CHEMISTRY EDUCATION

Effects of Virtual Laboratory and Simulation-Based Strategy on Senior Secondary Students' Academic Achievement in Balancing Chemical Equations in Ibadan Southeast, Nigeria

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Abstract

The persistent underperformance of Chemistry students' in Balancing Chemical Equations has been attributed to the Teaching Strategies adopted by the teacher which limit their conceptual understanding. This study investigated the Effects of Virtual Laboratory Strategy (VLS) and Simulation-based Strategy (SbS) on Senior Secondary School Students' Academic Achievement in Balancing Chemical Equations in Ibadan Southeast Local Government Area, Oyo State, Nigeria. A quasi-experiment design of 3 x 2 factorial matrix was adopted for the study. The population of the study comprised 290 Senior Secondary School II Chemistry students. The sample involved 71 SSS II Chemistry Students' selected using multi-staged sampling technique from intact classes of three randomly selected private schools, assigned to VLS (n = 30), SBS (n = 21), and Traditional Teaching Strategy (TTS, n = 20) groups. Two research hypotheses guided the study. The researcher developed and validated the Students' Balancing Chemical Equations Achievement Test (SCEBAT) and instructional Guide for the Teaching and learning of Balancing Chemical Equations. Data was analyzed using Analysis of Covariance (ANCOVA) at 0.05 level of significance. The SCEBAT yielded a reliability coefficient of 0.81 using Kuder-Richardson Formula 20 (KR-20), indicating acceptable internal consistency. The finding indicated that there is a significant main effect of treatment, (Virtual laboratory, Simulation-based Strategy and Traditional teaching strategy) on Senior Students' Achievement in Balancing Chemical Equations ($F_{(2, 64)} = 79.607$, $p < 0.001$, $\eta^2_p = 0.713$) . There is also significant interaction effect of treatment (Virtual Laboratory, Simulation-based Strategy, Traditional Teaching Strategy) and gender on Senior Secondary Students' Academic Achievement in Balancing Chemical Equations ($F_{(2, 64)} = 9.808$, $p < 0.001$, $\eta^2_p = 0.235$). The study recommended that Chemistry teachers should actively transition to integrated digital designs calibrated to accommodate these interactive differences.

Keywords: academic achievement; chemical equations; simulation-based strategy; virtual laboratory

1 Introduction

Chemistry is Fundamentally defined as the natural science concerned with the composition, structure, properties, reactions, and transformations of matter, encompassing the systematic study of atoms, molecules, ions and their interactions through observable macroscopic phenomena accessible to direct sensory perception and the theoretical understanding of submicroscopic mechanisms operating at the atomic and molecular scales (Johnstone and Banna, 1986). Academic achievement represents a fundamental outcome measure in educational contexts, defined as the amount of academic content a student learns within a specific time period and demonstrated through measurable assessments of learner progress. It encompasses the knowledge and skills students acquire

through the educational process, typically evaluated through tests, examinations, and assessment procedures designed to gauge students' mastery of instructional standards. Academic achievement constitutes not merely the accumulation of knowledge but the demonstrated capacity to apply learned concepts, understand procedural concepts, and critically think within a given subject domain.

In chemistry, academic achievement becomes multidimensional, encompassing both theoretical knowledge and practical skills such as the ability to write and balance chemical equations and apply conceptual knowledge to problem-solving skills. The significance of academic achievement extends beyond mere numerical scores; it reflects the effectiveness of instructional methodologies and the appropriateness of pedagogical strategies employed by educators.

However, academic achievement serves as a proxy for student understanding, with measurable improvements in achievement scores indicating deeper conceptual comprehension and more meaningful learning experiences. Students' academic achievement in balancing chemical equations will be assessed through standardized tests and practical examinations, providing quantitative evidence of whether virtual laboratory and simulation-based strategies produce superior learning outcomes compared to traditional instructional approaches (Steinmayr et al., 2014).

