to provide context-specific solutions

8 Ethical statements

This study did not involve human participants or sensitive data. It was based on instructional materials and literature; therefore, ethical approval was not required.

9 Conflict of Interest

The author declares neither financial nor non-financial conflict of interest.

10 Author Contributions

S. Muhammad conceptualized the study, S. Bello developed the practical activities steps, Z. L. Gwandu conducted the Meta analysis, and prepared the paper.

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