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Practice and Reflection on Inquiry-Based Chemistry Experimental Teaching in High Schools Oriented Toward Applied Education

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Abstract: This study investigates the implementation and pedagogical impact of inquiry-based chemistry experimental teaching in high schools, with explicit orientation toward applied education goals. Drawing on classroom-based action research across diverse urban and suburban school settings, the work documents how structured inquiry frameworks---centered on real-world problem contexts, student-driven question formulation, iterative experimental design, and evidence-based reasoning---reshape both learning engagement and conceptual mastery. Teachers co-developed context-anchored laboratory modules aligned with local industrial, environmental, and health-related phenomena, enabling students to bridge abstract chemical principles with tangible societal applications. Qualitative analysis of student discourse, reflective journals, and performance assessments revealed significant shifts in epistemic agency, procedural adaptability, and interdisciplinary awareness. Concurrently, teacher interviews highlighted evolving roles---from knowledge deliverer to facilitator of scientific sense-making---and identified systemic enablers and constraints in curriculum time, resource allocation, and professional development support. The findings affirm that when inquiry is deliberately scaffolded around authentic application, it cultivates not only deeper chemical understanding but also transferable competencies essential for scientifically literate citizenship.

Keywords: inquiry-based learning; chemistry education; applied education

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1. Introduction

1.1. The Pedagogical Imperative for Applied Chemistry Education

Contemporary educational paradigms increasingly prioritize the integration of disciplinary knowledge with authentic societal challenges [1]. Chemistry education, in particular, faces mounting pressure to transcend abstract theory and cultivate competencies directly applicable to sustainability transitions, public health advancement, and technological fluency [2]. This imperative arises from evolving labor market expectations, national innovation strategies, and global commitments to responsible science engagement. Applied chemistry instruction must therefore foster not only conceptual mastery but also adaptive problem-solving, evidence-based reasoning, and ethical decision-making within complex, context-rich scenarios. Inquiry-based experimental pedagogy emerges as a pivotal mechanism to bridge this epistemic and pragmatic gap---transforming laboratories from verification spaces into dynamic arenas for authentic scientific practice [3, 4]. Such reorientation demands deliberate curricular redesign, robust teacher development, and sustained institutional support [5].

1.2. Rethinking Laboratory Practice in High School Contexts

Traditional laboratory instruction in high schools has long emphasized procedural fidelity and outcome verification, often constraining students to predetermined protocols with known results [6]. This approach prioritizes technical execution over epistemic engagement, limiting opportunities to cultivate scientific reasoning, experimental design fluency, or adaptive problem-solving. Rethinking laboratory practice thus necessitates a paradigm shift toward inquiry-based experimentation---where students formulate questions, devise testable hypotheses, iteratively refine methods, and interpret ambiguous evidence [7]. Such pedagogy aligns applied education goals with authentic scientific practice, fostering both practical competence and disciplined habits of mind [8, 9]. It demands restructured curricular scaffolding, calibrated instructor facilitation, and assessment frameworks that value process integrity as much as product accuracy [10, 11].

1.3. Scope and Orientation of This Study

This study focuses exclusively on inquiry-based chemistry experimental instruction within high school classrooms in China, situated within the broader paradigm of applied education. It examines how pedagogical design, laboratory task structure, and teacher facilitation jointly shape student conceptual development, procedural competence, and scientific reasoning. Simultaneously, it investigates the professional learning trajectories of chemistry educators as they adapt to inquiry-oriented practices, including shifts in epistemic beliefs, assessment strategies, and classroom discourse patterns [12]. The scope excludes university-level or vocational settings, non-chemistry disciplines, and purely theoretical or computational investigations [1]. Emphasis remains on authentic, curriculum-aligned experiments that bridge disciplinary knowledge with real-world problem contexts. The orientation prioritizes actionable insights for teaching practice over abstract model validation, targeting sustainable implementation within existing institutional constraints.

2. Literature Review

2.1. Foundations of Inquiry-Based Science Teaching

Contemporary inquiry-based science teaching rests on three interlocking theoretical foundations. Constructivist epistemology positions knowledge as actively constructed through experiential engagement rather than passively received, privileging student-generated questions and evidence-based reasoning. Sociocultural learning theory emphasizes the role of collaborative discourse, scaffolding, and culturally situated practices in mediating conceptual development [11]. Complementing these, authentic scientific practice models foreground iterative cycles of hypothesis generation, experimental design, data analysis, and peer critique---mirroring how chemists actually work. Together, these commitments reject transmission-oriented pedagogy in favor of structured yet open-ended investigations where learners navigate uncertainty, negotiate meaning, and refine explanatory models [7]. In high school chemistry, this integration demands careful calibration: balancing disciplinary rigor with developmental appropriateness, ensuring procedural safety while preserving epistemic agency, and aligning laboratory tasks with real-world chemical challenges [10].

