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Synthesizing Trends in Research on Virtual Laboratory Simulation, Structured Inquiry Strategies, Motivation, Critical Thinking, and Chemistry Performance: A PRISMA-Based Systematic Literature Review

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Abstract

This study presents a systematic literature review on research trends in Virtual Laboratory Simulation (VLS), Structured Inquiry (SI) Strategies, students' motivation, critical thinking, and academic performance in science education, with a focus on chemistry-related learning. Adopting the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, a total of 63 peer-reviewed empirical studies published between 2017 and 2025 were identified, screened, and reviewed across various databases. The findings reveal that VLS enhances students' motivation by providing interactive, low-risk environments for science experimentation. Similarly, SI also, significantly improves students' critical thinking through guided questioning. Both strategies were found to impact academic performance, especially when properly implemented. This review highlights the trend in research on VLS strategy and SIS as complementary, student-centered instructional methods and their impact on students' motivation, critical thinking and performance in chemistry. The study also identifies research gaps and suggests directions for future empirical investigations.

Keywords: Virtual Laboratory Simulation, Structured Inquiry, Motivation, Critical Thinking, Academic Performance, PRISMA, Science Education

Introduction

The growing emphasis on active learning in science has prompted researchers and educators to investigate and explore innovative teaching approaches that promote deeper student engagement, critical thinking, and improved academic performance. Among these strategies, Virtual Laboratory Simulation (VLS**)** and Structured Inquiry (SI) Strategies have emerged as powerful pedagogical tools with the potential to transform traditional classroom instruction into an engaging, interactive, and student-centered learning experience (Solihabonu, 2024; Chen et al., 2024). According to Suwono et al. (2023) and Ahzan et al. (2024) affirmed that by leveraging technology and inquiry-based approaches, VLS and SI strategies enhance conceptual understanding, increase critical thinking and promote active participation in science. These strategies bridge the gap between theoretical knowledge and practical application, making learning more accessible, immersive, and effective for diverse learners. VLS strategy provides interactive, computer-based environments where students can conduct experiments virtually, enabling safe, repeatable, and cost-effective practical experiences. On the other hand, SI strategy emphasizes student-centered learning, where learners construct knowledge through guided inquiry, problem-solving, and critical reflection.

The integration of these strategies has gained global recognition for enhancing students' motivation, inquiry skills, and conceptual understanding, particularly in science disciplines such as chemistry. Despite the increasing body of research supporting the effectiveness of VLS and SI, strategies findings are often fragmented, context-dependent, or limited to specific educational levels and subject areas. In particular, there is a need for a more systematic synthesis of existing evidence regarding their effects on key student outcomes such as motivation, critical thinking**,** and academic performance outcomes that are essential for lifelong learning and scientific literacy. This systematic literature review seeks to bridge that gap by identifying, analyzing, and synthesizing empirical studies that have investigated the impact of VLS and SI strategies on students' learning outcomes. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, the review aims to provide a transparent and methodical overview of existing research, highlight trends and

inconsistencies, and identify areas for future investigation. By focusing on motivation, critical thinking, and performance, this review contributes to the ongoing dialogue on evidence-based instructional practices in science education and offers practical insights for educators, curriculum developers, and policymakers.

Methodology

This study adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to guide the selection and evaluation of literature for the systematic review. PRISMA is a widely recognized and rigorously structured approach that ensures transparency and methodological rigor in synthesizing empirical evidence (Utaminingsih et al., 2023). By systematically gathering and analyzing data from multiple studies, this approach facilitates a comparative assessment of how Virtual Laboratory Simulation (VLS) and Structured Inquiry (SI) Strategies influence students' motivation, critical thinking, and academic performance in science education (Bamiro et al., 2024). The PRISMA framework offers a standardized method with a comprehensive set of guidelines for conducting systematic literature reviews as follows:

Research Questions

The main goal of this study is to undertake a comprehensive review of the body of knowledge that already exists on the subject under consideration. Thus, the following research questions have been raised:

1. What evidence exists in the literature regarding the effectiveness of Virtual Laboratory Simulation (VLS) and Structured Inquiry (SI) Strategies in enhancing students' motivation, critical thinking, and academic performance in science?
2. How do virtual laboratory simulation and structured inquiry strategies influence the interplay between motivation, critical thinking, and performance in chemistry, as reported in the reviewed literature?

