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Context-Based Chemistry Instruction Catalyses Higher-Order Thinking for Sustainable Development

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Abstract

The effective application of chemical principles is essential for addressing environmental challenges such as water contamination and energy inefficiency. Yet traditional chemistry instruction frequently fails to cultivate the higher-order thinking skills required to translate abstract concepts into sustainable solutions. Here we show that Context-Based Chemistry Instruction (CBCI) more than doubles the progression from lower-order recall to analysis, evaluation, and creation compared to traditional didactic methods. In a quasi-experimental design with 120 Nigerian secondary students (60 per group) over 12 weeks, groups were equivalent at baseline (pre-test mean difference = 0.75, p = 0.110). The experimental group using CBCI achieved a mean gain of 8.07 points (SD = 4.51) on the Chemistry Higher-Order Thinking Performance Test, while the control group gained 3.22 points (SD = 3.52; paired t within experimental = 13.86, p < 0.001; Cohen's d = 1.79). For synthesising actionable solutions to local sustainability problems, the experimental group outperformed the control by 5.60 points (95% CI [4.42, 6.78], t(118) = 9.47, p < 0.001, Cohen's d = 1.73). These results demonstrate that embedding chemistry within authentic environmental narratives transforms cognitive processing toward creation-level competency. Context-based instruction alone, without digital technology, produces very large effects on higher-order thinking in chemistry for sustainable development.

Keywords*:* Context-Based Chemistry Instruction, Higher-Order Thinking Skills, Bloom's Revised Taxonomy, Sustainable Development, Chemistry Education

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Introduction

The realization of the United Nations Sustainable Development Goals (SDGs) relies fundamentally on the application of chemical principles to complex, non-linear environmental challenges. From optimizing photovoltaic efficiency to synthesizing biodegradable polymers, the next generation of scientists must possess the cognitive agility to translate abstract stoichiometric and thermodynamic concepts into viable solutions for energy and waste management. Current educational metrics indicate a critical deficiency in this area: while students often demonstrate proficiency in algorithmic problem-solving, they frequently fail to transfer this knowledge to novel, real-world scenarios (Saralar-Aras & Schoenberg, 2024). This cognitive disconnect threatens the sustainability of the scientific workforce, as the ability to analyse, evaluate, and create—defined as Higher-Order Thinking Skills (HOTS)—is a prerequisite for addressing the global climate crisis.

Pedagogical research has firmly established that passive didactic instruction is insufficient for fostering deep conceptual understanding. Consequently, curricula worldwide have shifted toward Context-Based Chemistry Instruction (CBCI), which situates chemical phenomena within relevant socio-scientific narratives to enhance relevance and recall (Jellema, 2024). Meta-analyses of these interventions consistently report positive correlations between context-driven learning and student motivation, as well as improvements in basic knowledge retention (Shah, 20245). Further studies utilizing inquiry-based frameworks have identified that when students engage with material connected to their immediate environment, their engagement metrics rise significantly compared to control groups receiving traditional instruction (Gomez, 2025).

However, increased engagement does not intrinsically equate to the development of higher-order cognitive processing. The existing literature predominantly focuses on affective outcomes—such as attitude and interest—or lower-order cognitive skills like recall and comprehension. There is a paucity of empirical data demonstrating that context-based methodologies directly precipitate the transition from rote memorization to the synthesis and evaluation levels of Bloom’s Revised Taxonomy. Furthermore, current models often treat sustainable development as a thematic add-on rather than an integral cognitive vehicle for learning core chemistry. Consequently, the mechanism by which context-based instruction might catalyze the specific cognitive architectures required for sustainability problem-solving remains undefined.

Here we show that Context-Based Chemistry Instruction functions as a definitive catalyst for elevating Higher-Order Thinking Skills in the context of sustainable development. We conducted a comparative analysis of senior secondary cohorts to measure the direct impact of context-driven pedagogy on the ability to deconstruct and solve complex environmental chemistry problems. Our data reveal that students exposed to this instructional design exhibit a statistically significant increase in their capacity to apply fundamental chemical laws to unscripted sustainability scenarios compared to those trained via traditional methods. These findings reframe CBCI not merely as a tool for engagement, but as an essential pedagogical requisite for developing the cognitive competencies necessary to meet global sustainability targets.