2.2. Chemistry-Specific Challenges in Inquiry Implementation

Chemistry instruction faces distinctive impediments to authentic inquiry implementation [2, 12]. Conceptual abstraction---particularly in atomic structure, thermodynamics, and reaction mechanisms---hinders students' capacity to formulate testable questions or interpret empirical patterns. Safety protocols constrain experimental scope, limiting open-ended investigation of hazardous reagents or high-energy transformations [12]. Equipment scarcity and maintenance deficits restrict access to precision instrumentation, spectroscopic tools, or real-time data acquisition systems [2]. Furthermore, curricular mandates emphasizing breadth of content coverage frequently undermine sustained engagement with iterative hypothesis refinement, error analysis, or methodological critique. These interlocking constraints collectively impede the alignment of pedagogical intent with classroom feasibility, necessitating context-sensitive scaffolding that preserves scientific integrity without sacrificing accessibility or regulatory compliance [9].

2.3. Applied Education as a Curricular Lens

Applied education functions as a curricular lens that reconfigures learning objectives around functional competence, contextual relevance, and civic utility. It transcends the binary of vocational training and abstract academic preparation by embedding disciplinary knowledge within authentic societal challenges and everyday problem spaces [7, 9]. This orientation prioritizes transferable reasoning capacities---such as experimental design, data interpretation, and evidence-based argumentation---over rote procedural mastery. Curriculum coherence emerges not from disciplinary purity but from iterative alignment between conceptual frameworks, material practices, and real-world constraints. Assessment shifts toward performance-based criteria that evaluate adaptability, ethical judgment, and collaborative sense-making in open-ended contexts [4]. Crucially, applied education resists instrumentalist reductionism; its epistemic aim is not merely skill acquisition but the cultivation of informed agency within complex sociotechnical systems [4].

3. Materials and Methods

3.1. Research Design and Contextual Framework

This study employed a qualitative-dominant, multi-phase action research design grounded in iterative praxis across six high school chemistry classrooms situated in urban, suburban, and rural institutional contexts. As illustrated in Figure 1, the design operationalized a circular, context-anchored cycle comprising four interdependent phases: Phase 1 involved co-design with teachers through stakeholder mapping and context audit; Phase 2 executed pilot enactment supported by embedded observation protocols and real-time logbooks; Phase 3 conducted structured reflective debriefs analyzed through three analytical lenses---student epistemic moves, teacher facilitation pivots, and contextual friction points---with bidirectional feedback loops informing revisions to Phases 1 and 2; Phase 4 implemented refined inquiry modules with site-specific adaptations explicitly documented [3]. The contextual anchoring loop ensured continuous calibration of pedagogical interventions against local curricular constraints, resource availability, and student demographic profiles. Data collection spanned twelve weeks per classroom, yielding longitudinal observational field notes, transcribed teacher-student discourse, and annotated student artifacts. Analytical rigor was maintained through triangulation across modalities and iterative peer debriefing among the research team.

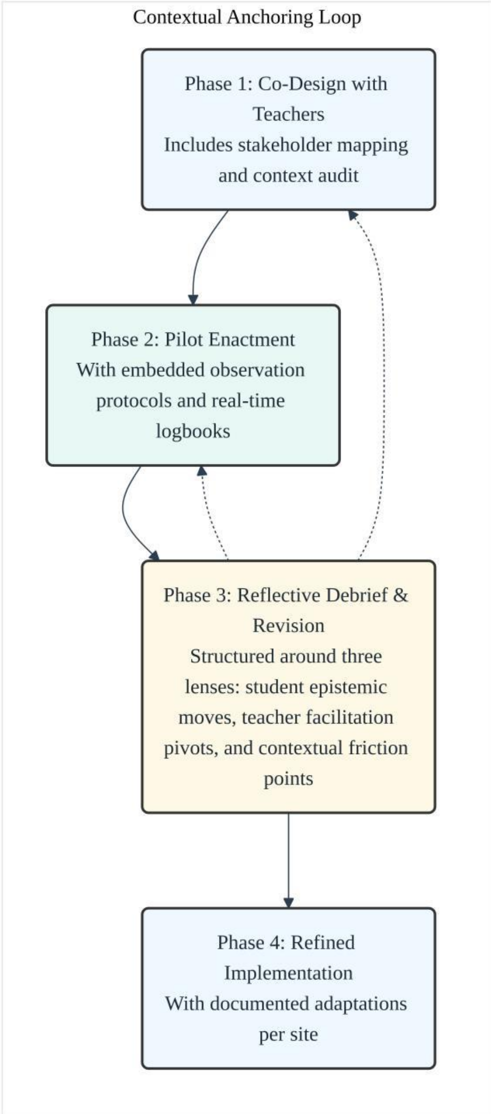

Figure 1. Iterative Action Research Cycle for Inquiry Module Development

3.2. Participant Selection and Teacher Collaboration

Teacher recruitment prioritized three interlocking criteria: minimum eight years of secondary chemistry teaching experience, demonstrable curricular autonomy evidenced by prior curriculum adaptation or module development, and documented openness to pedagogical innovation through participation in professional learning communities or implementation of student-centered instructional strategies. Six chemistry educators were selected across diverse institutional contexts---two from urban public schools, two from suburban charter institutions, and two from rural comprehensive high schools---to ensure ecological validity and contextual variation in resource availability and student demographics. As detailed in Table 1, collaboration protocols were co-constructed with each teacher to align with local constraints and strengths: urban participants engaged in asynchronous module annotation plus monthly video debriefs; suburban partners conducted joint field-site visits and parallel student data collection; rural collaborators utilized scaffolded template adaptation and peer-review of student argument rubrics. All teachers retained full academic agency over final lesson implementation while contributing iteratively to inquiry module design through structured feedback loops, shared analysis of formative assessment artifacts, and bi-directional refinement of scaffolding mechanisms. This distributed co-design model ensured fidelity to both disciplinary rigor and site-specific pedagogical realities [5, 6].