3. What patterns emerge in literatures on the use of research designs and geographical locations (foreign or local) in studies investigating the effects of Virtual Laboratory Simulation (VLS) and Structured Inquiry (SI) Strategies on students' motivation, critical thinking, and performance in chemistry?

Search Strategy

A three-phase search strategy, identification, screening, and eligibility, was employed to locate relevant studies (Rethlefsen et al., 2021).

i. Identification Phase

Comprehensive keyword searches were conducted across multiple databases (ERIC, ScienceDirect, Google Scholar, Journal Storage (JSTOR), Semantic Scholar, OpenSource, and SpringerLink) to identify peer-reviewed empirical studies published between 2017 and 2025. Boolean combinations included: "Virtual Laboratory Simulation" AND "Structured Inquiry Strategy"; (motivation OR critical thinking OR performance OR achievement) AND "students" AND "science education" The initial search yielded 1,232 records.

ii. Screening Phase

Duplicate records (331) were removed, leaving 901 articles for title and abstract screening. Studies unrelated to VLS/SIS in secondary or tertiary science education were excluded, reducing the pool to 63 full-text articles.

iii. Eligibility

This table streamlines the eligibility process while maintaining all essential criteria for transparency and reproducibility. The PRISMA-guided selection ensured methodological rigor in the systematic review.

Table 1: Eligibility Criteria for selection of the articles

Category	Inclusion Criteria	Exclusion Criteria

Category	Inclusion Criteria	Exclusion Criteria
Population	Secondary or tertiary-level science students	Non-science students (such as business, humanities)
Intervention	Studies investigating VLS and/or SIS	Studies not focused on VLS or SIS
Outcomes	Measured at least one: motivation, critical thinking, or academic performance	No empirical assessment of these outcomes
Study Design	Experimental, quasi-experimental, or mixed-method designs	Theoretical studies, opinion pieces, or non-empirical reviews
Publication	Peer-reviewed articles in English (2017–2025)	Dissertations, non-peer-reviewed articles, or studies outside the date range
Geographical Scope	Global studies	Regionally restricted studies (if not generalizable)

After applying these criteria, 63 studies were deemed eligible for final analysis. The selection process followed the PRISMA flow diagram by Page et al. (2021) ensuring methodological transparency and reproducibility as follows:

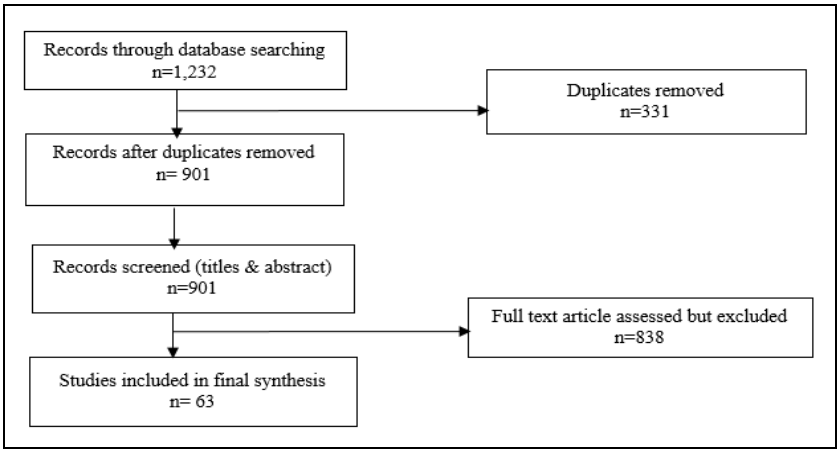

Figure 1: Textual Representation of the PRISMA Flow Diagram

Data Extraction and Analysis

Relevant data were extracted from each study, including author (s), year, title, research design country, sample size, instructional strategy used (VLS or SIS), and key outcomes. The extracted studies were grouped based on which dependent variables were measured (motivation, critical thinking, performance). Findings were narratively synthesized and compared across contexts. The summary report of the selected articles is presented in Table 1. The findings of the review are presented following the sequences, such as the name of the authors, publication years, titles, research design, country and reported effect on, motivation, critical thinking and performance.

