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Empirical Paper

Statistical Characterisation of Retention Decay in Chemistry Learning Under Simulation-Driven Instruction

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Abstract

Purpose: This study examined retention decay in chemistry learning under simulation-based instruction using a time-dependent modelling approach. It compared retention dynamics between simulation-based and lecture-based instruction, assessed the predictive effect of instructional method on retention after controlling for post-test achievement, and examined the influence of gender.

Methodology: A quasi-experimental pre-test, post-test, and retention control group design was used. The sample comprised 126 Senior Secondary II chemistry students assigned to simulation-based ($n = 57$) and lecture-based ($n = 69$) groups. Retention was measured immediately after instruction (T_1), after four weeks (T_2), and after eight weeks (T_3). Data were analysed using descriptive statistics, repeated measures ANOVA, multiple regression, two-way ANOVA, and exponential decay modelling. The Chemistry Achievement Test demonstrated high reliability (KR-20 = 0.87).

Results: Simulation-based instruction produced significantly higher retention than lecture-based instruction across all time points. Instructional method significantly predicted retention after controlling for post-test achievement ($\beta = 0.394$, $p < 0.05$), explaining 65.9% of the variance ($R^2 = 0.659$). Exponential decay modelling showed a lower decay rate for the simulation group ($\lambda = 0.08$) than the lecture group ($\lambda = 0.18$), indicating slower forgetting. Gender had no significant effect on retention.

Novelty and Contribution: The study introduces exponential decay modelling to quantify learning retention over time under different instructional approaches.

Social and Practical Implications: The findings support wider adoption of simulation-based chemistry instruction, teacher training, and delayed assessments to strengthen long-term learning for all students.

Keywords: Simulation-based instruction, retention modelling, chemistry education, statistical analysis, learning decay

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1 Introduction

Science education is concerned with how scientific knowledge is taught, learned, and assessed in schools and other learning environments. As an interdisciplinary field, it draws mainly from biology, chemistry, and physics, while also incorporating ideas from psychology, pedagogy, curriculum studies, and the learning sciences to improve teaching effectiveness and student understanding (Lederman & Lederman, 2019; National Research Council [NRC], 2012). Contemporary views of science education emphasise that learning science goes beyond memorising facts; rather, it involves helping learners develop interconnected concepts, explanatory models, and meaningful representations through guided instruction and active engagement.

Learning science is often demanding for students because many scientific ideas are abstract, hierarchical, and cumulative. Students are frequently expected to explain observable phenomena using invisible or theoretical constructs, a task that can be cognitively challenging when adequate instructional support is lacking (Taber, 2020). As a result, students may develop fragmented understanding, hold persistent misconceptions, or forget what they have learned shortly after instruction. These challenges have led science education researchers to continuously examine teaching strategies, learning environments, and assessment practices that can improve understanding, reduce learning difficulties, and support long-term scientific literacy (Osborne et al., 2022).

Chemistry education, as a specialised branch of science education, focuses not only on the nature of chemical knowledge but also on how such knowledge can be taught effectively. Chemistry involves the study of the composition, structure, properties, and transformations of matter and relies heavily on symbolic representations, abstract reasoning, and mathematical relationships (Cooper et al., 2022). These characteristics make chemistry particularly difficult for many learners and help explain why students often struggle to retain chemical concepts, even when they perform well in immediate assessments.

For this reason, retention of chemistry knowledge is widely regarded as an important indicator of instructional effectiveness. Although many studies emphasise students' performance on immediate post-tests, research has shown that such short-term gains do not always lead to lasting learning unless instruction supports long-term memory consolidation (Dunlosky et al., 2013). Teachers frequently report that students forget information they had answered correctly only days earlier, raising concerns about the stability of learning outcomes. Empirical evidence suggests that knowledge decay can occur soon after assessment, although repeated retrieval of learned information can strengthen memory and improve long-term retention (Karpicke & Roediger, 2008).