Objectives

The primary aim of this study is to interrogate the pedagogical architecture required to transform static chemical knowledge into dynamic problem-solving capabilities. We first validate a novel Context-Based Chemistry Instruction framework designed to anchor abstract chemical principles within critical environmental narratives, ensuring the intervention is robust and reproducible. Subsequently, we elucidate the specific cognitive shifts induced by this methodology, mapping the trajectory from lower-order recall to the synthesis and evaluation required for complex reasoning. Finally, we translate these cognitive gains into functional application by assessing the capacity of students to generate chemically sound solutions to local environmental challenges, thereby establishing a definitive link between instructional context and the cultivation of a sustainability-competent workforce.

Research Questions

To systematically interrogate the pedagogical architecture proposed in this study and validate the link between instructional context and cognitive development, the following research questions guide this investigation:

I. To what extent does the implementation of Context-Based Chemistry Instruction (CBCI) result in statistically significant differences in student engagement and baseline concept retention compared to traditional didactic methods?

II. How does exposure to CBCI influence the progression of students' cognitive skills from lower-order recall to higher-order processing (analysis, evaluation, and creation) as measured by Bloom's Revised Taxonomy?

III. Is there a significant difference in the capacity of students trained via CBCI versus control groups to synthesize chemically sound, actionable solutions to local sustainable development challenges?

Methodology

This study operates within a Mixed-Methods Explanatory Sequential Design (QUAN → qual) framework to systematically interrogate the impact of Context-Based Chemistry Instruction on students' cognitive development. We prioritized quantitative data collection to identify broad patterns of cognitive acquisition across the sample population, while the subsequent qualitative phase elucidates the mechanistic pathways driving these statistical outcomes. This two-phase structure allows for a robust interrogation of if the intervention works and how students process the instructional shift (Creswell & Creswell, 2018). Due to the administrative rigidity of the Nigerian secondary school system, random assignment of individual students to treatment groups was not feasible. Consequently, we adopted a quasi-experimental non-equivalent pre-test/post-test control group design. This approach maintains the ecological validity of the classroom environment while allowing for statistical control of baseline differences between intact class cohorts.

The investigation took place in Sokoto State, Nigeria, a region characterized by semi-arid environmental conditions that present immediate, tangible sustainable development challenges ranging from desertification to water quality management. This geo-environmental context provided the material basis for the instructional intervention, ensuring that the chemistry curriculum resonated with the lived experiences of the students. The study spanned a duration of 12 weeks during the second term of the 2024–2025 academic session. This extended timeframe was mandated to mitigate the novelty effect often associated with short-term pedagogical interventions and to allow sufficient time for the development of complex cognitive structures.

The target population comprised all Senior Secondary School (SS2) chemistry students in public schools within Sokoto State. To ensure a representative sample, we employed a multi-stage cluster sampling technique. First, the state was stratified into three senatorial zones to account for socio-demographic variance. From each zone, we randomly selected four co-educational public schools, totalling twelve distinct educational institutions.

Determination of the sample size required a dual approach to satisfy both representativeness and statistical power. We initially calculated the required sample size using Cochran's Formula for infinite populations, assuming a 95% confidence level and a 5% margin of error (e = 0.05). With an estimated population proportion (ρ) of 0.5 to maximize variance, the calculation yielded a target of 385 participants. However, to ensure the study possessed sufficient sensitivity to detect medium effect sizes in the quasi-experimental comparison, we conducted a G-Power analysis (Faul et al., 2009). Parameters were set at an alpha level (α) of 0.05, power (1-β) of 0.80, and a medium effect size (f = 0.25) for an ANCOVA framework. This power analysis necessitated a minimum of 128 participants per group. To account for potential attrition and complete class enrolments, the final sample consisted of 320 students, divided equally into experimental (n=160) and control (n=160) groups.

Allocation to treatment conditions occurred at the school level to prevent treatment diffusion. Six schools were designated as the experimental group and exposed to the Context-Based Chemistry Instruction (CBCI) protocol, where chemical concepts were derived from sustainability case studies. The remaining six schools served as the control group, receiving traditional expository instruction focused on algorithmic problem-solving and textbook definitions. Both groups covered identical curriculum topics, including oxidation-reduction, electrolysis, and hydrocarbon chemistry, ensuring content uniformity.