Table 2: Data Extraction and Analysis

S/N	Authors & Year	Interventions	Design	Country	Reported Effect on Motivation	Reported Effect on Critical Thinking	Reported Effect on Performance
1	Gambari et al. (2017)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on Performance
2	Herga et al. (2017)	VLS	Quantitative study	Slovenia	Not reported	Not reported	Strong positive effect on Performance
3	Achuthan and Murali (2017)	VLS	Quasi-experimental	India	Not reported	Not reported	High performance
4	Madathil et al. (2017)	VLS	A between-subjects experimental design	India	Not reported	Not reported	Strong positive potential to improve performance
5	Bortnik, et al. (2017)	VLS	Quasi-experimental	Russia.	Not reported	Not reported	Moderate improvement practices in performance
6	Rizki and Simorangkir (2018)	VLS	Quasi-experimental	Indonesia	Not reported	Not reported	Significantly enhance students' understanding and performance
7	Odewumi et al. (2019)	VL	Quasi-experimental	Nigeria	Not reported	Not reported	Significant positive improvement in performance
8	Falode et al. (2020)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on Performance
9	Famuwagun and Mohammed (2020)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on Performance
10	Yaki et al. (2020)	VLS	Experimental design.	Nigeria	Not reported	Not reported	Significant improvement in Performance

11	Agbonifo et al. (2020)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Significant improvement in Performance
12	Mohammed et al. (2021)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on Performance
13	Samuel and Busayo (2021)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on Performance.
14	Usman (2021)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Significant improvement in Performance
15	Peter (2021)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on Performance.
16	Oladejo et al. (2021)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Significant improvement in Performance
17	Tsai (2021)	VLS	Quasi-experimental	Taiwan	Significant improvement in motivation	Not reported	Significant improvement in Performance
18	Shehu (2021)	VLS	Quasi experimental	Nigeria	Not reported	Not reported	positively effect on students' performance
19	Okunuga and Okafor (2022)	VLS	Quasi-experimental,	Nigeria	Not reported	Not reported	Moderate positive effect
20	Yanto et al. (2022)	VLS	Quasi-experimental	Indonesia	Not reported	Not reported	Significant improvement in student performance
21	Al-Nakhle (2022)	VLS	Quasi-experimental	Saudi Arabia	Significant improvement in Motivation	Not reported	Not reported
22	Pal (2022)	VLS	Mixed Method Approach	India	Not reported	Not reported	Positively effect on students' performance

23	Hendrajanti (2022)	VLS	Classroom action research	Indonesia	Not reported	Not reported	Moderate improvement in Performance
24	Ali et al. (2022)	VLS	Quasi-experimental	Pakistan	Not reported	Not reported	Significantly improved students' performance
25	Lakka et al. (2023)	VLS	Experimental comparison	Greece	Not reported	Not reported	Significant improvement in performance
26	Onyinye et al. (2023)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on performance
27	Manyilizu (2023)	VLS	Quasi-experimental	Tanzania	Not reported	Not reported	Strong positive effect on performance
28	Mulyani et al. (2023)	VLS	ADDIE model	Indonesia	Not reported	Not reported	Significant improvement in performance
29	Viitaharju et al. (2023)	VLS	Quasi-experimental	Finland	Not reported	Not reported	Significant improvement in performance
30	Fitriyana et al. (2024)	VLS	Quasi-experimental	Indonesia	Not reported	Not reported	Significant improvement in performance
31	Munthe et al. (2024)	VLS	Quasi-experimental	Indonesia	Not reported	Improved critical thinking	Significant improvement in performance
32	Yazici and Nakıboğlu (2024)	VLS	Qualitative	Turkey	Not reported	Not reported	Significant improvement in performance
33	Naz et al. (2024)	VLS	A Causal comparative design	Pakistan	Not reported	Not reported	Moderate positive effect in performance
34	Abouelenein et al. (2024)	VLS	Quasi - experimental	Egypt	Not reported	Not reported	positive impact of virtual chemistry labs on scientific practices

