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Effects of Simulation and Structured Inquiry Strategies on Critical Thinking Skills in Titration among Secondary Schools Students in Kano State, Nigeria

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Abstract

Critical thinking is essential for effective science learning, yet secondary school students often experience limited opportunities to develop critical thinking through conventional laboratory method. This study investigated the effects of Virtual Laboratory Simulation Strategy (VLSS) and Structured Inquiry Strategy (SIS) on senior secondary school students' critical thinking skills in acid base titration in Kano State, Nigeria. A pretest-posttest non-equivalent control group quasi-experimental design was adopted. The population comprised 12,516 Senior Secondary II chemistry students, from which 321 students (149 males and 172 females) were purposively selected from six schools, with one intact class selected from each school. Data were collected using the validated Acid Base Titration Critical Thinking Skills Test (ABTCTST), which demonstrated test-retest reliability of $r = .82$ and internal consistency of $\alpha = .88$. Data were analyzed using mean, standard deviation, and ANCOVA. Students taught using VLSS and SIS had significantly higher posttest critical thinking scores than those taught using the conventional method, $p < .001$, while the two experimental groups did not differ significantly, $p > .05$. Gender had no significant main effect, $p = .424$; however, the Group × Gender interaction was significant, $F(2, 314) = 27.68$, $p < .001$, $\eta p^2 = .150$. The findings support the use of VLSS and SIS to enhance critical thinking skills development in secondary school chemistry. It was therefore recommended that teachers should adopt the use of VLSS and SIS, when teaching titration.

Keyword: virtual laboratory simulation, structured inquiry, critical thinking

1 Introduction

The systematic development of critical thinking skills has become a primary goal in teaching and learning of science in the twenty-first century education. Modern educational systems increasingly emphasize the need for learners to move beyond memorization of scientific facts toward the acquisition of higher order cognitive skills such as analysis, evaluation, inference, problem-solving, and evidence-based reasoning (Rosario, 2025). Critical thinking is recognized as one of the essential competencies required for academic success, lifelong learning, and participation in a knowledge driven society (Akbar, 2023; Öztürk, 2023). Within science education, critical thinking and scientific thinking are considered closely related intellectual processes that enable learners to examine evidence, evaluate claims, and make informed decisions based on logical reasoning (García-Carmona, 2025). Therefore, efforts to equip students with critical thinking competencies have become a major concern among researchers and practitioners in chemistry. Chemistry is often regarded as a central science and an important secondary school subject because it provides foundational knowledge for careers in medicine, pharmacy, engineering, agriculture, and other science-related fields (Ikuejube, 2024). However, many chemistry concepts appears to be abstract and require learners to connect theoretical knowledge with practical experiences (Pazicni & Flynn, 2019). Among these concepts, acid-base titration is one of the most important yet challenging topics to teach, in secondary schools chemistry curriculum. The West African Examination Council (WAEC) every year includes titration as one of the compulsory aspect in chemistry practical examination. The topic requires students to be taught theory and practical, understand neutralization reactions, interpret colour changes, analyze quantitative data, determine equivalence points, and make conclusions based on experimental observations (Okolafor & Omoifo, 2024). Consequently, effective learning of acid base titration demands not only conceptual understanding but also well-developed critical thinking skills. A key part of learning chemistry involves mastering its practical applications and the development of critical thinking skills.

Despite the importance of critical thinking in chemistry learning, in Nigeria many public secondary school students continue to experience difficulties in applying scientific reasoning and problem solving skills during chemistry instruction (Haruna et al., 2024). This may be attributed to inconsistency in conducting chemistry practical and most schools only conduct practical when external examination bodies provided specimens (Oluboyo, 2021). Subsequently, students often perform experiments only to meet examination requirements, affecting their critical thinking skills which will lead to better performance. West African Examination Council (WAEC, 2024) reports shows a consistent decline in students' practical chemistry results, especially in titration. This may be linked to poor laboratory resources, unqualified teachers, and teacher centered methods that hinder student engagement (Folashade, 2023). Concerns have been raised regarding students' overreliance on rote learning and procedural memorization, which often limit the development of critical thinking skills (Wijesekera & Hameed, 2025). One factor frequently associated with the limited development of critical thinking skills is the over dominance on conventional teacher centred instructional strategies. (Srirak, 2024). One major flaws in conventional chemistry practical instruction often emphasizes transmission of information from teacher to students, leaving little room for inquiry, exploration, reflection, and independent reasoning.