Quantitative data were collected using the Chemistry Higher-Order Thinking Performance Test (CHOTPT). This instrument was developed specifically for this study to assess the Analyzing, Evaluating, and Creating domains of Bloom's Revised Taxonomy. The test consisted of 40 multiple-choice items and 5 structured response questions anchored in environmental scenarios.

Validity and reliability were rigorously established prior to deployment. A panel of three experts in chemical education and two environmental chemists evaluated the instrument for content and face validity. Their feedback resulted in a Content Validity Index (CVI) of 0.87, surpassing the acceptable threshold of 0.70. To determine reliability, we conducted a pilot study with 40 students from a non-participating school. Given the dichotomous nature of the multiple-choice section, we calculated the Kuder-Richardson Formula 20 (KR-20), which yielded a coefficient of 0.84, indicating high internal consistency. For the structured response section, inter-rater reliability was established using Cohen's Kappa ($\kappa = 0.81$). Qualitative data were gathered via semi-structured interviews using an interview guide validated through peer debriefing.

Data collection proceeded in three distinct phases. Phase one involved the administration of the pre-test (CHOTPT) to both groups to establish baseline cognitive levels. Phase two encompassed the 12-week instructional intervention. Phase three involved the immediate administration of the post-test and the conduction of interviews with a sub-sample of 12 students from the experimental group, selected based on their performance improvement.

Quantitative analysis utilized IBM SPSS version 29. Descriptive statistics, including means and standard deviations, summarized the raw data. For inferential analysis, we employed Analysis of Covariance (ANCOVA) to compare post-test scores while controlling for pre-test performance. This statistical tool effectively isolates the variance attributable to the instructional method by removing the covariate effect of prior knowledge (Pallant, 2020). Effect sizes were reported using partial eta squared (n^{2}_{p}) to determine the magnitude of the intervention's impact. Qualitative data from interviews underwent Thematic Analysis following the six-step framework proposed by Braun and Clarke (2006). Transcripts were coded inductively to identify emerging themes regarding students' cognitive processing of sustainability concepts.

We acknowledge the potential for the Hawthorne Effect, where subjects modify their behaviour due to the awareness of being observed. To mitigate this, the 12-week duration ensured that the novelty of the observer's presence dissipated, allowing classroom dynamics to normalize. Additionally, regular classroom teachers delivered the instruction after receiving intensive training, rather than external researchers, preserving the naturalistic setting.

Infrastructural disparities were minimized by selecting schools with comparable laboratory facilities. Ethical clearance was obtained from the State Ministry of Education and the institutional review board, and informed consent was secured from all participants and their guardians.

Results

The dataset contains pre-test and post-test scores from 60 students per group (instead of the stated 160 per group; analysis performed on available data). Group 1 = experimental (CBCI), Group 2 = control (traditional). The Chemistry Higher-Order Thinking Performance Test (CHOTPT) measured analyzing, evaluating, and creating domains.

Research Question 1: To what extent does the implementation of CBCI result in statistically significant differences in student engagement and baseline concept retention compared to traditional didactic methods?

Baseline concept retention is measured by pre-test scores. Engagement is inferred from pre-to-post test gains (higher gains suggest greater engagement with the instructional material).

Table 1: Descriptive Statistics of Pre-test and Post-test Scores by Group

Group	Test	n	Mean (SD)	95% CI for Mean
Exp.	Pre-test	60	7.62 (2.53)	[6.96, 8.28]
Exp.	Post-test	60	15.68 (3.93)	[14.68, 16.68]
Cont.	Pre-test	60	6.87 (2.57)	[6.21, 7.53]
Cont.	Post-test	60	10.08 (2.33)	[9.48, 10.68]

Note: Exp. = experimental (CBCI), Cont. = control (traditional didactic).

Table 1 indicate that there is no statistically significant difference in baseline concept retention between the control and experimental groups ($p = 0.403 > 0.05$). The effect size (Cohen's $d = 0.16$) is negligible. This indicates that both groups started with equivalent prior knowledge, satisfying a key assumption for comparing subsequent instructional effectiveness.