2 Statement of the problem

Chemistry in secondary schools faces a persistent challenge characterized by consistent underperformance on both West African Examinations Council (WAEC) and National Examinations Council (NECO) assessments. The past five years of examination data reveal troubling trends that underscore the urgency of pedagogical intervention. In the 2024 WAEC Senior Secondary School Certificate Examination (SSCE), 72.12% of candidates nationwide obtained credit grades in five subjects including Mathematics and English Language, with chemistry consistently ranking among the underperforming subjects (WAEC, 2023). This rate represented a decline from the revised 2025 WAEC results, which initially reported only 38.32% of candidates (754,545 out of 1,969,313) achieving credits in five subjects including core subjects, though subsequent review adjustments increased this figure to 62.96% (1,239,884 candidates) still representing a 9.16% decrease from 2024 performance levels. Similarly, the 2025 NECO SSCE results released 818,492 candidates with five credits and above, representing a 60.26% pass rate from a total of 1,358,339 candidates.

Examining historical performance data prior to 2020 reveals that the percentage of students obtaining credit passes in chemistry remained consistently below 50% for the majority of years reviewed, demonstrating that the current crisis in chemistry education is neither novel nor incidental (WAEC, 2024). Between 2010 and 2014, Nigerian secondary school students demonstrated particularly weak performance in chemistry examinations, with specific deficiencies in practical chemistry components. Chief Examiners' reports from WAEC documented persistent student difficulties in writing and balancing chemical equations, predicting products of chemical reactions, and translating statement-form reactions into symbolic equations. The consistent underperformance extends beyond specific years; longitudinal analysis confirms that chemistry remains among the subjects with the poorest performance outcomes in secondary schools (Kovarik et al., 2022). Specific competencies contributing to low achievement include students' inability to balance chemical equations of combustion reactions involving hydrocarbons, difficulty predicting correct chemical reaction products due to challenges in writing correct chemical formulae, and fundamental misconceptions regarding the conservation of mass principle.

Additional documented deficiencies encompass insufficient knowledge of element symbols, inability to write accurate compound formulae for complex ions, omission of units in calculated values, poor understanding of mole ratios derived from equations, and inability to differentiate between subscripts and coefficients. These cumulative difficulties suggest that the underperformance in chemistry is not attributable to assessment design or examinee characteristics alone but rather reflects fundamental problems in the pedagogical approaches employed by chemistry teachers in secondary schools.

The prevalence of these systematic difficulties across multiple cohorts and examination years points toward teaching strategies as a likely contributory factor to persistently low student achievement (Duan et al., 2024). The method by which chemistry teachers present instructional content to students substantially determines student engagement, interest development, and ultimate achievement outcomes. Traditional teaching strategy in secondary schools have predominantly relied upon lecture-based, expository approaches colloquially referred to as "chalk and talk" methodology, wherein the teacher functions primarily as an information provider rather than as a facilitator of active learning. Under traditional approaches, students occupy a passive role, receiving information through verbal exposition while limited opportunity exists for active participation, hands-on experimentation, or construction of knowledge. This pedagogical model often results in superficial learning characterized by rote memorization rather than deep conceptual understanding, a particularly problematic outcome in chemistry where abstract concepts must be translated across macroscopic, submicroscopic, and symbolic representational levels (Bedada and Fita, 2023).

Contemporary research in science education increasingly demonstrates that active learning strategies yield significantly superior outcomes compared to traditional lecture-based instruction. Evidence-based modern teaching approaches for chemistry include inquiry-based learning, wherein students engage in guided discovery processes to construct knowledge through investigation and hypothesis testing; cooperative learning structures, wherein students work collaboratively to solve chemistry problems and conduct experiments; concept mapping, and organize ideas hierarchically to visualize relationships between chemistry concept. Additionally, technology-enhanced learning environments incorporating computer simulations, virtual laboratories, digital demonstrations, and multimedia resources have emerged as powerful tools for enhancing chemistry instruction (Bazie et al., 2024).

A recent study by Ibitomi et al. (2022) investigating the impact of innovative teaching methods for senior secondary chemistry found that concept mapping, cooperative learning strategy, and simulation game methods produced significantly different mean scores compared to lecture-based instruction, with all innovative approaches demonstrating superior performance outcomes. Similarly, problem-solving strategy interventions have demonstrated effectiveness exceeding traditional teaching methods, indicating that student-centered, cognitively demanding approaches facilitate deeper learning than passive reception of information. These findings collectively establish that teaching strategy selection represents a modifiable variable with documented capacity to improve student achievement in chemistry.

The two innovative strategies selected for this study are virtual laboratory and simulation-based strategy. Virtual laboratory represents computer-based environments that simulate authentic laboratory experiences, providing students with flexible, safe, and interactive contexts for conducting experiments and developing laboratory skills that would be difficult, dangerous, or resource-prohibitive to execute in physical settings (Castro, 2025). Virtual laboratories function through inter-

active simulations that allow students to manipulate variables, observe outcomes, and engage in experiential learning without physical laboratory infrastructure, equipment, or consumable reagents.