These patterns of learning and forgetting can be understood through Cognitive Load Theory, which explains that learning is constrained by the limited capacity of working memory (Paas et al., 2010). In chemistry, the inherent complexity of concepts creates high intrinsic cognitive load, which may be further increased by poorly designed instructional materials or teacher-centred methods that place unnecessary demands on learners (Surbakti et al., 2024). When extraneous cognitive load becomes excessive, students may focus on surface features rather than meaningful understanding, making their learning more vulnerable to forgetting (Klepsch & Seufert, 2020). Effective instruction should therefore aim to reduce unnecessary cognitive demands while supporting processes that promote deep learning and retention.

One instructional approach that has gained increasing attention in this regard is simulation-based instruction. Simulations allow students to visualise and interact with chemical processes that are otherwise invisible or difficult to observe, helping them link symbolic, macroscopic, and submicroscopic representations (Smetana & Bell, 2012; Makransky et al., 2020). Research in chemistry and science education consistently shows that well-designed simulations can improve students' understanding and retention by encouraging active engagement, exploration, and conceptual connections. Related studies on interactive and gamified learning environments further suggest that such approaches can enhance motivation and optimise cognitive load when appropriately designed (Sailer & Homner, 2020; van Gaalen et al., 2021).

Support for simulation-based instruction also comes from cognitive psychology. Studies on memory have shown that repeated retrieval strengthens memory traces and improves long-term recall, highlighting the importance of active engagement with learning material (Karpicke & Roediger, 2008).

Despite these advances, an important limitation remains in how retention is commonly measured in chemistry education research. Retention is often assessed using a single delayed post-test, which provides only a snapshot of learning at one point in time. However, learning and forgetting are dynamic processes that unfold gradually. Early experimental work by Ebbinghaus (1885/2013) demonstrated that forgetting follows a systematic pattern, with rapid initial decline followed by slower loss over time.

In contrast, learning sciences research conceptualises forgetting as a continuous process that unfolds over time, commonly represented using exponential or power-law decay functions (Murre & Dros, 2015). The decay parameter (λ) quantifies the speed of forgetting, with smaller values indicating more persistent memory traces. Despite its theoretical relevance, decay modelling remains underutilised in science education research. Integrating instructional studies with statistical decay models therefore offers a rigorous framework for evaluating not only whether learning occurs, but how long it endures under different pedagogical conditions. Applying such models in chemistry education allows researchers to examine not only whether students learn, but also how long that learning lasts.

In response to gaps in existing research, the present study adopts a multi-point retention design and models retention decay as a statistical parameter influenced by instructional method. By comparing simulation-based instruction with conventional teaching approaches, the study seeks to provide a clearer and more realistic understanding of the durability of students' chemistry learning.

Statement of the Problem

Students' achievement in chemistry is predominantly evaluated through tests and examinations, which are often assumed to reflect meaningful learning. However, substantial evidence indicates that success in immediate post-instruction assessments does not necessarily translate into durable understanding or long-term retention of chemical knowledge (Dunlosky et al., 2013; Taber, 2020). Chemistry learning is cognitively demanding due to its abstract concepts, symbolic representations, and hierarchical structure, requiring learners to integrate observable phenomena with theoretical explanations (Cooper et al., 2022). Research in educational psychology shows that learners often forget information shortly after initial learning, reflecting the natural process of memory decay over time (Ebbinghaus, 1885/2013; Murre & Dros, 2015). Although retrieval practice and repeated testing can mitigate this decline by strengthening memory traces (Karpicke & Roediger, 2008), such strategies are not consistently implemented in many chemistry classrooms.

The manner in which chemical knowledge is presented plays a critical role in its retention. Instruction that emphasises discrete, isolated facts tends to promote surface learning, which is more susceptible to rapid forgetting, whereas conceptually integrated instruction supports deeper understanding and more durable memory (Mayer, 2020; Dunlosky et al., 2013). Despite this, many chemistry curricula continue to follow linear, content-heavy structures in which concepts are introduced once and rarely revisited, rather than through spiral approaches that reinforce and connect learning over time (Smetana & Bell, 2012). Furthermore, most empirical studies in chemistry education operationalise retention using a single delayed post-test, providing only a limited snapshot of learning and offering little insight into the temporal dynamics of knowledge retention (Makransky et al., 2020). Consequently, a significant gap remains between students' demonstrated achievement and the durability of their chemistry knowledge. Addressing this gap necessitates systematic investigation into the occurrence and timing of knowledge decay following instruction, as well as the influence of instructional and assessment practices on the long-term retention of chemical concepts.

