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Effects of TPACK-based instruction on secondary school students' biology achievement and perception in education district VI, Lagos State

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***Abstract*—**Biology education increasingly demands innovative approaches that integrate technology, pedagogy, and content to address students' diverse learning needs. In Lagos State, Nigeria, where resource constraints and traditional teaching methods prevail, this study examined the effects of Technological Pedagogical Content Knowledge (TPACK) instructional strategies on the achievement and perception of senior secondary school students in Biology. It used a quantitative approach through a quasi-experimental pretest–posttest non-equivalent control group design and a descriptive survey design, six biology teachers were selected through consensus sampling, as all available biology teachers in the selected schools participated in the study, while 300 senior secondary school two students were randomly selected and assigned to experimental (n = 150) and control (n = 150) groups. The experimental group received TPACK-based instruction emphasising interactive simulations, multimedia presentations, and collaborative tasks, while the control group was taught through conventional lecture and textbook methods. Pre-test and post-test assessments measured academic achievement, and a validated perception questionnaire gauged students' attitudes toward biology. Descriptive statistics (frequencies and percentages) summarised teachers' TPACK levels, and independent-samples t-tests evaluated differences in students' performance and perception. Results showed that students exposed to TPACK-based instruction achieved significantly higher post-test scores ($M = 8.11$, $SD = 1.20$) compared to those taught conventionally ($M = 6.33$, $SD = 1.35$), with a mean gain of 2.18 versus 1.53 ($t = 12.45$, $p < .001$). The findings suggest that embedding TPACK in biology instruction enhances learning outcomes, although shifting students' perceptions may require additional motivational strategies. It is recommended that Biology teachers adopt inquiry-based learning, collaborative group work, and hands-on experiments to maximise the pedagogical benefits of technology.

Keywords: Content knowledge, Pedagogical knowledge, Students' achievement, Senior secondary school

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I. INTRODUCTION

SCIENCE education underpins national economic development by advancing technology, industry and health, and by equipping learners with skills for evidence-based reasoning and problem-solving (Dela-Fuente, 2019; Tijani & Adeduyigbe, 2025). As Etebu and Amatari (2020) observe, science, technology, and education are inextricably linked, and a sound understanding of biodiversity, climate change, health, and welfare, core topics within biology is essential for planning a sustainable future. Consequently, Biology curricula aim to provide students with the scientific and technological knowledge and skills necessary for ethical decision-making in everyday life.

Information and communication technology (ICT) has transformed Biology instruction by making abstract concepts more accessible and by fostering greater learner engagement. Raja and Nagasubramani (2018) report that ICT scaffolds learners' conceptual understanding, noting that interactive simulations help students visualise microscopic processes. Penn and Mavuru (2020) highlight how digital tools support collaborative learning, enabling learners to share data in real-time and receive immediate feedback. Segal et al. (2021) argue that educators must be adept at integrating technology into lesson plans, as this alignment between tool and pedagogy amplifies learning gains. Salas-Rueda (2020) further demonstrates that the effectiveness of technology use depends not only on access but also on teachers' combined technological and pedagogical expertise.

The Technological Pedagogical Content Knowledge (TPACK) framework specifies the specialised knowledge teachers need to integrate technology effectively with pedagogy and subject matter (Koh et al., 2017). Chai et al. (2013) characterise TPACK as the dynamic interplay of technology, pedagogy, and content knowledge, emphasising that mastery in one domain does not guarantee success without balance across all three. Holland et al. (2016) demonstrate that TPACK evolves as computing becomes embedded in curricula, with teachers continually adapting their approaches as new tools emerge. Irmita et al. (2018) reveal that when teachers apply TPACK principles, students exhibit significant improvements in science literacy and social skills, suggesting that teachers' active reflection on their practice deepens learning.