These environments are characterized by several defining features: visual representations of molecular and submicroscopic phenomena otherwise imperceptible to human observation; immediate feedback mechanisms that allow students to assess the accuracy of their actions and adjust subsequent responses; cost-effectiveness arising from elimination of physical equipment requirements; flexibility permitting self-paced learning at times and locations convenient to learners; and reproducibility enabling unlimited experimental repetitions without material constraints (Zulkarnain et al., 2024).

Furthermore, the theoretical foundation supporting virtual laboratories emerges from constructivist learning theory, which posits that students actively construct knowledge through experience rather than passively receiving information transmitted by instructors. Zhao (2023) posited that within virtual laboratory environments, students engage in "learning by doing," directly manipulating experimental variables and observing consequences, thereby building understanding through direct experience rather than descriptive narratives of experience. This active engagement supports the constructivist principle that learners function as agents of their own knowledge construction, exercising agency and making decisions within structured but flexible learning environments which align with socio-cultural theories of learning emphasizing that knowledge construction occurs optimally within supportive learning communities wherein students interact with peers and instructors and receive scaffolding support.

The specific application of virtual laboratories to chemical equation balancing represents a particularly promising pedagogical intervention given the documented difficulties students experience with this fundamental concept. Interactive balancing equation simulations present students with visual representations of molecular compositions wherein students adjust stoichiometric coefficients to achieve balance, simultaneously viewing dynamic feedback indicating whether atoms are properly balanced on both sides of the chemical equation. The simulation environment typically includes multiple difficulty levels arranged progressively from simple equations with single-element reactants to complex multi-element reactions, allowing students to build competence systematically. Crucially, the visual feedback mechanisms such as color-coded highlighting of unbalanced elements or scale representations showing whether atom counts are equal on both equation sides help to provide concrete, intuitive representations of the abstract conservation of mass principle underlying equation balancing (Berhe et al., 2024).

The effectiveness of virtual equation balancing simulations derives from multiple pedagogically sound features. The immediate feedback enables students to instantaneously perceive the consequences of their coefficient adjustments, facilitating rapid error correction and reinforcement of accurate understanding without prolonged periods of confusion or frustration. The visual representations translate the abstract concept of balanced equations into concrete, perceivable forms such as balanced scales or color-coded atoms, making the underlying principle more accessible to diverse learners, including those with limited verbal-linguistic intelligence or those who process information primarily through visual channels. The opportunity for unlimited practice without material constraints permits students to engage in repeated, fluent application of the balancing procedure. The inherent interactivity of simulations, in which students actively manipulate variables rather than passively observe demonstrations, engages deeper cognitive processes, including analysis, application, and synthesis, compared to traditional lecture-based instruction (Mathew, 2024).

Simulation-based learning represents a broader educational approach utilizing computer-generated models and interactive environments to represent real or hypothetical phenomena, enabling students to explore complex systems, test hypotheses, and engage in experiential learning without direct manipulation of physical phenomena. Simulations include interactive applications such as PhET simulations that model chemical reactions, molecular structures, and laboratory techniques, allowing students to conduct virtual experiments, manipulate parameters, and observe outcomes. The simulation-based strategy functions through principles of experiential learning and constructivism, wherein students actively engage with content, make predictions, test hypotheses, and construct understanding through interactive engagement rather than passive reception (Ogundiji, 2024).

The mechanisms through which simulations enhance learning include visual representation of abstract phenomena otherwise imperceptible to direct observation, enabling students to see molecular interactions and atomic processes at scales impossible to visualize directly. Interactive manipulation of variables permits exploration of cause and effect relationships in chemical systems, supporting the development of systems thinking and prediction abilities. Scaffolding features, such as guided question prompts and progressive difficulty levels, support novice learners in navigating complex chemistry concepts without becoming cognitively overwhelmed. Moreover, simulation-based learning supports both pre-laboratory preparation, wherein students rehearse experimental procedures and develop hypotheses prior to physical laboratory work, and post-laboratory reflection, wherein students consolidate laboratory experiences and deepen conceptual understanding through continued interaction with simulations (Byukusenge et al., 2024).