35	Chen et al. (2024)	VLS	Quasi-experimental	China	Not reported	Not reported	strong positive effect in performance
36	Ali et al. (2024)	SIS	Quasi-experimental	Pakistan	Not reported	Not reported	improved students' performance
37	Sylvanus and Eke (2017)	SIS	Quasi-experimental,	Nigeria	Not reported	Not reported	enhanced academic performance
38	Sagita et al. (2018)	SIS	Research and Development (R&D)	Padang Indonesia	Not reported	Not reported	Significant improvement in performance
39	Abbey-Kalio and Ibiyengibo (2019)	SIS	Quasi-experimental	Nigeria	Not reported	Not reported	Significant improvement in in performance
40	Tsakeni et al. (2019)	SiS	Phenomenon-based case study	South Africa	Not reported	Not reported	Moderate positive effect in Performance
41	Bako and Phang (2020)	SIS	Quasi-experimental	Nigeria	Not reported	Not reported	Moderate positive effect
42	Adriani et al. (2021)	SIS	Research and Development (R&D)	Indonesia	Not reported	Not reported	Strong positive improvement
43	Berhanu and Sheferaw (2022)	SIS	Quasi-experimental	Indonesia	Not reported	Not reported	Improvement in performance.
44	Lenggogeni and Mawardi (2022)	SIS	Quasi-experimental	Germany	Not reported	Not reported	Strong positive effect in performance
45	Bako et al. (2022)	SIS	Survey Design	Nigeria	Not reported	Strongest gains in higher-order thinking	Not reported
46	Aidoo et al. (2022)	SIS	Quasi-experimental	Ghana	Not reported	significant increase in students' critical thinking skills	Significant increase in students' performance
47	Nzomo et al. (2023)	SIS	Correlational	Kenya	Not reported	Not reported	Moderate positive effect

48	Orosz et al. (2023)	SIS	Quasi-experimental	Hungry	Not reported	Not reported	Moderate positive effect
49	Kelubia et al. (2023)	SIS	Quasi-experimental	Nigeria	Not reported	Not reported	Significant improvement
50	Mandina (2024)	SIS	Mixed-method approach	Zimbabwe	Not reported	Not reported	Moderate positive effect
51	Usman and Sabo (2018)	SIS	Quasi-experimental	Nigeria	Not reported	Not reported	Significant improvement in performance
52	Ogologo and Pepple (2018)	SIS	Survey.	Nigeria	Not reported	Not reported	Positive effect on performance
53	Santoso et. al. (2018)	SIS	group pretest-posttest design	Indonesia	Not reported	Significant gains	Not reported
54	Malik et al. (2018)	SIS	Quasi-experiment	Indonesia	Not reported	Strongest gains in higher-order thinking	Not reported
55	Alkan (2018)	SIS	A pretest–posttest design	Turkey	Not reported	Strongest gains in higher-order thinking	Not reported
56	Roviati et al. (2019)	SIS	Quasi-experimental	Indonesia	Not reported	Strongest gains in higher-order thinking	Not reported
57	Said et al. (2019)	SIS	Cross sectional survey	Nigeria	Not reported	Critical thinking skills was found to be low.	Not reported
58	Woldeamanuel (2019)	SIS	Correlational	Ethiopia	Significant improvement in motivation	Not reported	Not reported
59	Ngozi & Hyacinth (2021)	SIS	Quasi-experimental	Nigeria	Not reported	Strongest gains in higher-order thinking	Not reported

60	Widiandari and Redhana (2021)	SIS	Quasi-experimental	Indonesia	Not reported	Strongest gains in higher-order thinking	Not reported
61	Liu et al. (2022)	SIS	Quasi-experimental design	China	Not reported	Not reported	Strong positive effect on Performance
62	Tella, and Ogundiya (2022)	SIS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive effect on Performance
63	Avwiri and Odiri (2025)	VLS	Quasi-experimental	Nigeria	Not reported	Not reported	Strong positive Performance

Research Question One: What evidence exists in the literature regarding the effectiveness of Virtual Laboratory Simulation (VLS) and Structured Inquiry (SI) Strategies in enhancing students' motivation, critical thinking, and academic performance in science?