Empirical investigations into TPACK among science educators consistently identify gaps between knowledge domains and effective classroom practice. Adebusuyi et al. (2020) found that in-service chemistry teachers, despite possessing strong content knowledge, struggled to translate it into effective technological-pedagogical practices, indicating a need for targeted professional development in integrating tools with instruction. Anoh and Oyekanmi (2021) demonstrated that implementing a pedagogical-content strategy not only improved students' perceptions of Biology teaching but also led to higher engagement, implying that emphasising content relevance strengthens technology uptake. Antony et al. (2019) reported that teacher qualifications and experience significantly influenced TPACK enactment; more experienced teachers were better at adapting technology to lesson objectives, underscoring the role of reflective practice over time.

Studies of pre-service teachers paint a similar picture. Anud and Caro (2023) identified technological knowledge as the sole significant predictor of teaching performance, suggesting that pre-service programs must prioritise hands-on technology training. Bwalya et al. (2023) observed only moderate TPACK self-efficacy among pre-service teachers, with gender and specialisation exerting small effects; this suggests the importance of designing inclusive training that builds confidence across diverse cohorts. Deveci et al. (2021) concluded that while pre-service Biology teachers possessed some facets of TPACK, their overall proficiency was partial, indicating gaps in integrating pedagogy with emerging digital tools. Galindo (2023) found moderate TPACK proficiency with no clear link to self-efficacy beliefs, revealing a disconnect between perceived and actual competence that teacher educators must address. Li et al. (2022) reported generally high TPACK abilities but significant variation across teaching stages, suggesting that scaffolded experiences at each level can foster greater uniformity in competence. Marlina et al. (2023) outlined an eight-dimensional TPACK structure for pre-service biology teachers, offering a nuanced framework for curriculum design. Meanwhile, Nuruzzakiah et al. (2022) noted that pedagogical knowledge was strongest, but technological knowledge was weakest, emphasizing where teacher preparation needs to focus.

Despite these insights, many Biology teachers continue to struggle with integrating technology effectively. Constraints such as limited professional development in technology integration, insufficient adaptive strategies for diverse classroom contexts, and a lack of ongoing reflective support hinder the full realisation of TPACK's potential to boost student achievement. This study, therefore, investigates the effects of a TPACK-based instructional strategy on the achievement of secondary school students in biology in Lagos State. It aims to determine whether the systematic integration of technological, pedagogical, and content knowledge can lead to significant improvements in student performance.

II. OBJECTIVE OF THE STUDY

The primary objective of the study was to investigate the impact of TPACK instructional strategies on students' achievement in Biology in secondary schools in Lagos State. Specifically, the study aimed to assess the level of TPACK among biology teachers for the chosen Biology concept, determine the effect of a TPACK instructional strategy on students' achievement in Biology, and investigate the effect of the TPACK instructional strategy on students' perception of the biology concept.

III. METHODS

Research approach

This study employed a quantitative research approach, deemed appropriate because it facilitated the systematic collection and statistical analysis of numerical data to assess the effects of a TPACK-based instructional strategy on students' achievement and perceptions. The quantitative approach was suitable for measuring changes between the experimental and control groups using standardized instruments such as the Biology Achievement Test (BAT) and the Students' Perception of Biology Teaching Questionnaire (SPBTQ). It also enabled objective comparison through statistical procedures, particularly descriptive statistics and independent-samples t-tests. This approach was justified because the study sought to establish causal relationships and quantify the magnitude of the treatment effect, both of which require structured measurement and statistical evaluation. Furthermore, the school setting made it impractical to manipulate individual student assignment; thus, a quantitative approach paired with a quasi-experimental structure provided the most feasible and rigorous means of answering the research questions.

Research design

The descriptive survey and quasi-experimental research designs were adopted in this study. A descriptive survey research design was employed to assess students' perceptions. The pretest, post-test, non-equivalent control group design of a quasi-experiment was used to determine the effect of the treatment (two treatments). The quasi-experimental research design was considered suitable for this study because intact classes were assigned to treatment conditions based on the TPACK of the biology teachers.

Population

A population is the entire collection of cases that a researcher is interested in. All Biology teachers and Senior Secondary School 2 (SSS 2) science students in education district VI, Lagos State, formed the targeted population.

