UNIOFFA JOURNAL OF INTERDISCIPLINARY STUDIES (U-OJIS)
A Multidisciplinary Journal of Science, Management and Social Sciences
Website: www.unioffajis.com
ISSN:3141-5571
E-ISSN:3141-558X

Effects of Technology-Based Teaching Strategies on Students' Comprehension and Retention of Biology Concepts

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Volume 2:1

Abstract

Background: *Biology is a core science subject in Nigerian secondary schools, yet performance in external examinations remains persistently low, particularly on abstract topics such as cell biology, ecosystems and physiological processes. Lecture-dominated instruction is widely blamed.* ***Purpose:*** *This article synthesises the evidence from four studies on technology-based teaching strategies in secondary school biology to determine their effects on students' comprehension (measured as achievement or performance) and retention.* ***Method:*** *A structured narrative synthesis was conducted. Three quasi-experimental studies (interactive smart board instruction, AI-supported virtual simulations, and computer simulation instruction) and one descriptive survey of teachers' perceptions were analysed for design, sample, intervention, instruments, results and methodological quality.* ***Findings:*** *All three experimental studies found that students taught with technology scored higher on post-tests than students taught by lecture, with gains of 14.7 to 20.1 points over comparison groups in the studies reporting them. Only one study measured retention, and it found a slight but statistically non-significant advantage for the technology group. Gender did not significantly moderate outcomes in the one study that tested it. The survey study indicated that teachers' technological knowledge and in-service training condition effective use. However, the reported effect sizes were inconsistent across the studies' own tables, and several design weaknesses limit causal confidence.* ***Conclusion:*** *Technology-based strategies, especially those that visualise abstract processes, consistently improve immediate comprehension of biology concepts. Evidence for long-term retention is thin and inconclusive. Adoption should be accompanied by teacher training, infrastructure, and more rigorous, longer-term evaluation.*

Keywords: technology-based instruction; biology education; comprehension; retention; interactive smart board; computer simulation; Nigeria

Introduction

Biology occupies a distinctive place in the Nigerian secondary school curriculum. It is a gateway to medicine, pharmacy, agriculture and environmental management, and it enrols more candidates in the senior school certificate examination than physics or chemistry (Tubo & Shuaibu, 2024). Despite this importance, achievement has been persistently poor. Chief examiners' reports cited in the reviewed studies show that many candidates demonstrate weak understanding of key concepts and a poor ability to apply what they have learned (Hadiza et al., 2025; Tubo & Shuaibu, 2024). One of the reviewed studies reports that, for Borno State, only a small and fluctuating minority of candidates obtained credit-level passes in the 2020 to 2022 WASSCE biology examinations (Tubo & Shuaibu, 2024).

The literature attributes this situation largely to instructional practice. Teacher-centred lecturing, crowded classrooms, inadequate laboratories and limited use of information

ISSN:3141-5571
E-ISSN:3141-558X

and communication technology (ICT) are repeatedly named as causes (Anonymous, n.d.; Hadiza et al., 2025; Tubo & Shuaibu, 2024). Many biological concepts, including cell organelles, DNA replication, trophic interactions and physiological feedback loops, cannot be observed directly, and students taught by verbal explanation and chalkboard notes struggle to form clear mental representations of them.

Technology-based teaching strategies have been proposed as a response. These range from interactive smart boards to computer simulations and virtual laboratories. They can display images, animations and video, let learners manipulate variables, and make unobservable processes visible. Yet evidence from Nigerian classrooms is scattered across topics, technologies and designs, and few studies address both comprehension and retention. A consolidated reading of the evidence is therefore useful to teachers, curriculum planners and researchers.

This article addresses that need. It synthesises four studies on technology-based biology instruction and asks four questions:

> What is the effect of technology-based teaching strategies on students' comprehension (achievement and performance) in biology compared with conventional lecture instruction?
>
> What is their effect on students' retention of biology concepts?
>
> Do outcomes differ by gender or topic?
>
> What conditions, such as teacher competence and infrastructure, determine whether these strategies work?