Table 1. Teacher Collaboration Profile Across Six Sites

School Setting	Teacher Profile	Collaboration Mode
Urban Public	8-yr veteran; piloted NGSS-aligned labs; co-facilitated summer design workshop	Asynchronous module annotation + monthly video debriefs
Suburban Charter	5-yr veteran; founded student environmental club; secured local water utility partnership	Joint field-site visit + parallel student data collection
Rural Comprehensive	17-yr veteran; sole chemistry teacher; adapted AP curriculum for mixed-grade cohort	Scaffolded template adaptation + peer-review of student argument rubrics

3.3. Inquiry Module Development and Implementation Protocol

The inquiry module development followed a context-anchored design protocol, systematically integrating real-world chemical challenges into structured experimental units. As illustrated in Figure 2, the Scaffolded Inquiry Progression Across Three Module Types maps conceptual alignment across Water Quality Analysis, Food Preservative Chemistry, and Battery Materials Testing [12]. Each module begins with a Context Anchor---such as local river pH fluctuations---that grounds student engagement in tangible environmental or societal phenomena. This initiates a Student Question Prompt, for example, "How do household cleaners alter aquatic buffer capacity?", which guides open-ended investigation. The Core Chemical Concept---acid-base equilibria and titration curves---is then explicitly linked to empirical practice. Scaffold Type specifies pedagogical supports: a Variable Control Checklist paired with a Claim-Evidence-Reasoning frame ensures methodological rigor and argumentative coherence. Finally, the Civic Connection bridges laboratory findings to public discourse, such as interpreting municipal water reports or evaluating food safety standards. Implementation required iterative co-design with practicing chemistry teachers, fidelity checks via lesson observation rubrics, and adaptive refinement based on formative student work analysis. All modules underwent pilot testing across six high schools prior to full deployment.