Accordingly, there is a growing recognition among science teachers that innovative learner centred instructional strategies are required to promote meaningful learning and critical thinking skills development in chemistry (El Hammoumi, 2020). Developing these skills empowers students to approach experiments systematically and make sound decisions. Challenges like inadequate facilities, high reagent costs, and safety concerns hinder effective titration instruction in conventional classrooms. The challenges facing conventional laboratory teaching have led to the adoption of innovative strategies such as virtual laboratory simulations and structured inquiry strategies in developed countries, which have shown great possibilities of enhancing students' learning and understanding (Radhamani, et al., 2019; Aditomo & Klieme, 2020). Nevertheless, Sugumar (2024) proclaimed that virtual laboratory simulation strategy (VLSS) has emerged as a promising instructional strategy, for enhancing students' engagement and critical thinking skills in science. These virtual laboratories provide interactive digital environments where learners can conduct experiments, manipulate variables, observe outcomes, and repeat procedures without many of the constraints associated with conventional laboratories (Hamed & Aljanazrah, 2020). Through visualization, experimentation and immediate feedback, virtual laboratory simulations encourage learners to actively construct knowledge and engage in analytical reasoning. Technology enhanced learning environments have been reported to support inquiry, exploration and critical evaluation of scientific phenomena, thereby creating opportunities for the development of critical thinking skills (Bower & Vlachopoulos, 2018).

Similarly, structured inquiry strategy have gained considerable attention because of its potential to promote critical thinking and scientific reasoning (Arifin, 2025). Structured Inquiry Strategy (SIS) involves the active participation of learners in investigating scientific problems using teacher provided procedures and guidance (Bogador, 2024). Through questioning, data collection, analysis, interpretation and drawing conclusions, students actively engage in the scientific inquiry process. Authors such as (Rosidah et al., 2024; Yadav & Singh, 2026) have shown that inquiry oriented learning environments enhance students' problem solving abilities, scientific process skills, and critical thinking by encouraging them to actively construct understanding rather than passively receive information. The potential of VLSS and SIS to support critical thinking can be understood from cognitive and social constructivist perspectives, which are elaborated in the theoretical framework. Despite growing interest in Virtual Laboratory Simulation (VLS) and Structured Inquiry Strategies (SIS) as learner centred, limited empirical evidence exists on their effects on secondary school students' critical thinking skills specifically in acid base titration in the Nigerian context. Existing studies have largely examined academic achievement, general science learning outcomes, or science process skills, with less attention to critical thinking within specific chemistry practical topics such as acid base titration. Moreover, limited evidence is available, comparing VLS and SIS with conventional laboratory method, in developing students' critical thinking skills in this context. This gap is significant because acid base titration requires students to analyze experimental evidence, interpret results, evaluate relationships, and draw scientifically justified conclusions.

2 Statement of the Problem

Despite the importance of critical thinking in chemistry, its development remains a concern among secondary school students in Nigeria. Students are expected to apply reasoning, interpret experimental evidence, solve problems, and draw scientifically justified conclusions, yet evidence indicates persistent difficulties in these processes (Atiku & Abdulkadir, 2025; Hassan, 2025). The problem is particularly relevant to acid base titration because the topic requires students to integrate conceptual knowledge with observation, data analysis, interpretation, and evidence based reasoning. However, students may focus on reproducing procedural steps without sufficiently engaging with the underlying principles and reasoning required to solve unfamiliar titration problems (Rahmawati et al., 2019; Putri & Kurniawati, 2021; Reeves et al., 2021). A major instructional concern is that opportunities for developing of these skills may be constrained by continued reliance on conventional teacher centred methods and limited practical engagement in some secondary schools. Conventional laboratory method often emphasizes the transmission of information, procedural demonstration, and examination preparation, with fewer opportunities for students to question, investigate, analyze data, reflect on observations, and construct explanations independently (Bature & Campus, 2020). In addition, inadequate laboratory facilities and limited opportunities for regular practical activities may further restrict students' engagement with authentic experimental processes (Jolaoluwa et al., 2024). Consequently, there is a need for instructional strategies that can provide students with more active and meaningful opportunities to develop critical thinking skills while learning acid base titration.

Although VLSS and SIS offer promising alternatives because they can facilitate experimentation, investigation, data interpretation, and active engagement, also an important empirical gap was identified in the literature, relatively little evidence exists on the effects of these two strategies on secondary school students' critical thinking skills specifically in acid base titration, particularly within the Nigerian context. It is therefore unclear whether VLSS and SIS can enhance students' critical thinking skills beyond what is achievable through conventional laboratory method. This unresolved problem provided the basis for the present study which investigated the effects of VLSS and SIS on secondary school students' critical thinking skills in acid-base titration in Kano State, Nigeria.

3 Literature Review

The literature reviewed examines the relationship between instructional strategies and students' critical thinking skills, with particular emphasis on VLSS) and SIS.