Literature Review and Theoretical Framework

Why biology concepts are difficult

Cell biology, genetics and ecology involve abstract, multi-step and often microscopic or large-scale processes that students cannot physically observe (Tubo & Shuaibu, 2024). When such content is delivered through verbal explanation, learners have little opportunity for visualisation or interaction, which makes it difficult to form mental models and to retain information over time (Hadiza et al., 2025). Ecological and physiological topics add a quantitative dimension, such as population growth equations and predator-prey dynamics, that traditional methods often fail to convey (Yusuf et al., 2025).

Forms of technology-based instruction

The reviewed studies cover three forms of technology use.

> **Interactive smart boards** are large touch-sensitive displays linked to a computer and projector. They let teachers present multimedia, annotate, and involve students physically in manipulating content (De Vita et al., 2014; Tubo & Shuaibu, 2024).
>
> **Simulations and virtual laboratories** model biological systems digitally so that learners can change variables and observe outcomes in real time (Smetana & Bell, 2018; Yusuf et al., 2025).
>
> **General technology teaching strategies** include internet resources, email, online discussion and video- or web-conferencing used by teachers to support instruction (Anonymous, n.d.).

Theoretical foundations

Several theories explain why these tools might improve learning. **Constructivism** holds that learners build understanding through active engagement. Piaget's emphasis on experience and Vygotsky's idea of scaffolding within the zone of proximal development both support interactive, guided simulation environments (Yusuf et al., 2025). **Cognitive Load Theory** (Sweller, 1988) suggests that well-designed visual and interactive displays reduce extraneous load, freeing working memory for the intrinsic complexity of the topic. **TPACK** (Mishra & Koehler, 2006) stresses that technology helps only when integrated with pedagogical and content knowledge, which is why teacher competence is central. Finally, multimodal presentation is thought to serve visual, auditory and kinesthetic learners at once (Tubo & Shuaibu, 2024).

A counterpoint comes from research on guided instruction, which indicates that minimally guided activities can be ineffective and that strong teacher guidance can make lecture and simulation outcomes comparable (Kirschner et al., 2018). Technology is therefore not expected to help unconditionally.

ISSN:3141-5571
E-ISSN:3141-558X

Comprehension and retention

Comprehension refers here to students' understanding and application of concepts as measured immediately after instruction. Retention refers to what is remembered after a delay. Prior research on retention is mixed: some studies report significant benefits of simulation, while others find no clear difference from lecture (Abdulrahaman et al., 2020; Smetana & Bell, 2018). Evidence from Northern Nigeria is limited (Hadiza et al., 2025).

Methodology

Design

This article is a structured narrative synthesis of a purposively assembled set of four studies. A meta-analysis was not appropriate because the studies differ in topic, technology, outcome measure and reporting quality, and because their reported statistics were not fully consistent.

Source studies

The four studies analysed were: (a) Tubo and Shuaibu (2024) on interactive smart board instruction in cell biology in Maiduguri, Borno State; (b) Yusuf et al. (2025) on AI-supported virtual simulations for teaching mathematical models in ecology and human physiology; (c) Hadiza et al. (2025) on computer simulation instruction and its effect on performance and retention in ecosystem in Kaduna North; and (d) an unpublished study (author and date not stated in the file supplied, cited here as Anonymous, n.d.) on technology teaching strategy and biology achievement in Langtang North, Plateau State.

Data extraction and appraisal

For each study the following were extracted: design, population and sample, intervention, duration, instruments and reliability, outcomes, analysis and main results. Methodological quality was appraised qualitatively against five criteria: group equivalence, assignment, control of teacher effects, outcome measurement, and internal consistency of reported statistics. Standardised mean differences were recomputed where means, standard deviations and group sizes were reported, as a check on the authors' own figures.