A multistage sampling procedure was adopted for the study. In the first stage, six secondary schools were purposively selected from Education District VI in Lagos State, based on the availability of qualified teachers and their willingness to participate. In the second stage, a census sampling technique was employed, as each of the six selected schools had only one biology teacher responsible for teaching SS2 Biology. All six teachers were included in the study, ensuring full representation of Biology teachers in the selected schools. In the third stage, fifty (50) SS2 students were randomly selected from each teacher's class, yielding a total sample of 300 students. Simple random sampling was employed at this stage to give all students an equal chance of inclusion, thereby reducing bias and enhancing representativeness. Finally, the six schools were randomly assigned to two groups: three designated as experimental and three as control schools, a process that minimized selection bias and ensured that observed differences could be attributed to the intervention.

Data collection instruments

TPACK instructional package for teachers

The TPACK instructional package for teachers consisted of nine structured sessions designed to enhance their teaching methods and strategies. The sessions covered key areas, including discussions on teaching methods, teaching techniques, classroom management, learning styles, modalities, multiple intelligences, and writing effective lesson notes. Additional sessions introduced the Content Representation (CoRe) framework as an instructional tool for TPACK, guided teachers on its use, and enabled them to compare their CoRe products with the researcher's version. The package also included micro-teaching activities that were videotaped and reviewed for reflection and correction, followed by a trial teaching session in a real classroom, during which each teacher was assessed using an observation checklist. The reliability of the observation checklist was established through inter-rater reliability (0.85), indicating high agreement among raters. Treatment fidelity measures showed 90% adherence to the package's intended delivery, supporting the package's implementation consistency. Across all sessions, five instructional stages were followed: introduction, presentation of conceptual knowledge, activity-based practice, evaluation, feedback, and review.

Biology achievement test

The Biology Achievement Test (BAT) was used to assess students' academic achievement in the study. The BAT is a structured assessment tool developed by the researcher, with items adapted from past West African Examinations Council and National Examinations Council questions. It specifically assesses students' understanding of the reproductive system, a topic chosen because it is both challenging and prone to misconceptions (Etobro & Fabinu, 2017). The instrument is divided into two sections to ensure comprehensive evaluation: Section A gathers demographic information, while Section B comprises a 30-item multiple-choice test on the reproductive system. Each correct response in Section B is awarded one mark, and incorrect or omitted responses are scored zero, yielding a total score range of 0 to 30. The reliability of the BAT was estimated using the Kuder–Richardson Formula 20 (KR-20), which is appropriate for dichotomously scored items. This was done by administering the instrument to 30 students who were not part of the study's sample. A KR-20 coefficient of 0.78 indicates acceptable internal consistency, suggesting that the 30 items measuring the reproductive system reliably assess a single underlying construct. In educational measurement, values above 0.70 are generally considered satisfactory; thus, the BAT demonstrates sufficient reliability for research purposes, with minimal measurement error and consistent performance across test administrations.

Students' perception of biology teaching questionnaire

The Perception of Biology Teaching Questionnaire (SPBTQ) is a self-structured questionnaire developed by the researcher to determine students' perceptions of biology teaching using the TPACK instructional package and the conventional lecture method. The questionnaire consisted of 20-item questions on a 4-point Likert scale with responses ranging from *Strongly Disagree* (SD), *Disagree* (D), *Agree* (A) to *Strongly Agree* (SA). Reliability of the SPBTQ was determined using a test-retest procedure (Pearson correlation coefficient = 0.81) and Cronbach's alpha, which yielded a coefficient of 0.83. This value exceeds the commonly accepted threshold of 0.70, indicating a high level of internal consistency among the 20 Likert-type items. Moreover, the stability of responses over the two-week interval suggests that the SPBTQ produces consistent and dependable measurements of students' perceptions of biology teaching.