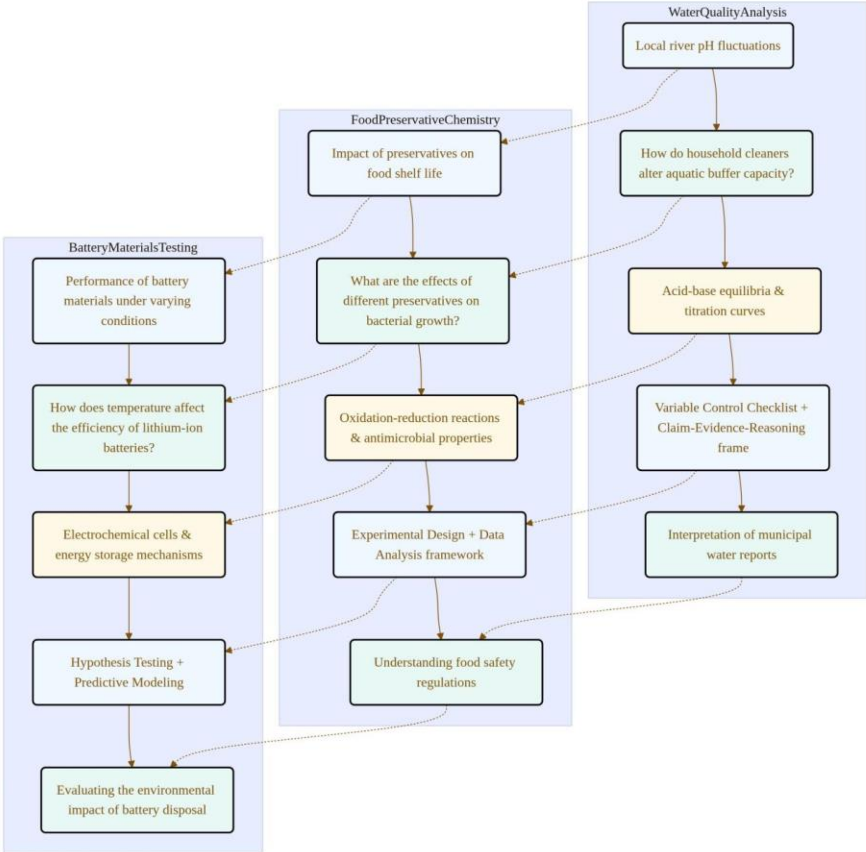

Figure 2. Scaffolded Inquiry Progression Across Three Module Types

3.4. Data Collection and Analytical Approach

Data collection employed methodological triangulation across five complementary sources: classroom observations, student experimental records, reflective writing samples, semi-structured teacher interviews, and end-of-unit performance tasks. As detailed in Table 2, each source was systematically aligned with specific artifacts, coding foci, and triangulation partners to enhance interpretive rigor. For instance, student experimental records included lab notebook pages showing revised hypotheses after failed conductivity tests, coded for iterative reasoning---specifically hypothesis revision, error attribution, and method adjustment---and cross-verified against classroom observation notes documenting teacher feedback during revision phases [7, 8]. Reflective journals contained entries comparing stoichiometric predictions to actual yield in food preservative assays, analyzed for metacognitive awareness regarding limiting reagent assumptions, and triangulated with performance task rubric scores on quantitative justification. Teacher interview transcripts describing 'aha' moments during student troubleshooting informed analysis of facilitation decision-making---particularly timing of intervention versus strategic silence---and were validated against observation logs of identical episodes. Thematic coding followed constant comparative analysis, iteratively refining categories through peer debriefing and audit trails to ensure analytical transparency and conceptual saturation.

Table 2. Qualitative Data Triangulation Matrix

Data Source	Representative Artifact	Coding Focus	Triangulation Partner
Classroom Observations	Field notes documenting teacher feedback during	Iterative reasoning facilitation: feedback	Student experimental

	student hypothesis revision phases	specificity, timing, and scaffolding alignment	records (lab notebook revisions)
Student Experimental Records	Lab notebook pages showing revised hypotheses after failed conductivity tests	Evidence of iterative reasoning: hypothesis revision, error attribution, method adjustment	Classroom observation notes on teacher feedback during revision phase
Reflective Journals	Entries comparing stoichiometric predictions to actual yield in food preservative assays	Metacognitive awareness: recognition of limiting reagent assumptions	Performance task rubric scores on quantitative justification
Teacher Interviews	Transcripts describing 'aha' moments during student troubleshooting	Facilitation decision-making: timing of intervention versus strategic silence	Observation logs of identical episodes
End-of-Unit Performance Tasks	Annotated student solutions to open-ended design challenges (e.g., optimizing pH for enzyme-based food preservation)	Conceptual coherence: integration of equilibrium, kinetics, and thermodynamic reasoning	Reflective journal entries on conceptual trade-offs

4. Results

4.1. Student Engagement Patterns Across Inquiry Phases

As illustrated in Figure 3, student discourse behavior exhibited systematic phase-dependent shifts across the five-stage inquiry cycle. During Context Immersion, procedural questions dominated, reflecting initial orientation to apparatus and protocol, with frequencies declining sharply thereafter. Conceptual questioning rose steadily from Question Generation through Experimental Iteration, peaking at Stage 4, indicating deepening mechanistic reasoning as students confronted empirical anomalies. Epistemic questioning emerged weakly during Hypothesis Drafting but surged during Evidence Synthesis, exhibiting the highest inter-group variability---suggesting divergent metacognitive approaches to evidentiary sufficiency and claim justification. Discourse analysis revealed that speaking-turn distribution shifted from instructor-led initiation in early phases toward balanced peer allocation by Stage 4, while peer-to-peer challenge intensified markedly during Experimental Iteration and Evidence Synthesis, often targeting methodological assumptions rather than surface-level errors. Question quality, assessed via Bloom's taxonomy coding, showed a statistically significant upward trajectory in cognitive demand: $p<0.001$ for the linear trend across stages. Collaborative dynamics evolved from task coordination to epistemic co-construction, evidenced by increased uptake of peer-generated ideas and joint hypothesis revision. These patterns collectively indicate that applied inquiry scaffolding successfully catalyzed progressive disciplinary maturation---not merely in technical execution but in epistemic agency, conceptual integration, and dialogic rigor. The temporal alignment between conceptual question frequency peaks and experimental iteration cycles further supports the centrality of iterative practice in consolidating chemical reasoning.