Characteristics of the included studies

Study	Design and sample	Technology	Duration	Instrument and reliability	Outcomes
Tubo & Shuaibu (2024)	Quasi-experimental, non-equivalent pretest-posttest; two intact classes in two co-educational schools (reported as 123 or 125 students)	Interactive smart board	6 weeks	Cell Biology Performance Test; test-retest r = 0.90	Post-test performance; gender
Yusuf et al. (2025)	Quasi-experimental pretest-posttest control group; 300 SS2 students, six schools, 150 per group	AI-supported virtual simulations	6 weeks	BMMAT (KR-20 = 0.84); SECQ (alpha = 0.87)	Comprehension and application of mathematical models in ecology and physiology
Hadiza et al. (2025)	Quasi-experimental pretest, posttest and delayed post-test; four intact classes, 177 students (92 experimental, 85	Computer simulation (ecosystem simulation videos)	6 weeks; delayed test after 2 weeks	50-item Ecosystem Performance Test; K-20 = 0.85	Performance and retention

ISSN:3141-5571
E-ISSN:3141-558X

Study	Design and sample	Technology	Duration	Instrument and reliability	Outcomes
	control)				
Anonymous (n.d.)	Descriptive survey; 120 respondents, simple random sampling	General technology teaching strategy	Not applicable	15-item questionnaire; analysed by mean	Perceived effects on achievement

Results

Effects on comprehension and performance (RQ1)

All three experimental studies favoured technology-based instruction.

Study	Technology group	Comparison (lecture) group	Difference
Tubo & Shuaibu (2024), post-test	M = 41.40, SD = 8.81 (n = 63)	M = 26.70, SD = 5.50 (n = 60)	14.70
Yusuf et al. (2025), ecology	Pre 39.82 to post 76.19 (gain 36.37)	Pre 40.05 to post 61.28 (gain 21.23)	Gain difference 15.14
Yusuf et al. (2025), physiology	Pre 41.27 to post 79.38 (gain 38.11)	Pre 41.52 to post 64.26 (gain 22.74)	Gain difference 15.37
Hadiza et al. (2025), ecosystem	Pre 27.17 to post 47.27 (gain 20.10)	Pre 26.67 to post 29.23 (gain 2.56)	Gain difference 17.54

The studies' inferential tests agree on direction. Tubo and Shuaibu reported a significant independent-samples t-test (df = 121) favouring the smart board group. Yusuf et al. reported significant ANCOVA group effects after controlling for pretest scores in ecology ($F(1,296) = 61.42$, $p < .001$, partial eta squared = .172) and physiology ($F(1,296) = 71.46$, $p < .001$, partial eta squared = .195). Hadiza et al. reported a significant treatment effect on performance in their ANCOVA. Gain scores in the two studies with pretests (Yusuf et al.; Hadiza et al.) show that the lecture groups also improved, though far less, which is what would be expected from instruction of any kind.

Effects on retention (RQ2)

Only Hadiza et al. (2025) measured retention, using a reshuffled version of the performance test administered two weeks after the post-test. The technology group's mean rose slightly (47.27 to 48.12, +0.85), while the lecture group's mean fell (29.23 to 28.00, −1.23). The authors interpreted this as a better mean gain in retention, but the ANCOVA showed no statistically significant difference between groups. The honest reading is that the technology group retained what it had learned at least as well as the lecture group, with no demonstrated retention advantage beyond its higher starting point. Yusuf et al. (2025) interpreted their results as consistent with improved retention reported elsewhere, but they did not test retention, and Tubo and Shuaibu (2024) did not either.

Gender and topic (RQ3)

Tubo and Shuaibu (2024) examined gender within the smart board group. Males scored somewhat higher than females (46.11 versus 41.67 in the descriptive table), but the t-test indicated no significant difference ($p = 0.32$), and the authors concluded that the strategy is gender friendly. Yusuf et al. and Hadiza et al. did not analyse gender, although Yusuf et al. balanced gender across groups at assignment.

Benefits appeared across diverse content: cell biology and genetics, ecology and quantitative modelling, human physiology, and food chains and trophic levels. No study compared topics directly, so differential effects by topic cannot be established.

ISSN:3141-5571
E-ISSN:3141-558X

Teacher knowledge and conditions of use (RQ4)

The Langtang North survey reported that, in teachers' and respondents' judgement, effectively used technology helps learners build mental models that support applied problem solving and transfer, and that well-informed knowledge of the strategy enables teachers to use technological learning resources effectively (Anonymous, n.d.). This is perception data, not achievement data, but it is consistent with the other studies' recommendations. Tubo and Shuaibu (2024) call for teacher retraining on smart board use and for computer laboratories in every school. Yusuf et al. (2025) note that technical resource demands and the need for training can hinder effective use, and Hadiza et al. (2025) selected only schools that had a functioning computer laboratory, an ICT-proficient staff member and electricity, which is itself a finding about prerequisites.