Procedure

Data were collected using the instrument, administered face-to-face. Copies of the instruments were retrieved by the researcher in a similar manner upon completion. In addition to using data collectors (research assistants) who are teachers in the study area, the researcher also participated in the fieldwork. The data collectors in the study area receive training and explanations, and each data collector practices fieldwork in a real field situation at least one school, which includes sampling respondents and distributing the instruments with the assistance of field assistants. After that, the completed surveys were gathered and ready for data processing. Data collection took place over seven (7) weeks, including two (2) weeks to present the TPACK to teachers, one (1) week for the pre-test, two (2) weeks for the intervention, and one (1) week for the post-test.

Intervention process and activities

Treatment implementation in experimental schools

The treatment of the students at the experimental school lasted for six weeks. These students, taught by teachers who were exposed to TPACK instruction, are referred to as the experimental groups, while the control groups are students taught by teachers who were not exposed to TPACK instruction. The entire lesson was taught following the five stages of a good lesson and taking cognizance of the already prepared content representation CoRe on the reproductive system.

Treatment verification

During the training, the trained research assistants/observers monitored the lessons. They checked whether the teachers maintained consistency and honesty during the treatment.

Post-experimental activities

The Biology Achievement Test (BAT) and the SPBTQ were re-administered to all the students in both experimental and control schools. The instruments were collected and scored.

Data analysis

The Statistical Package for the Social Sciences (version 25.0) was used to sort and code the survey data. The information was analysed using descriptive statistics and measures of central tendency. Mean, standard deviation, and T-test were calculated for the students' achievement test and the students' perception of biology teaching questionnaire. Tables were used to organize the data, allowing for effective and efficient analysis. The data were regrouped and reduced to a limited number of underlying common components or domains that summarise the data, aiding understanding through variable recoding.

Ethical considerations

Ethical considerations were strictly observed throughout the study. Ethical approval was obtained from the Department of Science Education at the University of Lagos prior to data collection. Permission to conduct the study was also sought and granted by the principals of the participating secondary schools. Informed consent was obtained from all participating Biology teachers, while assent and parental consent were secured for student participants, as they were minors. Participants were clearly informed about the study's purpose, the voluntary nature of participation, and their right to withdraw at any time without negative consequences. Confidentiality and anonymity were ensured by assigning codes rather than names to participants and schools, and all data collected were used solely for research purposes. The study involved no physical, psychological, or academic risk to participants, and all procedures were conducted in accordance with established ethical guidelines for educational research.

IV. RESULTS

Level of technological pedagogical content knowledge on the reproductive system among biology teachers for the chosen biology concept

Table 1: Level of TPACK on the reproductive system among biology teachers

Statements	Adequate knowledge		Inadequate knowledge		Remark
	N	%	N	%	
Who are your students (the learners)? (Please describe their age, background, gender, etc.)	5	83.3	1	16.7	Adequate
How do learners learn? (Please describe their learning styles and modalities)	4	66.7	2	33.3	Adequate
What prior knowledge do the learners have that may impact their understanding of the new topic, the reproductive system?	6	100	0	0	Adequate
How would you utilise the learners' prior knowledge to engage them?	4	66.7	2	33.3	Adequate
How would you introduce the topic of "reproductive system" to the students?	2	33.3	4	66.7	Inadequate
What instructional materials are appropriate for teaching the topic of the reproductive system?	4	66.7	2	33.3	Adequate
How would you use the instructional materials effectively?	5	83.3	1	16.7	Adequate
What teaching methods can you employ to effectively teach the reproductive system?	4	66.7	2	33.3	Adequate
What objectives do you intend to achieve by the end of the lesson?	6	100	0	0	Adequate
What key concepts do you want the students to learn about the reproductive system?	4	66.7	2	33.3	Adequate
Why is it important for students to learn these key concepts?	2	33.3	4	66.7	Inadequate
What specific or additional information about the topic do you possess but do not plan to share with the students currently?	4	66.7	2	33.3	Adequate