To address research question one, table 2, shows a total of 63 empirical studies which were reviewed. Evidence related to motivation revealed that two (2) studies reported significant increases when VLS strategy was employed to teach, largely due to its interactive features, visualization concepts, and provision of immediate feedback. Likewise, one (1) study on SIS indicated that motivation was improved through active engagement in inquiry-based tasks. Regarding critical thinking, eight (8) studies demonstrated that SIS consistently enhanced students' ability to analyze, evaluate, and synthesize information. Additionally, two (2) studies provided evidence that VLS strategy positively influenced both critical thinking and academic performance. In terms of academic performance, the strongest evidence emerged. Thirty-three (33) studies reported that VLS strategy significantly improved student performance across various science subjects, particularly chemistry. Similarly, seventeen (17) studies indicated that SIS yielded positive effects on students' academic performance.

Research question Two: How do virtual laboratory simulation and structured inquiry strategies influence the interplay between motivation, critical thinking, and performance in chemistry, as reported in the reviewed literature?

In table 2, three (3) studies on VLS confirmed that motivation served as a mediating factor, whereby students who were more engaged and stimulated by interactive simulations achieved higher performance in chemistry. Likewise, ten (10) studies demonstrated that SIS was more consistently associated with the development of critical thinking, which in turn contributed to improved problem-solving skills and enhanced performance outcomes. The reviewed literature indicates that Virtual Laboratory Simulation (VLS) and Structured Inquiry (SI) Strategies affect not only individual outcomes but also the interactions among motivation, critical thinking, and performance

Research question Three: What patterns emerge in literature on the use of research designs and geographical locations (foreign or local) in studies investigating the effects of Virtual Laboratory Simulation (VLS) and Structured Inquiry (SI) strategies on students' motivation, critical thinking, and performance in chemistry?

Table 2, shows an analysis of the methodological approaches across 63 reviewed studies, it can be observed that quasi-experimental designs predominated, accounting for 68.25% of the articles, whereas only 7.94% employed experimental designs. Mixed-methods, correlational designs, survey-based studies, and research and development (R&D) frameworks were each represented in 3.17% of the publications. The remaining methodologies including quantitative studies, the ADDIE model, classroom action research, qualitative approaches, causal-comparative designs, phenomenon-based case studies, and cross-sectional surveys were each utilized in 1.59% of the articles. These distributions are visually summarized in Figure 2. Show the graphical illustration

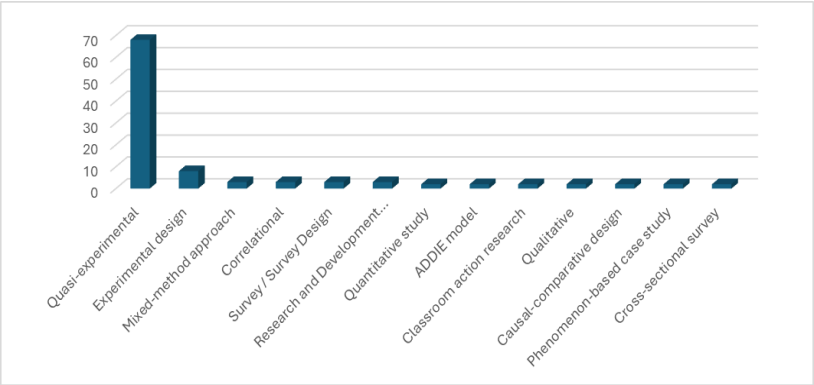

Figure 2: Research Designs across Literature

Country Affiliation

Table 2, shows how the research articles on the subject were distributed geographically. Articles within Nigeria local content was 40% and 60% Foreign content emerges as the most active contributor among the articles tested. This graphical illustration is shown in Figure 3.