Methodological quality and consistency of reported statistics

The direction of the findings is consistent, but the studies share weaknesses that readers should weigh.

Non-random assignment. Tubo and Shuaibu and Hadiza et al. used intact classes. Tubo and Shuaibu used one school per condition, so school and treatment are confounded. Yusuf et al. report random assignment of students, which is unusually strong for classroom research but is hard to reconcile with the school-level delivery described.

Teacher effects. Tubo and Shuaibu trained two research assistants to teach from fixed lesson plans, which is a good control, but the other studies do not describe how teacher effects were handled.

Equivalence at baseline. Pretest means were close in Yusuf et al. and Hadiza et al. Tubo and Shuaibu report that pretesting was done but present post-test results only.

Novelty and expectancy. Lessons lasted six weeks, a period in which novelty can inflate engagement and scores.

Instruments. Tests were researcher-developed and drew on past examination items, which supports content validity but is not independent of the teaching content.

Internal inconsistencies. Several tables conflict with the surrounding text. Tubo and Shuaibu report 125 students in the abstract but 123 in the body, swap group sizes in one table, give mean differences of 14.70 and 11.8 for the same comparison, and describe a p-value of 0.32 as less than 0.05 while retaining the null hypothesis. Hadiza et al. report 6,746 males and 6,746 females as a population of 14,951, list treatment degrees of freedom of 2 for a two-group comparison, and give p-values that differ between tables and text (.02 versus .002; .11 versus .011). Their pretest standard deviations (about 1.15) are implausibly small for a 50-item test.

Effect sizes. Recomputing from the reported means and standard deviations yields standardised differences of roughly 2.0 for Tubo and Shuaibu and about 2.3 for both Yusuf et al. comparisons, higher than the reported d of 1.35 and 1.49. Hadiza et al.'s figures imply an implausibly large difference. The effects are clearly positive, but the exact magnitudes should not be quoted without caution.

Discussion

Technology consistently improves immediate comprehension

Across different tools, topics and locations, students taught with technology outperformed lecture-taught peers at post-test, typically by 15 or more raw score points. This agrees with the broader empirical literature cited in the studies, which finds positive effects of interactive boards and simulations on science and mathematics achievement (Ifeakor et al., 2020; Onder & Aydin, 2016; Smetana & Bell, 2018). The consistency across three independent research teams, three technologies and three contexts is the strongest feature of the evidence. Because every study carries design limitations, however, the findings are best described as consistently promising rather than definitive.

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E-ISSN:3141-558X

Why the strategies seem to work

The mechanisms proposed are plausible and mutually reinforcing. First, **visualisation** makes abstract or unobservable processes concrete, which addresses the core difficulty identified for cell biology and ecosystems (Hadiza et al., 2025; Tubo & Shuaibu, 2024). Second, **interactivity** lets students manipulate variables, such as population parameters, and see consequences immediately, consistent with constructivist accounts (Yusuf et al., 2025). Third, **reduced extraneous cognitive load** from organised multimedia may free attention for the underlying concepts. Fourth, **engagement and motivation** rise when lessons are novel, physically involving and visually large (Tubo & Shuaibu, 2024). These mechanisms were inferred from the literature rather than tested directly by any of the studies, since none measured cognitive load or engagement as mediators of the outcome. Yusuf et al. included an engagement questionnaire, but its results were not reported.

The retention question

The retention finding deserves careful interpretation. The technology group's edge on retention was not statistically significant, and the retention interval was only two weeks. That result matches some prior studies and conflicts with others (Abdulrahaman et al., 2020; Owusu et al., 2020; Smetana & Bell, 2018). Two reasonable explanations were offered by the authors: both groups covered the same content and objectives, and the exposure to simulation was short (Hadiza et al., 2025). A further possibility is that teacher-led simulation, in which the teacher ran the simulation while students observed, produces strong immediate understanding without the repeated retrieval and hands-on practice that consolidate long-term memory. The claim that technology improves retention is therefore not yet supported by evidence from these studies. What is supported is the narrower claim that technology-taught students do not forget more than lecture-taught students and that they hold a higher level of knowledge throughout.