3.1 Virtual Laboratory Simulation Strategy and Critical Thinking Skills

Virtual Laboratory Simulation Strategy provides an interactive environment in which learners can conduct experiments, manipulate variables, observe outcomes, and repeat procedures without some of the resource and safety constraints associated with conventional laboratories (Hamed & Aljanazrah, 2020). Such environments can support visualization, exploration, and active engagement, which are important for higher-order learning (Bower & Vlachopoulos, 2018). Moreover, Sugumar (2024) identified VLSS as a promising strategy for enhancing students' engagement and higher order thinking. The potential of VLSS is to develop critical thinking which can be explained through Cognitive Constructivist Theory. Piaget (1973) conceptualized learning as an active process in which learners construct and reorganize knowledge through interaction with their environment. Accordingly, VLS may support critical thinking skills by allowing students to interact with experimental phenomena, compare observations with prior knowledge, manipulate experimental conditions, and reflect on outcomes. These processes provide opportunities for analysis, interpretation, evaluation, and problem solving. Thus, VLSS is theoretically expected to support critical thinking by transforming students from passive recipients of procedures into active constructors of experimental understanding.

3.2 Structured Inquiry Strategy and Critical Thinking Skills

Structured Inquiry Strategy involves guided investigation in which the teacher provides the problem and procedures while students actively collect, analyze, and interpret evidence and draw conclusions (Bogador, 2024). Unlike conventional laboratory method, structured inquiry provides students with opportunities to participate directly in the reasoning processes underlying scientific investigation. Studies have reported that inquiry oriented learning can enhance problem solving, scientific process skills, and critical thinking by encouraging students to construct understanding through investigation (Rosidah et al., 2024; Yadav & Singh, 2026). Structured Inquiry Strategy is anchored in Social Constructivist Theory, which emphasizes learning through social interaction, guidance, and scaffolding (Vygotsky, 1978). Within structured inquiry, teacher guidance and interaction with peers can support students as they engage in questioning, evidence analysis, interpretation, and conclusion drawing. Such guided participation can progressively develop students' ability to reason independently. Therefore, the theory provides a mechanism through which SIS may enhance critical thinking skills teacher guidance and interaction facilitate inquiry processes, which in turn provide opportunities for analysis, evaluation, inference, and problem-solving.

The reviewed literature indicates a common shift from transmission oriented instruction toward learner centred strategies that actively engage students in experimentation, inquiry, and reasoning. VLSS emphasizes interaction with simulated experimental environments, whereas SIS emphasizes guided investigation and social interaction. Although both strategies provide opportunities for higher-order cognitive engagement, they operate through somewhat different learning mechanisms: VLSS primarily facilitates individual interaction, visualization, and experimentation, while SIS emphasizes guided inquiry, interaction and scaffolding. This distinction provides a basis for examining their comparative effects on critical thinking. Despite growing evidence supporting VLSS and SIS in science teaching, limited empirical evidence has examined their effects specifically on critical thinking skills in acid base titration among secondary school students in Nigeria. Moreover, comparatively little is known about whether VLSS and SIS differ in their effects when compared with conventional laboratory method. The present study addresses this gap by examining the effects of VLSS and SIS on secondary school students' critical thinking skills in acid base titration in Kano State, Nigeria. The framework therefore links the instructional strategies (VLS & SIS) to critical thinking skills through active knowledge construction, guided inquiry, evidence analysis, reflection, and problem-solving.

3.3 Objectives of the Study

The study specifically seeks to:

1. Determine the difference in critical thinking skills ability between students taught acid base titration with simulation, structured inquiry strategies and their counterparts taught with conventional chemistry laboratory method.
2. Examined the difference in gender critical thinking skills between students taught acid base titration using simulation, structured inquiry strategies and their counterparts taught using conventional chemistry laboratory method.

3.4 Research Questions

In the course of this study, the following guided research questions were asked;

1. What is the difference in critical thinking skills ability between students taught acid base titration with simulation, structured inquiry strategies and their counterparts taught with conventional chemistry laboratory method?
2. What is the difference in gender critical thinking skills, between students taught acid base titration using simulation, structured inquiry strategies and their counterparts taught using conventional chemistry laboratory method?

3.5 Hypotheses

The following null hypotheses were formulated

1. There is no significant difference in critical thinking skills ability between students taught acid base titration with simulation and structured inquiry strategy their counterparts taught with conventional chemistry laboratory method.
2. There is no significant difference in gender critical thinking skills, between students taught acid base titration using simulation, structured inquiry strategies and their counterparts taught using.

4 Materials and Methods

The study adopted a pre-test, post-test, nonequivalent control group quasi experimental design. The population of the study comprises of 12,516 (8,024 males, 4,492 females) all of which were senior secondary school two (2) chemistry students in Science and Technical Schools in Kano state, Nigeria, under the Kano State Science and Technical Schools Board (STSB). Six schools were purposively selected based on relevant criteria, which include laboratory facilities, computer resources, and stable electricity supply. Six schools were required because secondary schools in the study area are predominantly single sex, while gender was examined as a moderating variable; thus, both male and female participants were included across the instructional groups. A total of 321 SSII students (149 males and 172 females) participated. From each school, one intact class with fewer students was purposively selected to ensure manageable and reasonably comparable group sizes, resulting in six intact classes. The classes were retained as naturally constituted groups: Experimental Group 1 (52 males, 61 females) were taught using VLSS, Experimental Group 2 (48 males, 59 females) were taught using SIS, and the control group (49 males, 52 females) were taught using the conventional chemistry laboratory method. Although the use of intact classes disallowed individual random assignment, this was consistent with the quasi-experimental design, for this reason, baseline differences were assessed and appropriately statistically controlled. No attrition occurred during the study; all 321 students who participated at pretest were present for the posttest, resulting in a final sample of 321 students.