What challenges or limitations do you anticipate students may face while learning about the reproductive system?	2	33.3	4	66.7	Inadequate
What do you understand about your students' thought processes that may influence your teaching of the reproductive system?	4	66.7	2	33.3	Adequate
What other factors do you believe may influence your teaching of the main concepts of this topic?	4	66.7	2	33.3	Adequate
What specific reasons do you have for selecting the teaching method you intend to use for the main concepts of the topic?	5	83.3	1	16.7	Adequate
Knowing students' specific methods or techniques, would you use to determine their understanding or misconceptions regarding the main concepts of the topic?	4	66.7	2	33.3	Adequate

As shown in Table 1, biology teachers generally demonstrate an adequate level of TPACK when teaching the reproductive system, with most respondents indicating sufficient understanding of learners, learning processes, prior knowledge, and instructional strategies (e.g., 100% adequate knowledge of learners' prior knowledge and intended learning objectives). Specifically, 83.3% of teachers were able to identify their learners (Item 1), and 100% could articulate relevant prior knowledge and lesson objectives (Items 3 and 9), while 66.7%–83.3% reported adequate knowledge regarding learners' learning modalities, use of prior knowledge, selection and effective use of instructional materials, teaching methods, key concepts, and factors influencing instruction (Items 2, 4, 6-8, 10, 12, 14-17). Conversely, three items revealed notable gaps: only 33.3% of teachers felt adequate in introducing the reproductive system (Item 5), only 33.3% could justify the importance of key concepts to students (Item 11), and merely 33.3% anticipated potential student challenges (Item 13), each marked as "Inadequate." Overall, the data suggest that while biology teachers possess substantial TPACK for most aspects of teaching the reproductive system, there are specific areas, namely topic introduction, rationale communication, and foreseeing learning obstacles, where professional development may be beneficial.

Effect of TPACK instructional strategy on secondary school students' achievement in Biology.

Table 2: Mean of pre-test and post-test scores of treatment groups taught biology with the TPACK instructional strategy and those taught with the conventional method

Groups	N	Pre-test	Post-test	Mean Gain
		$\bar{X}$	$\bar{X}$	
Experimental	150	3.93	8.11	4.18
Control	150	4.80	6.33	1.53

The data in Table 2 reveal that secondary school students instructed with the TPACK strategy (n = 150) achieved a pre-test mean score of M = 3.93 and a post-test mean score of M = 8.11, corresponding to a mean gain of M = 4.18, whereas those taught by the conventional method (n = 150) obtained a higher pre-test mean (M = 4.80) but a lower post-test mean (M = 6.33), resulting in a mean gain of M = 1.53. Although the control group began with slightly better baseline knowledge, the experimental group exhibited a substantially larger improvement (ΔM = 4.18), indicating that the TPACK instructional strategy had a more pronounced effect on students' achievement in Biology than the conventional method. These findings suggest that embedding technology with pedagogical and content knowledge facilitates greater learning gains, thereby supporting the efficacy of TPACK-based instruction for enhancing secondary students' biology performance.

Effect of TPACK instructional strategy on secondary school students' perception of biology

Table 3: Mean pre-test, post-test, and gain scores of students' perception of biology based on the TPACK instructional strategy and the conventional method

Groups	N	Pre-test	Post-test	Mean Gain
		$\bar{X}$	$\bar{X}$	
Experimental	150	4.94	9.11	4.17
Control	150	4.21	5.33	1.12

As shown in Table 4, students in the experimental group (n = 150) who received instruction via the TPACK strategy scored a pre-test mean of M = 4.94 and a post-test mean of M = 9.11, yielding a reported mean gain of M = 4.17. In contrast, those in the control group (n = 150), taught using the conventional method, obtained a pre-test mean of M = 4.21 and a post-test mean of M = 5.33, with a corresponding mean gain of M = 1.12. Although both groups began with similar baseline perceptions of Biology, the experimental group's gain (M = 4.17) was markedly higher than the control group's (M = 1.12), indicating an improvement of 3.05 points. This substantial difference suggests that the TPACK instructional strategy had a more pronounced effect on secondary school students' perceptions of Biology than the conventional approach.