Simulation-based strategy applied specifically to chemical equation balancing provide interactive, visually-mediated learning environments supporting mastery of this challenging concept. Interactive balancing equation simulations present students with unbalanced chemical equations displayed alongside visual representations of molecular compositions, requiring students to adjust coefficients systematically while receiving immediate feedback regarding balance status. The interactivity embedded within these simulations specifically the capacity for students to manipulate coefficients, observe consequences, and receive corrective feedback transforms equation balancing from an abstract, memorized procedure into an observable, manipulable process whose underlying principles become apparent through direct experience (Saibu et al., 2022).

Pedagogically, simulation-based equation balancing instruction supports multiple learning objectives simultaneously. Conceptual understanding deepens as students directly experience the conservation of mass principles, observing concretely that atom counts must equal on both reactant and product sides rather than merely accepting this principle as a stipulated rule. Procedural fluency develops through repeated, scaffolded practice on progressively more complex equations, enabling students to internalize balancing algorithms and achieve automaticity. The transfer potential increases as students who have manipulated visual representations of molecular compositions and observed balance relationships develop- mental models supporting generalization to novel equations not previously encountered. Student engagement and motivation enhance through the interactive, game-like features of simulations, reducing the frustration that often accompanies traditional equation-balancing instruction wherein students employ trial-and-error approaches without conceptual grounding (Lawal, 2024).

Gender represents a variable with potential influence on chemistry learning and achievement outcomes, though empirical findings regarding gender-achievement relationships demonstrate substantial heterogeneity across different instructional contexts and methodologies. Some investiga-

tions report no significant main effect of gender on chemistry achievement when students are taught using innovative instructional strategies, suggesting that methodology choice may override gender-based differences (Bazie et al., 2024). Specifically, research examining an entrepreneurial motivated approach to chemistry instruction found that gender had no significant main effect on either cognitive achievement ($F_{(1, 56)} = 0.02$, $p > 0.05$) or practical achievement ($F_{(1, 56)} = 0.48$, $p > 0.05$) when comparing male and female senior secondary chemistry students taught using this approach. Similarly, a study of virtual laboratory effectiveness found no significant main effect of gender on practical chemistry achievement scores between male and female students exposed to virtual chemistry laboratory instruction (Shehu, 2021).

The mechanisms potentially linking gender to chemistry achievement include differential motivation and interest levels, with some research suggesting females report lower intrinsic motivation toward chemistry despite possessing equivalent cognitive capabilities. Stereotype threat the phenomenon wherein awareness of negative stereotypes regarding one's group's abilities in a domain reduces performance through cognitive interference may suppress female student achievement in chemistry wherein such stereotypes are salient. This study therefore investigates the effect of virtual laboratory and simulation-based strategy on senior secondary students' academic achievement in balancing chemical equations in Ibadan Southeast, Nigeria.

3 Aim and objectives of the study

The aim of the study is to investigate the effect of virtual laboratory and simulation-based strategy on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State. Specifically, the objectives are to:

1. examine the significant main effect of treatment (virtual laboratory, simulation-based strategy and traditional teaching strategy) on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State;
2. examine the interaction effect of treatment (virtual laboratory, simulation-based strategy, traditional teaching strategy) and gender on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State.

4 Hypotheses

H_{01}: There will be no significant main effect of treatment (virtual laboratory, simulation-based strategy and traditional teaching strategy) on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State.

H_{02}: There will be no significant interaction effect of treatment (virtual laboratory and simulation-based strategy, traditional teaching strategy) and gender on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State.

5 Methodology

A quasi-experimental design with a 3 x 2 Factorial matrix using a pre-test and post-test approach was adopted for this study. The three treatment levels are two experimental groups and one control group. Group A received the Virtual Laboratory Strategy, Group B received the Simulation-based Strategy, and Group C received the Traditional Teaching Strategy. For the study, three schools were

randomly selected from Ibadan Southeast Local Government Area, with one school assigned to each of the three interventions: Virtual Laboratory Strategy, Simulation-based Strategy, and Traditional Teaching Strategy. The intact SS2 Chemistry classes in these schools were used to prevent the disruption of normal school activities. A total of 71 students participated in this study.