The instruments used for data collection was Acid Base Titration Critical Thinking Skills Test (ABTCTST). The items of the instrument was adapted from Purwanto et al. (2022), Salirawati et al. (2021) and WASSCE (2022) respectively, using critical thinking indicators developed by SCIT 1020 (2013). The purpose is to assess the critical thinking skills of secondary school students in the context of acid base titration and to evaluate how well students can apply logical reasoning, analyze titration data, identify assumptions, recognize patterns, consider multiple perspectives, evaluate scientific evidence, and avoid logical fallacies during chemistry titration practical tasks. The face and content validity of the instrument were determined by three experts. Furthermore, the instrument had a maximum possible score of 100, with higher scores indicating higher levels of critical thinking skills. The reliability of the ABTCTST was established using test retest and internal consistency procedures. The test-retest reliability coefficient was r = .82, while Cronbach's alpha was α = .88, indicating good internal consistency of the two scored components. Data collected was analyzed using mean, standard deviation and analysis of ANCOVA, which was tested at 0.05 level of significance.

5 Results

5.1 Research Question One

What is the difference in critical thinking skills ability between students taught acid base titration with simulation, structured inquiry strategies and their counterpart taught with conventional chemistry laboratory method?

In order to answer the research question, the ABTCTST scores obtained from the pretest and posttest, were subjected to descriptive statistics (mean & standard deviation). The results were presented in Table 1.

Table **1**

Mean and Standard Deviation of Pretest and Posttest Students' Critical Thinking Skills in Acid Base Titration by Instructional Strategy

		Pretest		Posttest		Mean
Groups	**N**	**Mean**	**SD**	**Mean**	**SD**	**Difference**
Exp. 1	113	5.51	3.85	47.58	8.59	42.07
Exp. 2	107	4.44	4.21	46.63	9.68	42.19
Control	101	5.62	4.63	12.08	6.54	6.46

Table 1 revealed considerable variation in critical thinking skills across the instructional strategy. Students in the Simulation group (Experiment 1) pretest and posttest of mean and standard deviation obtained were $M = 5.51$ ($SD = 3.85$, $N = 113$) and $M = 47.58$ ($SD = 8.59$, $N = 113$) respectively resulting in a mean difference of 42.07 in favour of posttest. Similarly students in the Structured Inquiry group (Experiment 2) pretest and posttest recorded a mean score of $M = 4.44$ ($SD = 4.21$, $N = 107$) and $M = 46.64$ ($SD = 9.69$, $N = 107$) respectively resulting in a mean difference of 42.19 in favour of posttest. In contrast, students in the Conventional Laboratory group (Control) obtained a considerably lower mean score for pretest and posttest of $M = 5.62$ ($SD = 4.63$, $N = 101$) and $M = 12.09$ ($SD = 6.55$, $N = 101$) respectively resulting in a mean difference of 6.46 resulting in favour of the post test. The standard deviations indicate that the Experiment 2 group exhibited slightly more variability in scores than the Experiment 1 group, while the Control group was the most homogeneous. The descriptive findings indicate a substantial difference in critical thinking skills across instructional strategies. Students taught using Simulation and Structured Inquiry strategies demonstrated markedly higher critical thinking skills compared to those taught using the Conventional laboratory method. Both experimental groups demonstrated substantially higher critical thinking skills than the Conventional group, with differences exceeding 34 points, indicating a large practical advantage for the Simulation and Structured Inquiry strategies.

5.2 Research Question Two

What is the difference in gender critical thinking skills, between students taught acid base titration using simulation, structured inquiry strategies and their counterpart taught using conventional chemistry laboratory method?

In order to answer the research question, descriptive statistics (mean & standard deviation) were computed to examine the differences in posttest critical thinking scores between male and female students across the three instructional groups. See Table 2 for the results.

Table **2**

Mean and Standard Deviation of Posttest Critical thinking Skills Scores by Group and Gender

Group	Gender	N	Mean	Std. Deviation
Exp. 1	Male	52	45.52	7.48
	Female	61	49.34	9.13
Exp. 2	Male	48	51.27	5.65
	Female	59	42.86	10.65
Control	Male	49	8.67	5.12
	Female	52	15.31	6.14

The results in Table 2, revealed that in Experiment 1 (simulation group), female students (M = 49.34, SD = 9.13, N = 61) obtained higher posttest mean scores than male students (M = 45.52, SD = 7.48, N = 52). In Experiment 2 (structured inquiry group), male students (M = 51.27, SD = 5.65, N = 48) scored higher than female students (M = 42.86, SD = 10.65, N = 59). In the Control group (conventional laboratory method), female students (M = 15.31, SD = 6.14, N = 52) recorded higher mean scores than male students (M = 8.67, SD = 5.12, N = 49). The descriptive statistics indicated that gender differences in students' critical thinking skills varied across the instructional strategies. Although the experimental groups showed substantial improvement from pretest to posttest, the possibility of a ceiling effect was considered. The ABTCTST had a maximum possible score of 100, whereas the experimental groups obtained posttest means of 47.58 and 46.64. These means outcomes were well below the maximum possible score, indicating that the observed gains did not reflect near ceiling. Thus, the instrument provided sufficient score range to detect differences in students' critical thinking performance following the intervention.