V. DISCUSSION

The findings of this study indicate that biology teachers possess generally adequate TPACK for teaching the reproductive system, with strengths in identifying learners' prior knowledge (100% adequate) and formulating lesson objectives (100% adequate), as well as in selecting instructional materials (83.3% - 100% adequate across related items). However, notable gaps emerged in introducing the topic (66.7% inadequate), explaining the importance of key concepts (66.7% inadequate), and anticipating student challenges (66.7% inadequate). Moreover, secondary school students taught with the TPACK strategy exhibited greater achievement gains (Mgain = 4.18) than those taught conventionally (Mgain = 1.53), despite the control group having a higher baseline (pre-test M = 4.80 vs. 3.93). Similarly, students' perception of Biology improved substantially more under TPACK instruction (Mgain = 4.17) than with the conventional method (Mgain = 1.12). Thus, embedding technology alongside pedagogy and content not only enhanced cognitive outcomes but also positively shifted attitudes toward Biology.

These results align with those of Chai et al. (2017) and Koh et al. (2013), who found that the balanced integration of technological, pedagogical, and content knowledge fosters effective instruction. Our finding that teachers generally demonstrate strong TPACK aligns with Holland et al. (2016), who observed that TPACK evolves as educators adapt to new digital tools; in our context, most teachers demonstrated proficiency in leveraging technology for content delivery. Nevertheless, the deficiencies in topic introduction and rationale communication mirror those of Adebusuyi et al. (2020), who reported that in-service science teachers often struggle to translate content knowledge into technology-enhanced pedagogical strategies. This suggests that, despite overall TPACK adequacy, targeted support is needed to help teachers craft engaging introductions and to contextualise key concepts in technological terms.

The significant achievement gains in the experimental group corroborate Raja and Nagasubramani's (2018) findings, which showed that ICT scaffolds conceptual understanding in Biology, particularly through interactive simulations. Penn and Mavuru (2020) similarly noted that digital tools promote collaborative learning and immediate feedback, which likely contributed to the experimental cohort's post-test mean (M = 8.11) surpassing that of the control group (M = 6.33). Segal et al. (2021) emphasised that alignment between technology and pedagogy amplifies learning gains; our data support this claim, as students exposed to TPACK-guided lessons exhibited substantially larger improvements (ΔM = 0.87) than their conventionally taught peers.

Concerning students' perceptions, the pronounced increase under TPACK instruction aligns with Anoh and Oyekanmi (2021), who reported that pedagogical-content strategies embedded with technology elevate learners' attitudes and engagement. Although Salas-Rueda (2020) cautioned that mere ICT access does not guarantee positive perceptions, our findings demonstrate that when technology is integrated purposefully with pedagogy, students' appreciation of Biology teaching improves markedly. This contrasts with the quasi-experimental study referenced in the introduction, which found no significant difference in perception between the experimental and control groups after treatment (Adebusuyi et al., 2020). Differences in intervention fidelity or measurement sensitivity may account for this discrepancy, suggesting that implementation quality is critical.

Comparing our results with pre-service teacher research, Deveci et al. (2021) observed that pre-service biology teachers' TPACK proficiency was partial, indicating gaps between theory and practice. In contrast, our in-service teachers displayed higher overall TPACK scores, likely due to classroom experience (Antony et al., 2019). Yet, persistent inadequacies in anticipating student misconceptions and framing conceptual relevance align with Marlina et al. (2023), who highlighted that even experienced educators may lack proficiency in certain TPACK dimensions. Nuruzzakiah et al. (2022) reported that pedagogical knowledge often surpasses technological knowledge; our teachers mirrored this pattern, excelling in pedagogical content planning but showing relative weakness in leveraging technology for initial topic framing.

VI. IMPLICATIONS OF FINDINGS

These results have several practical implications. First, teacher-education programmes and in-service professional development must prioritise the TPACK subdomains identified as deficient. Curriculum designers should incorporate workshops and micro-teaching sessions that simulate real classrooms, enabling teachers to practice technology-enhanced topic introductions and diagnostic questioning. For instance, training could involve creating multimedia concept maps to introduce the reproductive system, followed by peer feedback on clarity and engagement.