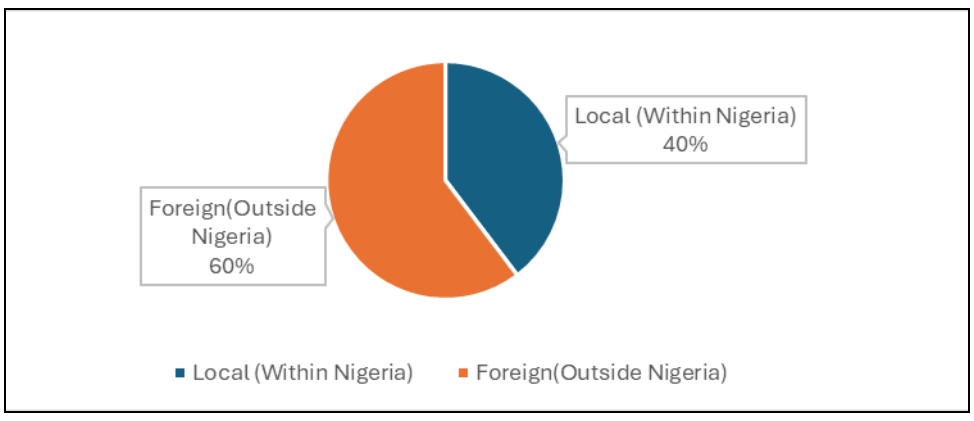

Figure 3: Country of Affiliation

Discussion

This systematic review, grounded in the PRISMA framework, synthesized findings from 63 empirical studies published between 2017 and 2025, with the aim of exploring the extent to which Virtual Laboratory Simulations (VLS) and Structured Inquiry (SI) Strategies influence key learning outcomes in science education. Across the reviewed literature, robust empirical evidence indicates that both instructional approaches significantly contribute to improving students' motivation, critical thinking, and academic performance, especially in chemistry-related subjects.

The findings from the literatures affirmed that VLS strategy enhances students' motivation by providing interactive, risk-free, and visually stimulating environments that allow students to explore scientific concepts at their own pace. Peter (2021), Rizki and Simorangkir (2018), and Chen et al. (2024) reported heightened students' engagement, reduced anxiety, and increased curiosity when students interacted with virtual chemistry laboratories. In many under-resourced settings, particularly in Nigeria and parts of Southeast Asia, VLS served as an effective alternative where physical laboratory infrastructure was lacking (Avwiri and Odiri, 2025; Agbonifo et al., 2020). The opportunity for repeated experimentation without fear of failure enhance intrinsic and self-confidence as key indicators of students' motivation.

Similarly, SI strategy emerged as a powerful driver of motivation, where students' actively construct knowledge through guided exploration, questioning, and problem-solving. This student-centered strategy enables students to take ownership of their learning, thereby sustaining attention and enthusiasm throughout the instructional process (Solihabonu, 2024; Adriani et al., 2021). Regarding critical thinking, SI strategy demonstrated strong efficacy in enhancing students' higher-order cognitive skills. Students exposed to structured inquiry consistently outperformed their counterparts in tasks requiring interpretation of data, drawing conclusions, evaluating claims, and justifying reasoning with evidence. Studies such as those by Alkan (2018), Santoso et al. (2018), and Aidoo et al. (2022) documented significant gains in critical thinking outcomes

The combined influence of VLS and SI strategies on academic performance revealed that students who received instruction through either of these strategies, generally scored higher on achievement tests and demonstrated superior performance in chemistry practical than those taught using conventional methods (Samuel & Busayo, 2021; Mohammed et al., 2021). Notably, the synergy of both strategies often yielded the most substantial learning gains, validating the constructivist premise where meaningful learning occurs when students are actively engaged in authentic, reflective, and socially mediated tasks (Ahzan et al., 2024; Munthe et al., 2024). Likewise, analysis revealed that quasi-experimental designs dominated both local and foreign studies. These has indirectly created gaps, as no studies have explicitly measured all five variables simultaneously on one study, future empirical research employing mixed-methods designs locally in Nigeria, could provide deeper insights into how these interactions unfold in classroom settings.

Conclusion

The review confirms that VLS and SI strategies were highly effective pedagogical strategies with demonstrable benefits for students' motivation, critical thinking, and academic performance in science education. Their implementation across varied contexts and content areas aligns with global efforts to enhance active, inquiry-driven, and technology-integrated learning environments. Nonetheless, the scarcity of localized studies focusing specifically on titration and related sub-topics within Nigerian secondary school curricula points to an important gap in empirical literature one that warrants further investigation.

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