Inferential statistics were conducted to determine whether the observed differences were statistically significant. Prior to conducting ANCOVA, the assumptions of normality of residuals and homogeneity of regression slopes were assessed. Although the Kolmogorov Smirnov test revealed a statistically significant departure from normality, $D(321) = .058$, $p = .011$, visual inspection of the residual histogram showed approximately normal distribution with slight negative skewness. Given the relatively large sample size ($N = 321$), ANCOVA was considered sufficiently robust to this modest departure from normality. The assumption of homogeneity of regression slopes was satisfied, as the Group × Pretest interaction was not statistically significant, $F(2, 315) = 0.33$, $p = .723$. Bonferroni-adjusted pairwise comparisons were used following significant ANCOVA results.

5.3 Hypothesis One

There is no significant difference in critical thinking skills between students taught acid base titration with simulation, structured inquiry strategy and their counterparts taught with conventional chemistry laboratory method.

To test the hypothesis, an Analysis of Covariance (ANCOVA) was conducted. Table 3 presents the analysis result.

Table **3**

Analysis of Covariance (ANCOVA) of Students' Posttest Critical Thinking Skills by Instructional Strategy

Source	Type III SS	*df*	MS	*F*	*p*	ηp^2
Corrected Model	85,008.901	3	28,336.300	399.158	< .001	.791
Intercept	159,190.100	1	159,190.100	2,242.422	< .001	.876

Pretest	0.525	1	0.525	0.007	.931	.000
Group	84,657.634	2	42,328.817	596.262	< .001	.790
Error	22,503.909	317	70.990			
Total	525,836.000	321				
Corrected Total	107,512.810	320				

Table 3 presents the results of a one way Analysis of Covariance (ANCOVA) conducted to evaluate the effect of three instructional strategies (Virtual Laboratory Simulation, Structured Inquiry Strategy, and Conventional Laboratory Method) on students' posttest critical thinking skills while statistically controlling for pretest scores. Preliminary evaluation of the covariate indicated that pretest scores did not significantly contribute to students' posttest critical thinking scores, $F(1, 317) = 0.01$, $p = .931$, $\eta p^2 = .000$. This indicates that pretest scores did not significantly account for variation in posttest critical thinking skills across the instructional groups. After controlling for pretest scores, a statistically significant main effect of instructional strategy was observed, $F(2, 317) = 596.26$, $p < .001$, $\eta p^2 = .790$. Therefore, the null hypothesis that there was no significant difference in students' posttest critical thinking skills among those taught using VLS, SIS, and the conventional laboratory method was rejected.

The partial eta squared of .790 indicates a large effect of instructional strategy on posttest critical thinking skills. Thus, instructional strategy accounted for a substantial proportion of the variance in posttest critical thinking scores after controlling for pretest scores. The overall ANCOVA model was also statistically significant, $F(3, 317) = 399.16$, $p < .001$, $R^2 = .791$, adjusted $R^2 = .789$. These findings indicate that the instructional strategies were significantly associated with differences in students' posttest critical thinking skills. Following the significant omnibus effect of instructional strategy, the estimated marginal means, adjusted for the pretest covariate at a mean value of 5.19, were examined using Bonferroni-adjusted pairwise comparisons to determine the specific differences among the instructional groups.

Table **4**

Adjusted Mean Posttest Critical Thinking Skills Scores by Instructional Strategy

Group	Adjusted Mean	SE	95% CI
Experiment 1	47.581	0.793	[46.020, 49.142]
Experiment 2	46.643	0.819	[45.032, 48.254]
Control	12.085	0.840	[10.433, 13.737]

Note. SE = standard error; CI = confidence interval. Covariate: pretest = 5.19

Table 4 present the adjusted estimated marginal means indicated that students taught using the VLSS achieved the highest critical thinking posttest scores (M = 47.58, SE = 0.79), closely followed by those taught using the SIS (M = 46.64, SE = 0.82). Students taught using the Conventional Laboratory Method had substantially lower adjusted posttest scores (M = 12.09, SE = 0.84).