Gender

The single gender analysis found no significant difference between male and female students taught with the smart board. This is encouraging for equity because it indicates that technology need not widen gender gaps, but it rests on one small sample with a contradictory report of descriptive statistics, and it compared genders only within the experimental group. Whether technology narrows, preserves or widens a gender gap relative to lecture has not been tested.

Teachers and infrastructure as conditions

Technology does not teach by itself. In the TPACK view, effects depend on whether teachers can integrate tools with content and pedagogy. The reviewed studies converge on this point: Tubo and Shuaibu recommend retraining, Yusuf et al. call for professional development and ICT investment, and the Langtang survey recommends in-service training in computer use (Anonymous, n.d.). The experimental studies also ran under favourable conditions, namely trained research assistants, equipped computer laboratories and reliable power, which are not typical of many Nigerian schools. Results may therefore overstate what would happen under routine, under-resourced conditions. Kirschner et al. (2018) add that guided instruction can match technology when teaching is strong, so the comparison group's teaching quality matters.

Implications

For teachers. Use technology where content is abstract, dynamic or invisible, such as cell structure, cell division, DNA processes, food webs and physiological feedback. Pair simulations with student interaction, questioning and spaced practice rather than teacher demonstration alone, and add retrieval quizzes to support retention.

For schools and administrators. Provide computer laboratories, projectors or smart boards, simulation software and stable electricity, because these were prerequisites in the studies and their absence is a barrier to scale.

For teacher education. Include simulation design, classroom integration and facilitation in pre-service and in-service programmes, in line with the TPACK framework.

For curriculum planners. Integrate technology-based strategies into the biology curriculum as a complement to, not a replacement for, practical and discussion-based methods, and prioritise topics that examiners' reports identify as poorly understood.

For policy makers. Fund equitable access so that gains are not confined to well-resourced schools.

ISSN:3141-5571
E-ISSN:3141-558X

Limitations

This synthesis rests on only four studies, one of which is a perception survey, and the set was assembled from supplied sources rather than through a systematic database search, so publication bias and selection effects cannot be ruled out. The studies used different outcome measures and reported statistics inconsistently, which prevented formal meta-analysis. Secondary sources cited within the primary studies are reported as the authors presented them and were not independently verified. In particular, one frequently cited virtual reality study (Makransky et al., 2019) concluded that adding immersive VR to a science lab simulation increased presence but reduced learning, so it should not be taken as evidence that immersive technology uniformly improves learning. Finally, the evidence comes from northern and north-central Nigeria and may not generalise to other settings.

Recommendations for Future Research

Use randomised or well-matched designs with multiple schools per condition and statistical control for school-level clustering.

Measure retention at several intervals (for example two weeks, two months and six months) and include delayed tests in every technology study.

Test mechanisms by measuring engagement, cognitive load and student interaction with the technology.

Compare technology with strong guided or practical instruction, not only with lecture.

Examine moderators, including gender, prior ability, school resources and topic, with adequately powered samples.

Evaluate effects under routine classroom conditions with ordinary teachers, and report effect sizes and full statistical output transparently.

Conclusion

The evidence reviewed supports the conclusion that technology-based teaching strategies, including interactive smart boards and computer or virtual simulations, improve secondary school students' immediate comprehension of biology concepts relative to lecture instruction. The advantage appears across topics, tools and settings and is large enough to matter in practice, even allowing for inflated or inconsistently reported effect sizes. By contrast, evidence that these strategies improve long-term retention is limited to a single study with a two-week delay and a non-significant result. Gender differences were not significant in the one study that tested them. Effective use depends on teacher competence and adequate infrastructure. Technology should therefore be adopted as a well-supported way to teach abstract biology content, backed by teacher training, resources and stronger, longer-term research.

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