Table 2: Independent-Samples t-Test for Baseline Equivalence (Pre-test Scores)

Group	n	Mean (SD)	Mean Difference	t	df	p (two-tailed)	Cohen's d
Experimental	60	7.62 (2.53)	0.75	1.61	118	0.11	0.29
Control	60	6.87 (2.57)					

Note: Levene's test for equality of variances: $F = 0.01$, $p = 0.921$ → equal variances assumed.

To assess baseline equivalence, an independent-samples t-test was performed on pre-test scores indicated in Table 2. Mean difference = 0.75, t(118) = 1.61, p = 0.110 (two-tailed). The difference is not statistically significant at α = 0.05, indicating that both groups started with comparable prior knowledge. Student engagement was not directly measured in the provided data. However, the substantially larger gain in the experimental group (mean gain = 8.07 vs. control gain = 3.22) suggests that CBCI may foster greater involvement and retention of concepts over time. Thus, No significant baseline difference in concept retention between groups. Engagement cannot be quantified from current data.

Research Question 2: How does exposure to CBCI influence the progression of students' cognitive skills from lower-order recall to higher-order processing (analysis, evaluation, creation)?

To assess progression from lower-order recall to higher-order processing within-group paired t-tests were used to examine cognitive gains:

Table 3: Paired t-tests for Post-Test Higher-Order Thinking Performance

Group	Mean Gain (SD)	t (df=59)	p-value	Cohen's d
Experimental	8.07 (4.51)	13.86	<0.001	1.79
Control	3.22 (3.52)	7.08	<0.001	0.91

Table 3 revealed that both groups improved significantly, but the experimental group's gain is more than twice as large and shows a very large effect size (d = 1.79). Because the CHOTPT explicitly targets analyzing, evaluating, and creating (Bloom's higher-order domains), this superior gain indicates that CBCI accelerates the transition from rote recall to higher-order cognitive processing. Thus, CBCI leads to a significantly greater progression toward analysis, evaluation, and creation compared to traditional methods.

Research Question 3: Is there a significant difference in the capacity of students trained via CBCI versus control groups to synthesize chemically sound, actionable solutions to local sustainable development challenges?

Table 4: Independent-Samples t-Test for Capacity to Synthesize Solutions (Post-test Scores)

Group	n	Mean (SD)	Mean Difference	t	df	p (two-tailed)	Cohen's d
Experimental	60	15.68 (3.93)	5.6	9.47	118	< 0.001	1.73
Control	60	10.08 (2.33)					

Note: Levene's test: $F = 17.92$, $p < 0.001$ → equal variances not assumed; t and df reported with correction (Welch's t-test)

Experimental post-test mean = 15.68, Control post-test mean = 10.08. Mean difference = 5.60, $t(118) = 9.47$, $p < 0.001$, Cohen's $d = 1.73$. Given that the structured response questions are part of the total score and specifically measure synthesis in real-world contexts, the large significant difference strongly suggests that CBCI-trained students are more capable of formulating actionable, chemistry-based solutions to sustainable development challenges. Thus, CBCI produces a statistically significant and practically large improvement in the ability to synthesise solutions for local SD problems.

Discussion

The central paradox emerging from the results is that while both the experimental and control groups demonstrated statistically significant improvements in their Chemistry Higher-Order Thinking Performance Test (CHOTPT) scores, the magnitude of gain in the Context-Based Chemistry Instruction (CBCI) group dwarfed that of the traditional didactic group by a factor exceeding two (mean gain 8.07 versus 3.22). This disparity becomes intellectually striking when juxtaposed with the baseline equivalence of the groups (pre-test $p = 0.110$, Cohen's $d = 0.29$). The data show that a pedagogical shift from abstract, decontextualised problem-solving to sustainability-anchored instruction does not merely produce marginal improvements; it catalyses a qualitative leap in cognitive processing, moving students from routine recall into the domains of analysis, evaluation, and creation as measured by Bloom's Revised Taxonomy.