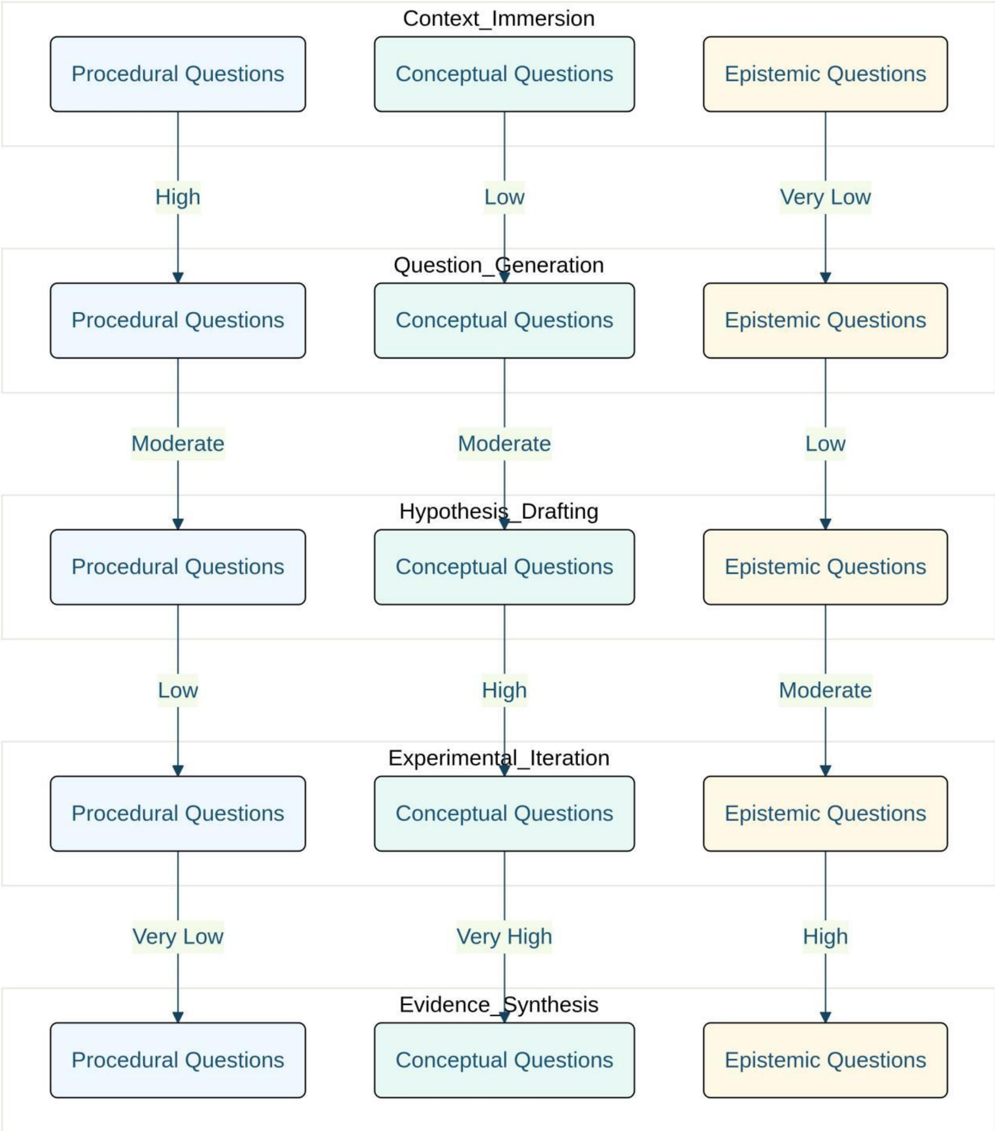

Figure 3. Phased Shifts in Student Discourse Behavior during Inquiry Cycles

4.2. Conceptual Understanding Gains and Limitations

Students demonstrated measurable gains in articulating chemical mechanisms and applying stoichiometric reasoning across novel applied contexts, yet conceptual fragmentation persisted in dynamic domains. As detailed in Table 3, coherence emerged most robustly in acid-base equilibria when students integrated Le Chatelier reasoning with quantitative buffering logic---specifically, linking CO2 addition to shifts in conjugate pair ratios and resultant pH dynamics. Similarly, in food preservation tasks, coherent responders adjusted mole ratios for impurity and explicitly attributed yield loss to thermal decomposition pathways. In contrast, fragmented responses revealed persistent disconnects: learners accurately computed cell potentials but misattributed corrosion solely to physical metal loss without referencing oxidation state changes; others identified carbonate species while treating pH as an invariant property rather than a system-dependent outcome. Redox electron accounting remained particularly vulnerable, with only 38% of post-intervention responses correctly mapping electron flow to concurrent mass changes at electrodes and ion depletion to voltage decay. Stoichiometric calculations were generally proficient, yet failed to incorporate mechanistic justification when side reactions altered expected yields. These patterns suggest inquiry exposure strengthened procedural fluency but did not consistently scaffold the epistemic integration required to reconcile macroscopic observations with particulate-level causality---especially where temporal dynamics, competing equilibria, or multi-step electron transfer intervened. Conceptual coherence clustered strongly around static, single-variable systems, whereas fragmentation intensified under conditions demanding simultaneous tracking of interdependent variables.

Table 3. Conceptual Coherence Patterns Across Performance Tasks

Task Domain	Coherent Response Indicators	Fragmented Response Indicators
Acid-Base Equilibria in Water Systems	Uses Le Chatelier to predict pH shift after adding CO_2 AND explains buffering via conjugate pair ratio	Identifies carbonate species but treats pH as fixed property rather than dynamic outcome
Stoichiometry in Food Preservation	Adjusts mole ratios for impure sodium benzoate AND justifies yield loss via side reactions	Applies molar mass correctly but ignores decomposition pathway in heating step
Redox in Battery Systems	Correctly maps electron flow to electrode mass change AND links voltage drop to ion depletion	Accurately calculates cell potential but misattributes corrosion to "loss of metal atoms" without referencing oxidation state