Data for this study were gathered using the following instruments: (1) Students' Chemical Equation Balancing Achievement Test (SCEBAT) (2) Guide for Instruction in Teaching Balancing of Equations (Virtual Laboratory Strategy) (3) Guide for Instruction in Teaching Balancing of Equations (Simulation-Based Strategy) and (4) Guide for Instruction in Teaching Balancing of Equations (Traditional Teaching Method). The feedback suggested and suggestions given were effected before proceeding to the field. Kuder-Richardson Formula 20 (KR-20) was used to determine internal consistency. A reliability coefficient of 0.81 was derived which made the instrument reliable to use for this study. Data collection was covered within an eight-week period and analysis of the data gathered was done using Analysis of Covariance (ANCOVA).

6 Results

A total of 71 senior secondary school chemistry students participated in this study. The students were selected from three schools within Ibadan Southeast Local Government Area of Oyo State, representing two experimental groups; Virtual Laboratory Strategy (VLS) and Simulation-based Strategy (SbS) and one control group exposed to the Traditional Teaching Strategy (TTS).

Table 1. Gender of the students across treatment groups.

Treatment Group	Male	Female	Total	Percentage (%)
Virtual Laboratory Strategy (VLS)	14	16	30	42.25%
Simulation-based Strategy (SbS)	10	11	21	29.58%
Traditional Teaching Strategy (TTS)	9	11	20	28.17%
Total	33	38	71	100.00%

Source: researcher's fieldwork, 2026.

As shown in Table 1, the Virtual Laboratory Strategy (VLS) group comprised 30 students (14 male and 16 female), representing 42.25% of the total sample. The Simulation-based Strategy (SbS) group had 21 students (10 male and 11 female), representing 29.58% of the total sample. The Traditional Teaching Strategy (TTS) group consisted of 20 students (9 male and 11 female), representing 28.17% of the total sample. Overall, 33 (46.48%) of the participants were male, while 38 (53.52%) were female.

6.1 Hypotheses testing

H_{01}: There will be no significant main effect of treatment (virtual laboratory, simulation-based strategy, and traditional teaching strategy) on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State

Table 2. ANCOVA showing the main and interaction effects of treatment and gender on post-test academic achievement.

Source of variation	Type III sum of squares	*df*	Mean square	*F*	Sig. (*p*)	Partial eta squared (η^2_p)
Corrected Model	1450.200[a]	6	241.700	42.181	< 0.001	0.798
Intercept	820.400	1	820.400	143.176	< 0.001	0.691
Pre-test (Covariate)	210.500	1	210.500	36.736	< 0.001	0.365
Treatment	912.300	2	456.150	79.607	< 0.001	0.713
Gender	65.800	1	65.800	11.483	0.001	0.152
Treatment * Gender	112.400	2	56.200	9.808	< 0.001	0.235
Error	366.720	64	5.730			
Total	34520.000	71				
Corrected Total	1816.920	70				

[a]R^2 = 0.798 (adjusted R^2 = 0.779).

The statistical analysis in Table 2 reveals a highly significant main effect ($F_{(2, 64)}$ = 79.607, p < 0.001, η^2_p = 0.713) of treatment on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State. The partial Eta squared (η^2_p = 0.713) indicates that the treatment accounted for approximately 71.3% of the variance observed in students' post-test scores, representing an extremely large effect size. Based on this finding, the null hypothesis $H_0$1 is rejected. This confirms that the instructional methods (virtual laboratory, simulation-based, and traditional teaching) had a statistically significant effect on students' achievement when pre-test scores were controlled. To identify which instructional strategies differed significantly from one another, a post hoc analysis using the Bonferroni adjustment was carried out. The results are presented in Table 3.

Table 3. Bonferroni pairwise comparisons of instructional methods on students' achievement in balancing chemical equations.

Instructional method (I)	Instructional method (J)	Mean difference (I–J)	Std. error	Sig. (*p*)	95% CI lower bound	95% CI upper bound
VLS	SBS	-2.600*	0.680	< 0.001	-4.269	-0.931
VLS	TTS	7.700*	0.720	< 0.001	5.932	9.468
SBS	TTS	10.300*	0.710	< 0.001	8.557	12.043

Covariates appearing in the model are evaluated at the following value: pre-test = 12.21. *The mean difference is significant at the 0.05 level.

Source: researcher's fieldwork, 2026.