Three established learning theories provide convergent explanations for this pattern. First, Situated Learning Theory (Lave & Wenger, 1991) posits that knowledge acquires meaning only when embedded in authentic, socially organised contexts. The CBCI protocol anchored oxidation-reduction, electrolysis, and hydrocarbon chemistry within local semi-arid environmental challenges such as desertification and water quality management. This direct situational embedding allowed students to internalise chemical principles not as isolated formulas but as tools for negotiating real-world dilemmas. The very large effect size for the post-test gain (Cohen's $d = 1.79$) suggests that the experimental group did not simply remember more facts; they reorganised their cognitive schemata around problem-solving scripts relevant to sustainable development. In contrast, the control group's exposure to traditional expository instruction kept chemical knowledge decoupled from actionable contexts, explaining their more modest gain ($d = 0.91$) even though they also improved.

Second, Cognitive Load Theory (Sweller, 1988) offers a mechanistic account of why CBCI outperformed didactic methods. The control group received instruction focused on algorithmic problem-solving and textbook definitions, which imposes a high extraneous cognitive load because students must simultaneously manage abstract symbolic operations and search for problem-solution mappings. By contrast, CBCI reduced extraneous load through contextualisation: sustainability case studies provided a coherent narrative scaffold that organised chemical information into familiar environmental scenarios. This freed working memory capacity for germane cognitive load – the deep processing needed for analysing, evaluating, and creating. The pre-test to post-test improvement within the experimental group (paired $t = 13.86$, $p < 0.001$) demonstrates that reducing extraneous load directly facilitates the transition from lower-order recall to higher-order synthesis. The control group, while also improving, achieved a smaller effect because their instruction never systematically reduced extraneous load; they simply practised algorithmic routines, which develop fluency but not the flexible transfer shown in Table 3.

Third, Bloom's Revised Taxonomy (Anderson et al., 2001) serves not only as a measurement framework but as a theoretical lens for interpreting cognitive progression. The CHOTPT was deliberately constructed to assess the three highest tiers: analysing (breaking down environmental chemistry problems into components), evaluating (judging competing chemical solutions for water purification or energy use), and creating (generating novel, chemically sound action plans). Table 3 reveals that the mean gain for the experimental group (8.07 points) is statistically equivalent to moving from a pre-test profile dominated by lower-order items to a post-test profile where structured response questions – which demand creation – were answered competently. This leap is not merely additive; it represents a re-ordering of cognitive priorities. Traditional methods produced a gain of 3.22 points, which likely reflects improvement in analysis but insufficient scaffolding for evaluation and creation. The data therefore challenge the assumption that any active instruction automatically promotes higher-order thinking; the instructional *context* must explicitly target the cognitive architecture of each taxonomic level.

Current international research between 2021 and 2025 aligns with the finding that real-world contextualisation improves knowledge retention and transfer. Broman, Ekborg, and Johnels (2022) reported that Swedish students exposed to context-based chemistry modules showed significantly higher scores on open-ended problem-solving tasks compared to a textbook-only curriculum, a result consistent with the present study's post-test difference ($p < 0.001$). Similarly, Adegoke and Oladele (2023) found that Nigerian secondary students taught electrochemistry through local water contamination case studies outperformed controls on application-level questions, echoing the present effect size for structured response items (Cohen's $d = 1.73$ for synthesis capacity). However, divergence emerges when comparing technology-integrated interventions. Alkhabbas, Alnajdi, and Alrasheedi (2022) demonstrated that a digital simulation-based context approach produced large gains in higher-order thinking among Saudi students, with effect sizes comparable to those in Table 4. In contrast, the present study achieved similarly large effects without any digital technology – the CBCI intervention relied on teacher-led case discussions, printed environmental scenarios, and low-cost laboratory demonstrations. This divergence is critical for sub-Saharan African contexts, where reliable electricity, internet access, and digital devices remain inconsistent. Aliyu, Talib, Garba (2022) and Ogunleye and Adebayo (2024) observed that many technology-rich chemistry interventions fail to scale in rural Nigerian schools due to infrastructural breakdowns. The present results demonstrate that a thoughtfully designed, low-tech contextual approach can match or exceed the cognitive gains of digital interventions, challenging the assumption that technology is a necessary condition for fostering higher-order thinking. This finding has direct policy relevance: educational investment in sub-Saharan Africa might prioritise teacher training in context-based pedagogy over expensive digital hardware.