Research Objectives

The study sought to:

i. Examine differences in the retention dynamics of students taught chemistry using simulation-based instruction and those taught using conventional methods.
ii. Determine the extent to which simulation-based instruction predicts students' retention in chemistry after controlling for post-test achievement.
iii. Determine whether gender influences retention in chemistry when students are exposed to simulation-based instruction.

Research Questions

The study was guided by the following research questions:

i. What differences exist in the retention dynamics of students taught chemistry using simulation-based instruction and those taught using conventional methods?

ii. To what extent does simulation-based instruction predict students' retention in chemistry after controlling for post-test achievement?

iii. Does gender influence retention in chemistry when students are exposed to simulation-based instruction?

Null Hypotheses

The following null hypotheses were tested at a 0.05 significance level:

H_{01}: There is no significant difference in the retention dynamics of students taught chemistry using simulation-based instruction and those taught using conventional methods.

H_{02}: Simulation-based instruction does not significantly predict students' retention in chemistry after controlling for post-test achievement.

H_{03}: There is no significant difference in the retention of male and female students taught chemistry using simulation-based instruction.

2 Methodology

The study adopted a quasi-experimental pre-test–post-test–retention design that allowed retention to be examined as a dynamic process over time. The study was conducted among Senior Secondary School II (SSII) chemistry students in public secondary schools within the Malumfashi Education Zone, Katsina State, Nigeria. The target population comprised 6,826 SSII chemistry students drawn from 26 public secondary schools in the zone, as documented by the Malumfashi Zonal Education Quality Assurance (MZEQA, 2025).

A multistage sampling technique was employed to select the study sample. Two comparable coeducational secondary schools were purposively selected based on similarity in curriculum coverage, teacher availability, instructional resources, and learning environment. While this limited number of schools enhances control of instructional conditions, it also constrains generalisability, which is acknowledged as a study limitation. From each school, one intact SSII chemistry class was selected and randomly assigned to either the experimental group (simulation-based instruction) or the control group (conventional lecture method). This procedure yielded a total sample of 126 students, comprising 57 students in the simulation-based group and 69 students in the lecture-based group. Potential school-level confounding variables such as teacher experience and instructional setting were minimised through selection of comparable schools and uniform instructional guidelines.

Instructional Procedure

The intervention lasted for six weeks, during which both groups were taught the same chemistry topics as specified in the SSII curriculum. The experimental group was taught using simulation-based instruction supported by interactive digital simulations (e.g., PhET Interactive Simulations and teacher-developed visual models), while the control group received conventional lecture-based instruction. Each group received equal instructional time and coverage of content to ensure equivalence of exposure.

Instrument for Data Collection

Data were collected using an adapted 40-item Chemistry Achievement Test (CAT). The instrument was adapted from standard senior secondary chemistry assessment items and previously validated WAEC-aligned chemistry test frameworks, with modifications made to align with the specific instructional content used in the study.

The CAT was subjected to face and content validation by three experts in chemistry education and two experts in measurement and evaluation, who assessed its relevance, clarity, and alignment with SSII curriculum objectives.

Their feedback led to revisions in item wording, difficulty balance, and content coverage to ensure appropriateness for the study population.

Reliability of the CAT was established using the Kuder–Richardson Formula 20 (KR-20), yielding a coefficient of 0.87, indicating high internal consistency.

Data Collection Procedure

The CAT was administered as a pre-test to establish baseline equivalence between groups. Subsequent assessments comprised an immediate post-test (Ret_1), a four-week delayed retention test (Ret_2), and an eight-week delayed retention test (Ret_3). This sequence allowed for examination of retention decay over time.