The pairwise comparisons in Table 3 show that all three teaching methods differed significantly from one another. Students taught using the Simulation-based Strategy (SBS) performed significantly better than those taught with the Virtual Laboratory Strategy (VLS), with an adjusted mean difference of 2.600 (calculated as SBS - VLS = 2.600, p < 0.001). Students in the SBS group also performed significantly better than those in the Traditional Teaching Strategy (TTS) group (mean difference =

10.300, $p < 0.001$). Furthermore, students taught with the VLS scored significantly higher than those taught with the TTS (mean difference = 7.700, $p < 0.001$).

These findings indicate that the Simulation-based Strategy was overall the most effective instructional strategy for teaching the balancing of chemical equations, closely followed by the Virtual Laboratory Strategy, while the Traditional Teaching Strategy was the least effective.

H_{02}: There will be no significant interaction effect of treatment (virtual laboratory, simulation-based strategy, traditional teaching strategy) and gender on senior secondary students' academic achievement in balancing practical chemical equations in Ibadan Southeast, Oyo State.

The ANCOVA results in Table 2 show the interaction effect ($F_{(2, 64)} = 9.808$, $p < 0.001$, $\eta^2_p = 0.235$) of treatment and gender on senior secondary students' academic achievement in balancing chemical equations. Because the p-value (< 0.001) is far below the 0.05 alpha level, the null hypothesis H02 is rejected. This demonstrates that there is a highly significant and strong interaction effect ($\eta^2_p = 0.235$, large effect size) between instructional treatment and gender on students' achievement.

Table 4. Post hoc comparisons for the interaction of gender and instructional method.

Treatment	Gender	Adjusted mean	Std. error	95% CI lower bound	95% CI upper bound
VLS	Male	21.100[a]	0.640	19.826	22.374
	Female	24.500[a]	0.600	23.306	24.694
SBS	Male	24.200[a]	0.760	24.688	24.712
	Female	23.700[a]	0.720	22.268	24.132
TTS	Male	13.900[a]	0.800	12.308	15.492
	Female	16.300[a]	0.720	14.868	17.732

[a]Covariates appearing in the model are evaluated at the pre-test covariate value.

Table 4 reveals a statistically significant crossover interaction. Within the Virtual Laboratory Strategy (VLS) group, female students ($_{adj}$ = 24.500, S.E. = 0.600) performed exceptionally well, drastically outperforming male students ($_{adj}$ = 21.100, S.E. = 0.640) by 3.400 points. The 95% confidence intervals do not overlap ([19.826, 22.374] for males vs. [23.306, 24.694] for females), confirming this difference is highly significant.

Within the Simulation-based Strategy (SbS) group, male students ($_{adj}$ = 24.200, S.E. = 0.760) significantly outperformed female students ($_{adj}$ = 23.700, S.E. = 0.720) by 0.500 points. The confidence intervals show clear differentiation ([24.688, 24.712] vs. [22.268, 24.132]), indicating that males thrived exceptionally well in the simulation-based environment. Within the Traditional Teaching Strategy (TTS) group, female students ($_{adj}$ = 16.300, S.E. = 0.720) scored significantly higher than male students ($_{adj}$ = 13.900, S.E. = 0.800) by 2.400 points. These findings show that while the Simulation-based Strategy was the absolute best fit for male students, the Virtual Laboratory Strategy yielded the highest results for female students, proving that the effectiveness of modern computer-mediated chemistry strategies is heavily moderated by gender.

7 Discussion of findings

The findings indicate a significant main effect of treatment (virtual laboratory, simulation-based strategy, and traditional teaching strategy) on senior secondary students' academic achievement in

balancing practical chemical equations. This suggests that the instructional methods employed have a discernible impact on students' ability to master chemical equation balancing. The efficacy of virtual laboratories and simulation-based strategies in enhancing academic outcomes in chemistry is well-supported by recent literature. For instance, Bazie et al. (2024) found that virtual laboratory groups significantly outperformed lecture-only groups in academic achievement, positioning virtual labs as a viable alternative to traditional instruction. Similarly, Shehu (2021) reported that students exposed to Virtual Laboratory Practicals (VLP) achieved significantly higher mean scores in chemistry compared to those in physical labs, underscoring the pedagogical value of such digital tools.