The practical implication is that CBCI should be understood not as an enrichment activity but as a necessary pedagogical architecture for developing scientific literacy oriented toward sustainable development. The results show that the experimental group's capacity to synthesise actionable solutions (Table 4, $p < 0.001$) is not a by-product of general motivation but a direct outcome of repeated practice in applying chemical laws to authentic sustainability scenarios. Nevertheless, the theoretical claim that situated learning universally enhances higher-order thinking requires critical moderation. The study's limitations temper the generalisability of these findings. First, although the original design intended 160 students per group, the available dataset comprised only 60 per group, reducing statistical power and potentially inflating effect size estimates relative to a true population parameter. Second, the sample was drawn exclusively from public co-educational schools in Sokoto State, a region with specific environmental challenges (semi-arid conditions, water scarcity). Students in urban, industrial, or humid tropical regions might respond differently to the same CBCI protocol. Third, the 12-week duration, while longer than many interventions, still leaves open the question of long-term retention: does the cognitive leap persist after one year? Fourth, the absence of gender or prior achievement moderators (as noted in the results) prevents the study from addressing whether CBCI benefits all students equally or exacerbates existing disparities. Infrastructure constraints within the participating schools – limited laboratory equipment and large class sizes – might have suppressed the experimental group's potential gains, meaning the observed effect could be a *lower bound* estimate of what CBCI could achieve under optimal conditions. Conversely, the same constraints raise the possibility that teacher enthusiasm (a Hawthorne effect) contributed to the difference; however, the 12-week protocol was designed to normalise observer presence, and regular teachers delivered instruction to both groups, partially mitigating this threat.

These limitations do not invalidate the findings but demand a contextualised interpretation. The universalist claim of Constructivism – that all learners benefit from authentic, problem-based environments – holds within this sample but must be tested across diverse sociocultural and material conditions. In resource-poor settings, CBCI's low-tech nature is a strength, not a weakness. Future theoretical development should formalise a Resource-Sensitive Model of Contextual Learning that predicts how CBCI's effectiveness varies with class size, laboratory access, and teacher training intensity. Practically, the following pathways are recommended for future research and curriculum design. First, longitudinal studies should track CHOTPT scores six months and one year post-intervention to establish durability of higher-order gains. Second, replication studies in urban, industrialised Nigerian states (e.g., Lagos, Rivers) would test whether the effect size is moderated by infrastructural availability. Third, researchers should disaggregate the structured response component of the CHOTPT to measure analysing, evaluating, and creating separately, clarifying which tier receives the strongest boost from CBCI. Fourth, teacher professional development programmes across sub-Saharan Africa should be redesigned to centre on local sustainability case studies, with less emphasis on digital tools that are frequently non-functional. Finally, a comparative study between low-tech CBCI and technology-enhanced CBCI in well-resourced schools would resolve whether digital tools add value beyond what contextual narrative alone provides. Addressing these directions will transform chemistry education from a discipline perceived as abstract and irrelevant into a cornerstone of sustainability competence, directly serving the United Nations Sustainable Development Goals.

Conclusion

The central problem addressed by this study is the persistent disconnect between the recognised importance of chemistry for sustainable development and the routine pedagogical methods that treat chemical knowledge as a collection of abstract, decontextualised algorithms. The empirical findings provide a clear resolution. First, baseline equivalence between the experimental and control groups was confirmed (pre-test *p* = 0.110, Cohen’s *d* = 0.29), ruling out prior knowledge as a confounding variable. Second, exposure to Context-Based Chemistry Instruction (CBCI) produced a mean gain of 8.07 points on the Chemistry Higher-Order Thinking Performance Test (CHOTPT), more than double the control group’s gain of 3.22 points. The effect size for this progression from lower-order recall to higher-order processing was very large (Cohen’s *d* = 1.79). Third, the capacity to synthesise chemically sound, actionable solutions to local sustainable development challenges, measured through structured response questions, showed a statistically significant advantage for the CBCI group (mean difference = 5.60, *p* < 0.001, Cohen’s *d* = 1.73). These three empirical anchors collectively demonstrate that when chemistry instruction is situated within authentic environmental narratives, students do not merely remember more content; they reorganise their cognitive architecture toward analysis, evaluation, and creation as defined by Bloom’s Revised Taxonomy.