Table **5**

Bonferroni Post-Hoc Pairwise Comparisons of Posttest Critical Thinking Skills by Strategy

(I) Group	(J) Group	Mean Difference (I − J)	SE	*p*	95% CI
Experiment 1	Experiment 2	0.938	1.143	1.000	[−1.812, 3.689]
Experiment 1	Control	35.496*	1.154	< .001	[32.719, 38.273]
Experiment 2	Experiment 1	−0.938	1.143	1.000	[−3.689, 1.812]
Experiment 2	Control	34.558*	1.176	< .001	[31.727, 37.389]
Control	Experiment 1	−35.496*	1.154	< .001	[−38.273, −32.719]
Control	Experiment 2	−34.558*	1.176	< .001	[−37.389, −31.727]

Note. SE = standard error; CI = confidence interval. Based on estimated marginal means. *p* values are Bonferroni-adjusted for multiple comparisons. $p < .05$.

Table 5 shows the Bonferroni-adjusted pairwise comparisons which revealed a clear pattern of differences across the instructional conditions. Experiment 1 versus Control: Students in the VLSS group scored significantly higher than those in the Conventional Laboratory group, with an adjusted mean difference of 35.50 points, 95% CI [32.72, 38.27], p < .001. Experiment 2 versus Control: Students in the SIS group also scored significantly higher than those in the Conventional Laboratory group, with an adjusted mean difference of 34.56 points, 95% CI [31.73, 37.39], p < .001. Experiment 1 versus Experiment 2: The comparison between the two experimental groups revealed no statistically significant difference in posttest critical thinking scores, with an adjusted mean difference of 0.94 points, 95% CI [-1.81, 3.69], p = 1.000. Collectively, these findings indicate that both VLS and SIS were associated with significantly higher posttest critical thinking scores than the Conventional Laboratory Method, while neither experimental strategy produced a statistically significant difference from the other after controlling pretest scores.

5.4 Hypothesis Two

There is no significant difference in gender critical thinking skills, between students taught acid base titration using simulation, structured inquiry strategies and their counterparts taught using conventional chemistry laboratory method.

A two way Analysis of Covariance (ANCOVA) was conducted at the 0.05 level of significance. The results of the analysis was presented in Table 6

Table **6**
Two-Way ANCOVA Showing the Effect of Instructional Group and Gender on Students' Posttest Critical Thinking Skills in Acid Base Titration

Source	Type III SS	df	Mean Square	F	p	ηp²
Corrected Model	88410.99	6	14735.17	242.22	< .001	.822
Intercept	159415.14	1	159415.14	2620.50	< .001	.893
Pretest	11.18	1	11.18	0.18	.668	.001
Group	85346.79	2	42673.40	701.48	< .001	.817
Gender	38.97	1	38.97	0.64	.424	.002
Group × Gender	3368.14	2	1684.07	27.68	< .001	.150
Error	19101.82	314	60.83			
Total	525836.00	321				
Corrected Total	107512.81	320				

Note. $R^2 = .822$ (Adjusted $R^2 = .819$). Pretest scores were used as a covariate

The results in Table 6, shows a two way factorial Analysis of Covariance (ANCOVA) which was conducted to assess the effects of instructional strategy (Simulation, Structured Inquiry, and Conventional Chemistry Laboratory Method) and gender on students' posttest critical thinking skills in acid base titration, while statistically controlling for pretest scores. Preliminary evaluation of the covariate indicated that pretest scores did not significantly contribute to posttest critical thinking scores, $F(1, 314) = 0.18$, $p = .668$, $\eta p^2 = .001$. After controlling for pretest scores, the main effect of gender was not statistically significant, $F(1, 314) = 0.64$, $p = .424$, $\eta p^2 = .002$. However, Table 6 revealed a statistically significant Group × Gender interaction, $F(2, 314) = 27.68$, $p < .001$, $\eta p^2 = .150$. The partial eta squared indicates a large effect, suggesting that the interaction accounted for a substantial proportion of the variance in posttest critical thinking skills scores. The significant interaction indicates that the effect of instructional strategy on students' critical thinking skills varied by gender. Therefore, the null hypothesis concerning the absence of a significant interaction between instructional strategy and gender was rejected. The overall model was statistically significant and accounted for 82.2% of the variance in posttest critical thinking scores ($R^2 = .822$, adjusted $R^2 = .819$), $F(6, 314) = 242.22$, $p < .001$. Given the significant Group × Gender interaction, interpretation of the main effects alone is insufficient; therefore, the estimated marginal means and pairwise comparisons were examined to determine the pattern of the interaction.

Table **7**

Adjusted Mean Posttest Critical Thinking Skills Scores by Instructional Strategy and Gender

Group	Gender	Mean	SE	95% CI
Experiment 1	Male	45.555	1.085	[43.420, 47.689]
	Female	49.341	0.999	[47.376, 51.306]
Experiment 2	Male	51.242	1.128	[49.023, 53.461]
	Female	42.827	1.019	[40.822, 44.832]
Control	Male	8.644	1.116	[6.447, 10.840]
	Female	15.373	1.092	[13.224, 17.523]

Note. Dependent Variable: Posttest Critical Thinking Skills Ability. Covariates in the model are evaluated at the mean pretest value: *Pretest Scores* = 5.19. CI = Confidence Interval.