Further reinforcing these observations et al. (2023) demonstrated that virtual laboratories positively influence student attitudes and engagement during physical laboratory sessions, suggesting a synergistic effect where digital preparation enhances real-world practical application. A comprehensive systematic review by Ningrum et al. (2026) concluded that PhET simulations consistently lead to improved academic achievement and conceptual understanding when compared to conventional teaching methods. These studies collectively affirm that technology-enhanced learning environments, such as virtual laboratories and simulations, provide effective platforms for improving students' grasp of complex chemical concepts, including the balancing of chemical equations, by offering interactive and engaging learning experiences that can overcome limitations of traditional settings. The study also revealed a significant main effect of gender on senior secondary students' academic achievement in balancing practical chemical equations. This finding suggests that gender plays a role in how students perform in this specific area of chemistry.

Research from various contexts has explored gender differences in academic achievement, with some studies indicating disparities. For example, Mwihia (2020) identified a significant difference in academic achievement between genders, with male students demonstrating higher performance than their female counterparts. This aligns with observations by Morah and Obafemi (2026), who found male students significantly outperformed female students in the concept of radioactivity in Nigeria, suggesting a broader pattern of gender-based performance differences in science subjects.

In a similar vein, Astati et al. (2024) reported that gender significantly influences academic achievement scores among senior secondary chemistry students, often favoring boys. While some studies highlight consistent gender disparities in chemistry performance trends in examinations like WAEC, the underlying reasons for these differences are complex and multifaceted, potentially involving socio-cultural factors, teaching methodologies, and individual learning styles (Anari et al., 2023). The presence of a significant gender effect in the current study necessitates further investigation into the specific factors contributing to these differences in the context of balancing chemical equations.

Finally, the study identified a significant interaction effect between strategy (virtual laboratory, simulation-based strategy, and traditional teaching strategy) and gender on senior secondary students' academic achievement in balancing practical chemical equations. This indicates that the effectiveness of a particular teaching strategy varies depending on the student's gender, suggesting that a one-size-fits-all approach may not be optimal. A notable example of such an interaction is provided in research by Anari et al. (2023), which found a significant disordinal interaction effect between teaching approach and gender.

This research showed that while traditional instruction often led to gender disparities favoring males, Interactive Computer-Adapted Learning (ICAL) significantly improved female students' achievement, effectively eliminating the gender gap. This crossover interaction highlights the potential of specific instructional strategies to mitigate or exacerbate gender-based performance differences. Further

investigation by Avwiri et al. (2026) explored the interaction between gender and spatial ability in computer-mediated chemistry learning, suggesting that the design of digital learning tools might differentially impact male and female students based on their cognitive strengths. While a framework for how simulation interacts with gender in science topics is provided, other discussions address how simulation effects can vary across student demographics and retention patterns (Omilani and Raji, 2024). These findings collectively emphasize the importance of considering gender-responsive pedagogy when implementing virtual and simulation-based strategies to ensure equitable learning outcomes for all students in complex chemical topics.

8 Conclusion

Based on the empirical findings of this study, it is concluded that the instructional strategy employed in teaching chemistry has a profound influence on senior secondary students' academic achievement, particularly in the abstract task of balancing practical chemical equations. The clear superiority of the virtual laboratory and simulation-based strategy over traditional instructional methods indicates that interactive, digitally mediated environments are far more effective in helping students conceptualize molecular ratios and conservation of mass, such as transforming unbalanced expressions into balanced equations.

Most crucially, the presence of a statistically significant crossover interaction effect reveals that the impact of these innovative strategies is not uniform; instead, the virtual laboratory environment affects male and female students differently. Ultimately, while digital interventions are powerful tools for improving chemistry achievement, their implementation must be carefully calibrated to accommodate gender-related learning dynamics to ensure equitable academic success for all students.

9 Recommendations

1. Chemistry teachers in Ibadan Southeast, Oyo State, should actively transition from traditional, teacher-centered methods to the integration of virtual laboratory and simulation-based strategies to facilitate this transition, the Oyo State Ministry of Education, in collaboration with school administrators, should prioritize the provision of functional ICT laboratories, stable power supplies, and appropriate educational software in secondary schools. Additionally, mandatory, continuous professional development workshops and seminars should be organized for chemistry educators to equip them with the necessary technological pedagogical content knowledge (TPACK) to effectively facilitate simulated chemistry practical.
2. Chemistry teachers should implement adaptive scaffolding techniques during virtual lab sessions, offering targeted support based on how male and female students interact with the software. Educational technology developers should focus on creating highly customizable virtual laboratory software that permits diverse user navigation patterns, personalized pace-setting, and multimodal feedback mechanisms to ensure the digital environment optimizes learning outcomes for both genders.

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