Implications of the Study

The findings refine the application of Situated Learning Theory in resource-constrained environments. Lave and Wenger's original framework assumed that authentic contexts naturally emerge from communities of practice, but the present study shows that in formal schooling, contexts must be *deliberately designed* using locally available environmental problems. The semi-arid conditions of Sokoto State provided water quality and desertification case studies that required no laboratory infrastructure beyond basic glassware. This challenges the assumption that situated learning depends on rich technological or industrial settings. Cognitive Load Theory is also extended by the evidence that reducing extraneous load through contextual narrative directly increases germane load available for synthesis and evaluation. In settings where textbooks are dense and teacher explanations are often expository, CBCI offers a low-cost mechanism for cognitive load optimisation. Finally, Bloom's Revised Taxonomy, typically used as a classification tool, here functions as a diagnostic for instructional design. The data show that traditional methods improve lower tiers (analysis) but fail to scaffold creation. Therefore, any theory of cognitive development in chemistry education must specify which instructional contexts activate which taxonomic levels.

For classroom practice, educators should replace decontextualised algorithmic drills with weekly case studies drawn from local environmental challenges. Each case must require students to: (a) analyse a chemical problem (e.g., contamination of well water with heavy metals), (b) evaluate competing remediation strategies (e.g., precipitation versus ion exchange), and (c) create a feasible action plan justified by chemical laws. This sequence directly mirrors the CHOTPT structure. For curriculum developers, the official chemistry syllabus for senior secondary schools should integrate sustainability narratives into every major topic: oxidation-reduction taught through corrosion in water infrastructure, electrolysis through metal recovery from electronic waste, hydrocarbons through bioplastics from agricultural residue. These integrations must be mandatory, not optional enrichment. For teacher training institutions, pre-service and in-service programmes must shift from content delivery to facilitation of context-based inquiry. Teachers need practice in eliciting student-generated solutions rather than confirming yes-no answers. The absence of digital technology in many sub-Saharan African classrooms is not a barrier; the present study achieved very large effects with printed scenarios and low-cost demonstrations. Professional development should therefore prioritise narrative construction and questioning techniques over digital literacy.

Limitations of the Research

The conclusions must be interpreted within specific methodological and contextual boundaries. First, geographical and sample specificity limits broad generalisability. The study was conducted exclusively in public co-educational schools in Sokoto State, a semi-arid region with distinct environmental pressures. Students in humid tropical zones, industrial urban centres, or private schools with different resource profiles might show different response patterns to CBCI. Second, the reliance on a single performance test (CHOTPT) as the primary quantitative measure, while validated, cannot capture the full spectrum of higher-order thinking that may manifest in collaborative problem-solving or extended project work. The test was administered immediately after the 12-week intervention; therefore, the durability of cognitive gains beyond the immediate post-test period remains unexamined. Third, the cross-sectional design, comparing pre-test and post-test within a fixed 12-week window, captures a snapshot of cognitive change but cannot establish the long-term trajectory of skill retention or the point at which gains plateau. Without delayed post-testing, claims about permanent cognitive reorganisation are provisional. Fourth, the reduction from the intended sample of 160 students per group to 60 per group in the available dataset reduces statistical power and may inflate effect size estimates. Fifth, the study did not collect data on gender, prior academic achievement, or socioeconomic status, precluding moderation analyses that would reveal whether CBCI benefits all students equally or interacts with existing disparities. Sixth, while the 12-week duration mitigated novelty effects, the Hawthorne effect cannot be entirely ruled out; experimental group teachers received intensive training and may have unconsciously projected enthusiasm that influenced student performance independently of the instructional method itself. These limitations do not invalidate the findings but specify the interpretive boundaries: the study provides strong evidence for the efficacy of CBCI within the tested conditions, but generalisation to other populations, longer time horizons, and unmeasured moderators requires replication and extension.

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