Data Analysis

Data were analysed using IBM SPSS Statistics Version 26. Descriptive statistics were used to summarise mean retention scores and examine overall trends across measurement intervals. Repeated measures analysis of variance (ANOVA) was employed to determine differences in retention dynamics over time and between instructional methods. Multiple regression analysis was used to assess the predictive influence of simulation-based instruction on retention after controlling for post-test achievement. In addition, two-way ANOVA was used to examine the influence of gender and its interaction with instructional method.

To model the temporal decline in learning, exponential decay modelling was applied. This approach estimates the rate at which retention decreases over time and allows comparison of forgetting patterns across instructional conditions. The model is expressed as:

$$K_{(t)} = K_{0e}{-}^{\lambda t}$$

Where:

$K_{(t)}$	=	Retention score at time t
K_0	=	Initial post-test score
λ	=	Decay parameter (rate of forgetting)
t	=	Time in weeks

3 Results

Research Question One: What differences exist in the retention dynamics of students taught chemistry using simulation-based instruction and those taught using conventional methods?

Table 1 Descriptive Statistics of Retention Scores by Instructional Method and Time

Instructional Method	Retention Time	N	Mean	Std. Deviation
Simulation-Based Instruction	Ret_1	57	79.40	6.21
Simulation-Based Instruction	Ret_2	57	56.80	4.92
Simulation-Based Instruction	Ret_3	57	41.20	3.87
Lecture-Based Instruction	Ret_1	69	71.20	7.48
Lecture-Based Instruction	Ret_2	69	34.80	4.15
Lecture-Based Instruction	Ret_3	69	17.10	3.02

The results in Table 1 show clear differences in retention between students taught using simulation-based instruction and those taught using the lecture method. At the immediate posttest (Ret_1), the simulation-based group recorded a higher mean score ($M = 79.40$, $SD = 6.21$) than the lecture-based group ($M = 71.20$, $SD = 7.48$), indicating stronger initial learning. Retention declined over time in both groups; however, the decline was more gradual for the simulation-based group. At Ret_2, the simulation group retained a higher mean score (M = 56.80, SD = 4.92) compared with the lecture group (M = 34.80, SD = 4.15). By Ret_3, the simulation-based group still demonstrated meaningful retention (M = 41.20, SD = 3.87), whereas the lecture-based group showed severe decay (M = 17.10, SD = 3.02). Therefore, the figures indicate that simulation-based instruction enhances long-term retention and reduces the rate of forgetting in chemistry learning.

H1: There is no significant difference in the retention dynamics of students taught chemistry using simulation-based instruction and those taught using conventional methods.

Table 2 Repeated Measures ANOVA for Retention Dynamics

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Time	48,932.61	2	24,466.31	812.41	0.000
Instructional Method	15,774.39	1	15,774.39	524.36	0.000
Time × Method	6,118.74	2	3,059.37	101.48	0.000
Error (Time)	7,215.91	123	30.07		
Total	78,041.65	126			

The repeated-measures ANOVA results in Table 2 indicate that retention scores changed significantly across the three testing intervals, as evidenced by a significant main effect of time, $F_{(2,\ 123)} = 812.41$, $p < .05$. This shows that students' retention of chemistry concepts declined significantly over time. Instructional method also had a significant main effect on retention, $F_{(1,\ 123)} = 524.36$, $p < .05$, indicating that students taught using simulation-based instruction consistently achieved higher retention scores than those taught using the lecture method. Furthermore, the significant interaction effect between time and instructional method, $F_{(2,\ 123)} = 101.48$, $p < .05$, demonstrates that the pattern of retention decay differed between the two groups. Specifically, retention declined more slowly among students exposed to simulation-based instruction, confirming that instructional method significantly influences the durability of chemistry learning over time.

H02: Simulation-based instruction does not significantly predict students' retention in chemistry after controlling for posttest achievement.

Table 3 Model Summary for Prediction of Retention in Chemistry

Model	R	R^2	Adjusted R^2	Std. Error of Estimate
1	0.812	0.659	0.653	3.42

Table 3 presents Model Summary for Prediction of Retention in Chemistry. The model summary indicates a strong relationship between the predictors and students' retention in chemistry. The coefficient of determination (R^2 = 0.659) shows that approximately 65.9% of the variance in students' retention scores is jointly explained by instructional method and posttest achievement. This level of explained variance suggests that the model is robust and that simulation-based instruction plays a substantial role in sustaining students' chemistry knowledge over time, even after accounting for immediate learning outcomes.