Table 7 presents the estimated marginal means and standard errors for students' posttest critical thinking scores, adjusted for the pretest covariate at a mean baseline value of 5.19. The adjusted means show different gender patterns across the instructional strategies. Within the Simulation strategy, female students had a higher adjusted mean (M = 49.34, SE = 1.00) than male students (M = 45.56, SE = 1.09). Conversely, within the Structured Inquiry strategy, male students had a higher adjusted mean (M = 51.24, SE = 1.13) than female students (M = 42.83, SE = 1.02). Within the Conventional Chemistry Laboratory group, female students also had a higher adjusted mean (M = 15.37, SE = 1.09) than male students (M = 8.64, SE = 1.12). These patterns indicate that the relationship between instructional strategy and critical thinking skills varied by gender. To determine whether the observed differences between genders within each instructional group were statistically significant, pairwise comparisons of the estimated marginal means were examined.

Table **8**

Simple Main Effects Pairwise Comparisons of Gender within Instructional Strategies

Group	(I) Gender	(J) Gender	Mean Difference (I − J)	SE	*p*	95% CI
Experiment 1	Male	Female	−3.786*	1.475	.011	[−6.688, −0.884]
	Female	Male	3.786*	1.475	.011	[0.884, 6.688]
Experiment 2	Male	Female	8.415*	1.516	< .001	[5.432, 11.398]
	Female	Male	−8.415*	1.516	< .001	[−11.398, −5.432]
Control	Male	Female	−6.730*	1.569	< .001	[−9.816, −3.643]
	Female	Male	6.730*	1.569	< .001	[3.643, 9.816]

Note. Dependent Variable: Posttest Critical Thinking Skills Ability. SE = Standard Error; CI = Confidence Interval for Difference. Adjustment for multiple comparisons: Bonferroni.
* The mean difference is significant at the .05 level.

Table 8 presents the Bonferroni-adjusted pairwise comparisons examining the simple effects of gender within each instructional strategy. The analysis showed statistically significant gender differences within all three instructional groups, although the direction of the differences varied across the instructional conditions. Within the Simulation Strategy, female students demonstrated significantly better than male students, with an adjusted mean difference of 3.79 points, 95% CI [0.88, 6.69], $p = .011$. Conversely, within the Structured Inquiry Strategy, male students significantly outperformed female students, with an adjusted mean difference of 8.42 points, 95% CI [5.43, 11.40], $p < .001$. Within the Conventional Chemistry Laboratory Method, female students also performed significantly better than male students, with an adjusted mean difference of 6.73 points, 95% CI [3.64, 9.82], $p < .001$. Overall, the findings indicate that the pattern of gender differences in critical thinking skills varied across instructional strategies, with female students developing better critical thinking skills when taught with simulation and conventional chemistry laboratory method, whereas male students demonstrate better critical thinking skills when taught acid base titration using the Structured Inquiry Strategy.

6 Discussion

The findings indicated that there was no significant difference in students' critical thinking skills at the pretest stage, suggesting that the groups were comparable prior to the intervention. After the treatment, there was a statistically significant difference in students' critical thinking skills ability across the instructional strategies when pretest scores were controlled. This indicates that the observed differences in posttest scores were primarily due to the instructional strategies employed. Both experimental groups demonstrated significantly better critical thinking skills than students taught using the conventional laboratory method. VLSS allows students to repeat experiments multiple times without fear of making mistakes, wasting chemicals, or facing time constraints. Similarly, SIS provides structured guidance that reduces confusion and anxiety while still allowing exploration. The findings are consistent with Social Constructivist Theory (Vygotsky, 1978), which emphasizes learning through interaction, scaffolding, and active knowledge construction. Both structured inquiry and virtual laboratory simulations provided opportunities for students to engage in problem solving, hypothesis testing, and reflection, thereby enhancing critical thinking skills. In contrast, the conventional method offered limited opportunities for such engagement, resulting in lower critical thinking skills.