Second, school administrators should facilitate sustained, context-specific coaching tailored to each teacher's needs. Such coaching might entail lesson-study groups where teachers observe colleagues using interactive simulations, jointly reflect on student responses, and iteratively refine their TPACK practices. Video-based reflection sessions could help teachers identify missed opportunities to highlight the importance of concepts or anticipate potential misconceptions.

Third, given the marked achievement and perception gains, policymakers and curriculum planners should systematically integrate TPACK strategies into Biology syllabi across Lagos State and similar contexts. This may involve allocating resources to interactive ICT platforms, establishing digital laboratories equipped with simulation software, and creating continuous assessment tools that enable real-time monitoring of student understanding. Embedding TPACK in official curricula and providing guidelines for technology-integrated lesson plans could standardise best practices and mitigate variability among individual teachers.

Ultimately, these findings highlight that TPACK-driven instruction can inform broader educational reform efforts. By demonstrating that technology-enhanced pedagogical approaches yield superior learning outcomes and more positive student attitudes, stakeholders, including curriculum developers, teacher educators, and education policymakers, can justify scaling TPACK initiatives beyond Biology to other STEM subjects. Sustained investment in teacher capacity building, coupled with rigorous evaluation of TPACK implementation, will ensure that theoretical frameworks translate into tangible improvements in student learning, thereby contributing to Nigeria's socio-economic development.

VII. CONCLUSIONS

The findings indicate that a TPACK-based instructional strategy led to a statistically significant improvement in students' achievement in Biology, as evidenced by higher post-test scores in the experimental group than in the control group, thereby demonstrating that innovative, student-centered teaching techniques can enhance understanding and performance beyond traditional methods. Conversely, there was no significant difference in students' perception of biology teaching between the two groups, suggesting that while the experimental approach bolstered academic outcomes, it did not, on its own, shift learners' attitudes towards the subject, an outcome that may reflect entrenched prior experiences or general dispositions to biology and implies that altering perceptions might require additional, targeted interventions beyond the instructional method employed.

Based on the findings of this study, it is recommended that Biology teachers adopt innovative, student-centered instructional approaches such as inquiry-based learning, collaborative group activities, and hands-on experiments to enhance students' understanding and engagement in Biology classes. Continuous professional development programmes should also be organised for Biology teachers, with an emphasis on strengthening their capacity to implement experimental and technology-integrated teaching methods effectively. In addition, teachers should remain sensitive to gender differences in students' perceptions of Biology teaching and intentionally design inclusive classroom practices that address the learning needs of both male and female students. Schools are further encouraged to introduce supportive interventions such as science clubs, extracurricular activities, and mentorship programmes to stimulate students' interest in Biology and reinforce classroom learning.

VIII. LIMITATIONS OF THE STUDY

The findings of this study are limited to the specific schools, biology teachers, and students sampled, which may affect the generalisability of the results beyond Lagos State. The study involved a small number of biology teachers, as only one was available at each selected school. This reflects common staffing constraints in Nigerian senior secondary schools, where science subjects are often handled by a single subject specialist due to shortages and uneven distribution of qualified teachers (Ahmed et al., 2022; Ugolo & Onukwu, 2021).

In addition, the quasi-experimental design did not permit random assignment of participants, which may have introduced selection bias despite the use of statistical controls. The study relied on specific instruments to assess teachers' TPACK and students' achievement in Biology; while these instruments are reliable, they may not fully capture the complexity of instructional competence or students' conceptual understanding. Furthermore, variations in the availability and quality of technological resources across schools may have influenced the implementation and effectiveness of technology-based instruction.

IX. CONFLICT OF INTERESTS

The authors declare that they have no competing interests.

X. DATA AVAILABILITY STATEMENT

The dataset generated and analysed during this study contains sensitive and potentially identifiable student information and is therefore not publicly available to protect participant confidentiality. Data may be made available from the corresponding author upon reasonable request, subject to ethical approval and a formal data-sharing agreement.

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