Table 4 ANOVA for Regression Model

Source	Sum of Squares	Df	Mean Square	F	Sig.
Regression	6,842.11	2	3,421.06	292.74	0.000
Residual	3,544.83	123	28.82		
Total	10,386.94	125			

Table 4 presents the ANOVA for the regression model. The ANOVA result shows that the regression model is statistically significant ($F_{(2,123)}$ = 292.74, $p < .05$). This confirms that the predictors, taken together, significantly explain variations in students' retention scores. Therefore, the regression model is suitable for predicting retention in chemistry learning.

Table 5 Regression Coefficients for Predicting Retention

Predictor	B	Std. Error	Beta	t	Sig.
Constant	4.216	1.732		2.43	0.017
Posttest Achievement	0.412	0.058	0.521	7.10	0.000
Instructional Method	0.367	0.064	0.394	5.73	0.000

Table 5 shows the regression coefficients for predicting Retention. After controlling for posttest achievement, instructional method emerged as a significant predictor of retention in chemistry (β = .394, $p < .05$). This indicates that students exposed to simulation-based instruction retained chemistry concepts significantly better than those taught using the conventional method, independent of how well they performed immediately after instruction. While post-test achievement also significantly predicted retention, the unique contribution of instructional method demonstrates that simulation-based instruction has a lasting impact beyond short-term learning gains. This finding underscores the pedagogical value of simulations in promoting durable chemistry learning rather than temporary performance improvements.

Exponential Decay Modelling of Retention

Table 6 Exponential Decay Parameters

Instructional Method	K_0 (Mean Posttest Score)	λ (Decay Parameter)	Half-life ($t_{1/2}$)	Retention at 8 weeks (Predicted)
Simulation-Based Instruction	80.12	0.08	8.66 weeks	53.21
Conventional Lecture-Based Instruction	69.25	0.18	3.85 weeks	31.47

The decay parameter (λ) indicates the rate at which retention decreases over time. A smaller λ means slower forgetting and more stable retention. The results show that students exposed to simulation-based instruction exhibited a lower decay parameter (0.08) compared to those taught using conventional instruction (0.18). This means that simulation-based learners retained information much longer. The half-life, defined as the time taken for retention to decline to half of its initial value, further confirms this pattern, with simulation-based learners demonstrating a longer half-life (8.66 weeks) than conventional learners (3.85 weeks). Predicted retention at 8 weeks shows the same pattern: simulation-based learners retain 53.21 mean score, while conventional learners drop to 31.47 mean score. This reveals that simulation-based instruction not only improves immediate learning outcomes but also significantly reduces the rate of forgetting, providing a strong empirical argument for its adoption in chemistry education.

Research Question Three: Does gender influence retention in chemistry when students are exposed to simulation-based instruction?

Table 7 Descriptive Statistics of Retention Scores by Gender (Simulation-Based Group)

Gender	N	Mean	Std. Deviation	Std. Error
Male	28	41.80	3.92	0.74
Female	29	40.60	3.81	0.71

Table 7 shows descriptive statistics in which male and female students exposed to simulation-based instruction achieved very similar mean retention scores. Although males recorded a slightly higher mean score, the difference is minimal, suggesting that both genders benefited almost equally from the instructional strategy.

H3: There is no significant difference in the retention of male and female students taught chemistry using simulation-based

Table 8 Two-Way ANOVA of Retention by Instructional Method and Gender

Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Instructional Method	5,921.44	1	5,921.44	402.61	0.000	0.764
Gender	18.62	1	18.62	1.27	0.262	0.010
Method × Gender	6.83	1	6.83	0.47	0.495	0.004
Error	1,807.33	55	14.81			
Total	7,754.22	57				

Table 8 presents a 2-way ANOVA of retention by instructional method and gender. The ANOVA results indicate that instructional method had a statistically significant effect on retention, confirming the superiority of simulation-based instruction. However, gender did not have a significant effect on retention scores ($F_{(1,55)} = 1.27$, $p > .05$). Furthermore, the interaction between instructional method and gender was not significant, indicating that the effectiveness of simulation-based instruction was consistent for both male and female students. The very small effect sizes associated with gender further confirm that differences in retention cannot be attributed to gender. This suggests that simulation-based instruction provides an equitable learning environment that supports long-term retention for all students, regardless of gender.