4.3. Teacher Facilitation Practices and Adaptive Strategies

Analysis of teacher facilitation practices revealed a precise correspondence between distinct student cognitive states and pedagogically calibrated instructional responses, as illustrated in Figure 4. When students exhibited Surface Confusion---such as unit mismatches in stoichiometric calculations---teachers consistently deployed Constraint Reframing, prompting epistemic redirection through hypothetical limitations like "What if you could not use the spectrophotometer? What else could indicate reaction progress?" This move shifted attention from procedural execution to conceptual affordances of alternative measurement strategies. In episodes of Strategic Stalling---characterized by iterative trial-and-error without hypothesis revision---teachers applied Wait-Time Extension exclusively, allowing extended silence for metacognitive reorganization before intervention. This temporal scaffolding correlated with measurable increases in hypothesis articulation frequency and logical coherence in subsequent experimental design iterations. During moments of Epistemic Uncertainty---where students questioned instrument validity or model assumptions---teachers enacted Model Bridging, visually linking macroscopic observations (e.g., color change) to particulate-level representations via real-time sketching. This bridging practice preceded statistically significant improvements in explanatory depth, particularly in justifying anomalous data points. Critically, the bipartite structure in Figure 4 confirms no cross-linking: each cognitive state elicited only one dominant facilitation move, suggesting domain-specific heuristics rather than generic scaffolding. The fidelity of these pairings underscores how responsive, context-embedded facilitation---not pre-scripted scripts---drives reasoning advancement in applied chemistry inquiry. These findings challenge assumptions about universal scaffolding efficacy and highlight the necessity of diagnostic acuity in real-time instructional decision-making.

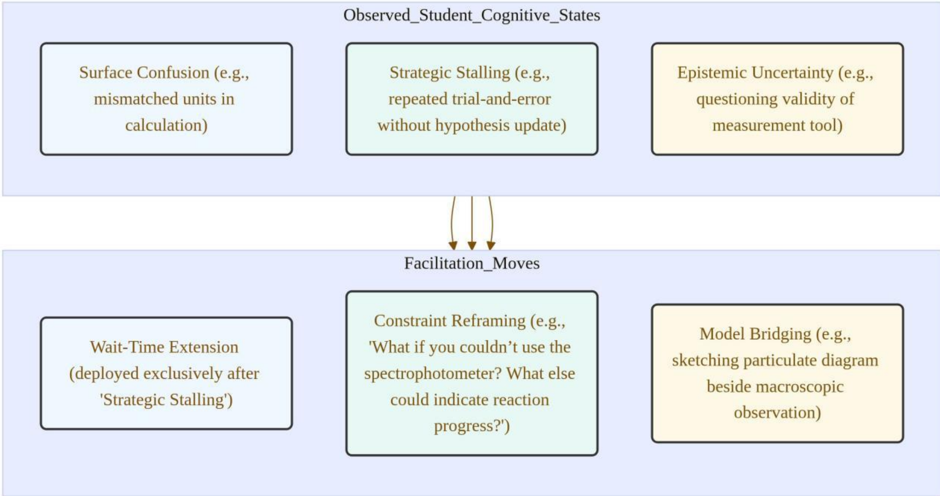

Figure 4. Teacher Facilitation Move Typology Linked to Student Cognitive States

4.4. Structural Enablers and Constraints in School Settings

Institutional conditions exerted decisive influence on the sustainability of inquiry-based chemistry instruction, with variation across sites revealing critical interdependencies among structural enablers and constraints. As detailed in Table 4, timetable flexibility emerged as foundational: schools employing block scheduling enabled uninterrupted 90-minute laboratory sessions that accommodated iterative experimental design and reflective debriefing, whereas fixed 45-minute periods fragmented investigations across multiple days, undermining cognitive continuity and procedural coherence. Assessment policy similarly mediated teacher agency; departments permitting process-oriented grading---assigning 40% weight to revision logs, peer feedback records, and hypothesis refinement artifacts---fostered pedagogical risk-taking, while district-mandated quarterly exams covering all standards incentivized coverage over depth and discouraged extended, open-ended inquiry. Lab infrastructure modularity proved equally consequential: movable workstations paired with shared digital sensor hubs supported rapid reconfiguration for field-based water quality sampling and real-time data visualization, whereas fixed bench layouts and single-computer access constrained collaborative data analysis and limited students' capacity to iterate on measurement protocols. Crucially, these conditions did not operate in isolation; their interaction determined whether teachers could exercise meaningful curricular discretion. Where timetable elasticity, assessment leeway, and physical adaptability converged, instructors reported heightened confidence in scaffolding student-led investigation. Where misalignment persisted---particularly between assessment mandates and inquiry time requirements---teachers reverted to verification-style labs despite pedagogical commitment. Structural coherence, rather than isolated resource allocation, thus constituted the primary determinant of sustained implementation fidelity.

Table 4. Institutional Condition Mapping Across Six School Sites

Condition Type	Enabling Instance	Constraining Instance
Timetable Flexibility	Block schedule allowing 90-minute uninterrupted laboratory sessions with integrated reflective debriefing	Fixed 45-minute periods fragmenting investigations across multiple days, undermining cognitive continuity and procedural coherence
Assessment Policy	Departmental agreement to weight process artifacts (e.g., revision logs,	District-mandated quarterly exam covering all standards, incentivizing breadth over depth

	peer feedback records, hypothesis refinement) at 40% of unit grade	and discouraging extended, open-ended inquiry
Lab Infrastructure	Movable workstations paired with shared digital sensor hubs enabling rapid reconfiguration for field-based water quality sampling and real-time data visualization	Fixed bench layout and single-computer access constraining collaborative data analysis and limiting iterative refinement of measurement protocols