The findings of this study are supported by existing empirical literature, which consistently demonstrates the effectiveness of innovative instructional strategies in enhancing students' critical thinking skills. Ikhsan et al. (2020) reported that students who engaged in virtual reality (VR) laboratory learning exhibited significantly higher critical thinking skills compared to those taught using conventional methods. This suggests that immersive and interactive environments promote deeper cognitive engagement. Similarly, Firdaus et al. (2022) found that students who participated in Immersive Virtual Reality (IVR)-based learning activities developed substantially higher critical thinking skills than their counterparts exposed to traditional instructional strategies. Their study provides strong empirical support for the use of IVR as an effective tool for improving higher order thinking skills in science. In addition, Ditingki et al. (2025) reported that students exposed to structured inquiry strategy demonstrated advanced critical thinking skills, particularly in analyzing, evaluating, and creating information. Bako et al. (2022) and Aidoo et al. (2022) similarly reported that inquiry based instructional strategies can enhance students' critical thinking skills. Importantly, the findings also revealed a significant interaction between instructional strategy and gender, indicating that the effectiveness of the instructional strategies varied by gender. Although gender alone did not significantly influence students' critical thinking skills, the interaction suggests that students responded differently to the instructional strategies. Female students demonstrated higher critical thinking skills than male students taught with the Virtual Laboratory Simulation strategy, whereas male students demonstrated higher critical thinking skills than female students when taught with SIS. This difference may be related to variations in how students responded to the structure, autonomy, and learning demands associated with each instructional strategy. The finding is consistent with Setiawan et al. (2024), who reported gender differences in critical thinking skills across instructional strategies. Similarly, Kanyonga et al. (2024) found that male students performed better in scientific inquiry competencies, particularly in hypothesis generation, data analysis and interpretation, and drawing conclusions. The higher critical thinking skills demonstrated by male students under structured inquiry may therefore be associated with the demands of inquiry based tasks, which require active engagement in hypothesis generation, evidence analysis, and independent problem solving. The present study did not directly examine the specific mechanisms underlying the observed gender differences.

Although studies have reported positive effects of VLSS and SIS on students' critical thinking skills, the findings are not entirely consistent. Sabrina et al. (2025) found no statistically significant difference in critical thinking skills between students who learned through guided inquiry using virtual laboratories and those who learned through real laboratories, suggesting that virtual laboratories are not inherently more effective than conventional practical work. Nevertheless, the present study found that both virtual laboratory simulation and structured inquiry strategy were effective in promoting students' critical thinking skills compared with the conventional laboratory method. These findings corroborate the results of the present study, indicating that both instructional strategies can promote students' critical thinking skills, although their effectiveness may vary according to gender and instructional context. Despite these findings, the study has some limitations. First, the quasi-experimental design involved non-random assignment of students to the instructional groups, which may have introduced pre-existing differences among the groups and limits strong causal inference. Secondly, the study was conducted in selected secondary schools in Kano State, which may limit the generalizability of the findings to other geographical and educational contexts. Thirdly, the study relied on a single researcher developed instrument for assessing critical thinking skills, which may limit the generalizability of the measurement. Finally, the use of virtual laboratory simulation may have introduced a novelty effect, whereby students' initial enthusiasm for the technology influenced their engagement and critical thinking skills.

7 Conclusion

This study concludes that VLSS and SIS are effective instructional strategies for enhancing secondary school students' critical thinking skills in acid base titration. Students exposed to either strategy demonstrated significantly higher critical thinking scores than those taught using the conventional method, while no significant difference was found between the two innovative strategies. Although gender did not have a significant main effect on students' critical thinking skills, the significant interaction between instructional strategy and gender indicates that the effectiveness of the instructional strategies varied by gender. Thus, the findings suggest that VLSS and SIS can enhance critical thinking skills, although students' responses to the instructional strategies may differ according to gender.

8 Recommendation

Chemistry teachers should adopt Virtual Laboratory Simulation and Structured Inquiry Strategies to enhance students' critical thinking skills in acid base titration and other chemistry concepts. Educational authorities should provide the necessary technological and instructional resources to support their implementation, while teacher training programmes, including Colleges of Education in Nigeria, should emphasize the use of VLS and SIS in chemistry teaching. Future research should replicate the study across different geographical and educational contexts and, where feasible, employ randomized controlled designs to strengthen causal inference. Longitudinal studies are also recommended to determine whether the effects of virtual laboratory simulation and structured inquiry on critical thinking skills are sustained over time. Future studies should also consider multiple measures of critical thinking skills and further investigate the gender differences observed across instructional strategies.

9 Declarations

Ethical statement: Permission to conduct the study was obtained through an introductory letter from the Department of Science Education, Federal University Dutsin-Ma, followed by approval from the Kano State Science and Technical Schools Board and permission from the principals of the participating schools. The purpose and procedures of the study were explained to the students, who communicated the information to their parents or guardians, in which their consent was obtained before participation. The students also provided assent after being informed about the study. Participation was voluntary, and the confidentiality and anonymity of all participants were maintained throughout the study. The data collected were used solely for academic and research purposes.

Conflict of Interest: The authors declare neither financial nor non-financial conflict of interest.

Author Contributions: Albert Alabi, conceptualized the study, collected the data, performed the statistical analyses, interpreted the findings, and prepared the original manuscript. Abdulmalik Sabitu supervised the research, contributed to the study design, interpreted the findings, and critically revised the manuscript. Omiola Matthew Adetayo contributed to the methodology, reviewed the manuscript for intellectual content, and approved the final version. All authors read and approved the final manuscript and agreed to be accountable for all aspects of the work.

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Data Availability Statement: The data supporting the findings of this study are not publicly available because they contain information relating to student participants. The data may be available from the corresponding author upon reasonable request, subject to appropriate ethical and confidentiality considerations.

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