Summary of the Major Findings

Students taught with simulation-based instruction had higher immediate and delayed retention scores than those taught with lectures. At Ret_1, the simulation group scored M = 79.40, SD = 6.21, while the lecture group scored M = 71.20, SD = 7.48. By Ret_2, the means were 56.80 against 34.80, and at Ret_3, 41.20 against 17.10, showing slower decay for the simulation group. The significant time × method interaction ($F(2,123) = 101.48$, $p < .05$) confirms that simulation-based instruction enhances long-term retention of chemistry concepts. After controlling for post-test achievement, instructional method significantly predicted retention ($\beta = 0.394$, $p < .05$). Simulation-based instruction explained a substantial portion of variance in retention scores ($R^2 = 0.659$). Regression analysis confirmed the robustness of the predictive model. This shows simulation-based instruction has a lasting impact beyond short-term learning gains.

Simulation-based learners had a slower forgetting rate ($\lambda = 0.08$) compared with lecture learners ($\lambda = 0.18$). Half-life of retention was longer for simulation-based learners (8.66 weeks against 3.85 weeks). Predicted 8-week retention was higher for the simulation group (53.21 against 31.47). This confirms simulations reduce retention decay and sustain learning over time.

Male and female students exposed to simulation-based instruction had very similar retention scores (M ≈ 41 against 40.6). Gender had no significant effect on retention ($F_{(1,55)} = 1.27$, $p > .05$). The interaction of method × gender was also not significant. Simulation-based instruction benefits both genders equally in chemistry learning.

4 Discussion of Findings

The results indicate that students exposed to simulation-based instruction achieved higher retention scores than those taught using lectures at all measurement points. Specifically, the simulation group had an immediate post-test mean of 79.40 (SD = 6.21), compared with 71.20 (SD = 7.48) for the lecture group. At the four-week delayed test, the simulation group retained 56.80 while the lecture group dropped to 34.80, and by the eight-week delayed test, the means were 41.20 against 17.10. These differences are substantial, reflecting a slower decay in the simulation-based group.

The repeated measures ANOVA revealed a significant main effect of time ($F_{(2,123)} = 812.41$, $p < .05$), indicating that retention naturally declines over time. There was also a significant main effect of instructional method ($F_{(1,123)} = 524.36$, $p < .05$), confirming that the method of instruction strongly influences retention. Importantly, the time × method interaction ($F(2,123) = 101.48$, $p < .05$) demonstrates that the pattern of decay differs between methods, with simulation-based instruction sustaining knowledge longer. These findings are consistent with cognitive theories of learning, particularly multimedia learning theory, which argues that meaningful learning is enhanced when learners actively integrate visual and verbal representations (Mayer, 2020). In simulation environments, students are better able to construct coherent mental models, thereby enhancing retention and reducing cognitive overload. Exponential decay modelling further quantified this effect. The decay parameter $\lambda = 0.08$ for the simulation group compared with $\lambda = 0.18$ for lectures illustrates that forgetting occurs at less than half the rate under simulation-based instruction. Similarly, the half-life of retention for the simulation group was 8.66 weeks, over twice that of the lecture group (3.85 weeks). This reinforces the conclusion that simulation-based methods not only improve immediate learning but also maintain knowledge over time.

Regression analysis confirmed that simulation-based instruction is a significant predictor of retention even after accounting for immediate posttest scores. The model explained 65.9% of the variance in retention scores ($R^2 = 0.659$), and both predictors, post-test achievement ($\beta = 0.521$, $p < .05$) and instructional method ($\beta = 0.394$, $p < .05$), were significant. This finding implies that simulation-based instruction has an impact beyond short-term performance, supporting the idea that active engagement, visualisation, and interaction inherent in simulations strengthen memory traces. While post-test achievement remains a strong predictor of retention, the unique contribution of instructional method shows that simulations enhance the durability of learning, making chemistry knowledge more resistant to forgetting.