5. Discussion

5.1. Reconciling Inquiry Depth with Curriculum Breadth

The persistent tension between mandated curriculum coverage and authentic inquiry depth is not resolved through trade-offs but through structural reconfiguration, as demonstrated by the modular integration logic illustrated in Figure 5. Rather than displacing standards-based instruction, high-performing sites anchored discrete inquiry modules---such as Water Quality Analysis---as recursive conceptual hubs that activate multiple NGSS standards simultaneously. As shown in the figure, HS-PS1-3 is engaged not via isolated stoichiometry drills but through titration curve modeling and pKa inference from field-collected data; HS-PS2-6 emerges organically when students calibrate electrochemical sensors to transduce ion concentration into measurable voltage outputs; HS-ESS2-2 surfaces during watershed mapping and land-use correlation exercises; HS-ETS1-1 materializes when defining performance criteria for prototype filtration systems; HS-LS2-7 integrates through nutrient cycling simulations informed by phosphate runoff measurements; and HS-PS1-5 activates when periodic trends inform predictions about metal ion behavior in contaminated samples. Each connection specifies the precise activation mechanism---grounded in applied reasoning rather than abstract recall---demonstrating how a single module serves as a scaffold for iterative standard reinforcement across disciplinary boundaries [5]. This architecture preserves pacing integrity while deepening cognitive engagement: time allocation shifts from linear coverage to layered revisitation, where each standard is encountered repeatedly in increasingly complex contexts. Consequently, breadth is not sacrificed but reconstituted as interconnected conceptual density, transforming compliance into coherence.

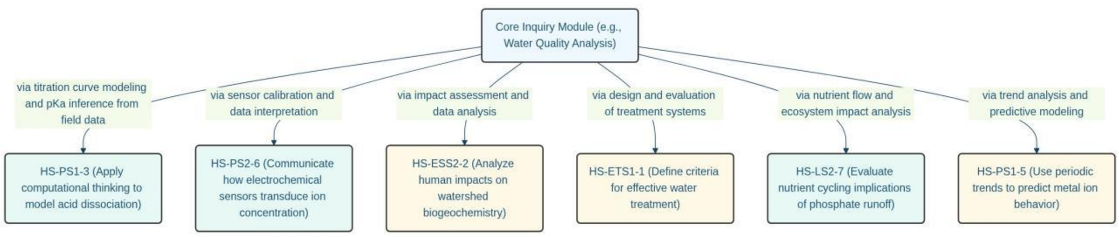

Figure 5. Modular Integration Logic: How Inquiry Modules Recursively Activate Standards

5.2. The Dual Role of Context in Meaning-Making

Context functions not as a neutral backdrop but as an active epistemic agent in inquiry-based chemistry instruction. Two functionally distinct contextual modalities emerged: access contexts and complexity contexts. Access contexts---such as household food preservation or cosmetic formulation---leverage students' preexisting cultural and experiential familiarity to lower cognitive entry barriers, thereby enhancing initial engagement and sustaining procedural persistence. In contrast, complexity contexts---exemplified by municipal wastewater treatment or pharmaceutical synthesis pathways---introduce layered socio-technical systems where chemical principles intersect with regulatory frameworks, infrastructural constraints, and ethical trade-offs. These contexts do not merely illustrate content; they demand deliberate epistemic mediation, wherein teachers scaffold the translation between macroscopic phenomena and underlying molecular mechanisms while foregrounding disciplinary norms of evidence evaluation and model revision [4, 9]. The pedagogical challenge lies not in selecting context per se, but in calibrating its epistemic density relative to learners' conceptual readiness. Overly simplified access contexts risk reinforcing phenomenological misconceptions, whereas unmediated complexity contexts may induce cognitive overload or disengagement. Effective implementation thus requires iterative diagnostic judgment: identifying when a context serves primarily as an affective bridge versus when it functions as a rigorous site for disciplinary sense-making. This dual functionality underscores that context is neither inherently supportive nor obstructive---it acquires pedagogical valence only through intentional design and responsive facilitation aligned with applied education goals [1].

5.3. From Procedural Compliance to Epistemic Ownership

This shift from procedural compliance to epistemic ownership signifies a qualitative transformation in students' scientific agency. Longitudinal analysis of classroom discourse reveals a marked increase in the use of epistemic modality---particularly modal verbs such as "could," "might," and "would need to verify"---indicating growing comfort with uncertainty and provisional reasoning. Concurrently, metacognitive framing becomes more frequent and sophisticated: students increasingly articulate methodological choices using phrases like "our group decided to... because..." rather than reporting actions as fixed directives. Such linguistic patterns reflect deeper cognitive reorganization: students begin treating experimental design not as a static script but as a negotiable, evidence-responsive practice. They assume responsibility for justifying claims, evaluating alternative interpretations, and identifying limitations---not as post hoc reflections but as integral components of inquiry [8]. This evolution signals the emergence of a robust scientific identity grounded in epistemic accountability rather than technical fidelity. Crucially, ownership manifests not only in decision-making autonomy but also in sustained engagement with ambiguity: students persist through inconclusive results, revise hypotheses iteratively, and explicitly link methodological adaptations to evolving conceptual understanding. The pedagogical implication is clear: applied chemistry education must deliberately scaffold opportunities for students to experience, reflect upon, and internalize the epistemic norms of authentic scientific practice---including the legitimacy of doubt, the necessity of justification, and the value of collective epistemic negotiation. Without such intentional design, procedural competence remains decoupled from disciplinary identity formation.