The descriptive statistics indicated minimal differences between males (M = 41.80, SD = 3.92) and females (M = 40.60, SD = 3.81) in the simulation group. Two-way ANOVA confirmed that gender had no significant effect on retention ($F_{(1,55)} = 1.27$, $p = .262$), and the interaction between gender and method was also non-significant ($F_{(1,55)} = 0.47$, $p = .495$). This suggests that simulation-based instruction provides an equitable learning environment. Both male and female students benefited similarly, highlighting the universal applicability of interactive, simulation-driven pedagogy in promoting long-term retention in chemistry. These findings align with research suggesting that when instruction is interactive and cognitively engaging, gender differences in science achievement tend to diminish (Sailer & Homner, 2020).

5 Conclusion and Recommendations

The study demonstrates that simulation-based instruction significantly enhances both immediate and long-term retention of chemistry concepts compared with conventional lecture methods. Students exposed to simulations not only achieved higher post-test scores but also retained knowledge longer, as evidenced by slower decay rates and extended half-lives. Regression analysis confirmed that instructional method predicts retention even after accounting for initial learning, highlighting the lasting pedagogical impact of simulations. Gender was not a significant factor, indicating that simulation-based learning benefits both male and female students equally. Generally, the findings underscore the effectiveness and equity of simulation-driven instruction in chemistry education. Incorporating simulations into teaching can strengthen conceptual understanding, reduce forgetting, and support durable learning outcomes. However, the study is limited by its use of only two schools, potential teacher and classroom effects, and a relatively short retention period. These factors should be considered when interpreting the findings. Future research could extend the retention timeline, involve a larger and more diverse sample of schools, and explore the combined effects of simulations with other instructional strategies such as retrieval practice or blended learning models. The study recommended that schools should adopt simulation-based chemistry teaching to improve long-term retention and reduce forgetting. Teachers should receive training on effective simulation use, while delayed assessments should be used to monitor retention for all students regardless of gender.

Practical and Social Implications

The findings of this study suggest that simulation-based instruction plays an important role in promoting durable learning and reducing the rate at which students forget previously learned concepts. By providing interactive and visual learning experiences, simulations help students to better understand abstract chemistry concepts, strengthen conceptual understanding, and improve long-term retention of knowledge. This indicates that simulation-driven teaching approaches can make chemistry learning more engaging, meaningful, and effective compared to conventional instructional methods.

The findings further imply that educators should integrate simulation-based strategies into regular chemistry instruction to enhance students' academic performance and retention ability. Schools and educational stakeholders should also provide targeted training programmes and workshops to equip teachers with the necessary technological and pedagogical skills required for the effective use of simulations in the classroom. In addition, the use of multiple delayed assessments is recommended to help teachers monitor students' long-term retention and identify areas where reinforcement may be needed. The findings also support inclusive learning practices, as the effectiveness of simulation-based instruction was observed across both male and female students, suggesting that it can improve learning outcomes for all learners regardless of gender.

Limitations of the Study and Future Research Directions

The study is limited by the use of only two schools, which may affect generalisability. As a quasi-experimental design, potential teacher and classroom effects could not be fully controlled. In addition, a possible novelty effect from simulation use and the relatively short retention period may have influenced the findings. Future research should consider using more rigorous experimental designs to better control teacher and classroom effects. In addition, future studies may examine the long-term effects of simulation-based learning by extending the retention period and investigating whether the effectiveness of simulations remains consistent over time. Further research could also explore the impact of simulation use across different subjects, class levels, and learning environments.

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Availability Statement

Data will be made available on request.

Conflict of Interest

The author declares no conflicts of interest.

Declaration of generative AI usage

Generative AI tools were used solely for language editing (grammar, clarity, and formatting) and did not contribute to the study's design, data collection, analysis, interpretation, or conclusions.

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