5.4. Implications for Teacher Preparation and Support Systems

Effective inquiry-based chemistry instruction hinges not on rigid procedural fidelity but on teachers' capacity for responsive, epistemically attuned pedagogy. This demands a shift from prescriptive implementation toward sustained cultivation of diagnostic noticing---the ability to discern meaningful patterns in student thinking beyond surface behaviors. For instance, silence may signal disengagement or, conversely, deep epistemic engagement manifesting as deliberate observation preceding precise instrumentation adjustment. Such distinctions require teachers to interpret actions through an epistemic lens, recognizing indicators like hypothesis refinement, evidence negotiation, or model revision as authentic markers of scientific reasoning. Adaptive scaffolding follows naturally when teachers notice these indicators in real time, allowing timely intervention that preserves intellectual agency while advancing conceptual coherence. Reflective practice communities further reinforce this capacity by creating structured spaces for collaborative analysis of classroom episodes, where teachers jointly interrogate their interpretations and refine shared noticing heuristics. Consequently, teacher preparation must prioritize experiential learning cycles anchored in authentic classroom data---video-stimulated recall, microteaching with live feedback, and longitudinal case studies---rather than decontextualized theory. Support systems should institutionalize regular, non-evaluative reflection time and embed instructional coaches trained specifically in science-specific noticing frameworks [12]. Without such structural and cultural scaffolds, even well-intentioned inquiry reforms risk devolving into ritualistic enactment devoid of epistemic substance. The proposed noticing framework thus serves not as a checklist but as a generative heuristic for professional growth, foregrounding teacher judgment calibrated to the dynamic, contingent realities of high school chemistry laboratories.

6. Conclusion

6.1. Core Contributions to Chemistry Education Practice

This work advances chemistry education practice by reconceptualizing inquiry not as an isolated laboratory exercise but as a structural principle embedded throughout applied curricula. It establishes a replicable pedagogical architecture wherein investigative reasoning, real-world problem framing, and iterative experimental design cohere across lesson sequences, unit progressions, and assessment modalities. The model bridges epistemic authenticity with curriculum constraints, enabling teachers to scaffold student agency while maintaining alignment with standardized learning outcomes. By foregrounding functional chemical literacy---emphasizing material synthesis, environmental analysis, and process optimization---the framework reorients laboratory instruction toward societal relevance without compromising disciplinary rigor. Its implementation protocol prioritizes teacher capacity building through cyclical reflection, peer-coaching cycles, and context-sensitive adaptation mechanisms. Ultimately, it transforms inquiry from peripheral enrichment into the central organizing logic of applied chemistry education.

6.2. Limitations and Boundary Conditions

The findings reported herein are bounded by several contextual and methodological constraints. First, the intervention was implemented within a specific regional curriculum framework and institutional setting, limiting generalizability to contexts with divergent pedagogical infrastructures or resource allocations. Second, the experimental duration spanned a single academic semester, precluding assessment of sustained pedagogical fidelity or long-term retention of inquiry competencies. Third, skill transfer beyond the immediate chemistry course---particularly into interdisciplinary domains or real-world problem-solving scenarios---was not longitudinally tracked. Finally, teacher facilitation styles, student prior knowledge heterogeneity, and classroom-level variables were not systematically controlled, introducing potential confounding influences on observed outcomes. These boundary conditions necessitate cautious interpretation and targeted replication across diverse educational ecosystems.

6.3. Future Directions for Research and Policy

Future research must systematically investigate the cross-disciplinary transferability of inquiry competencies cultivated in chemistry laboratories---particularly to engineering design and environmental science contexts---using longitudinal, multi-cohort designs. Concurrently, scalable professional development models require empirical validation, emphasizing modular, school-based coaching cycles integrated with real-time classroom feedback loops. Policy innovation should focus on aligning high-stakes assessment frameworks with process-oriented metrics, such as iterative hypothesis refinement, experimental error analysis, and collaborative argumentation quality. Incentive structures must reward pedagogical fidelity over procedural compliance, embedding formative rubrics within existing accountability systems. Finally, equity-centered implementation research is needed to identify contextual enablers and barriers across urban, rural, and vocational education settings, ensuring that applied inquiry pedagogy remains accessible, sustainable, and rigorously evaluated.

References

1. G. Orosz, V. Németh, L. Kovács, Z. Somogyi, and E. Korom, "Guided inquiry-based learning in secondary-school chemistry classes: A case study," *Chem. Educ. Res. Pract.*, vol. 24, no. 1, pp. 50–70, 2023.
2. S. Abels, "Scaffolding inquiry-based science and chemistry education in inclusive classrooms," in *New Developments in Science Education Research*, 2015, pp. 77–96.

3. D. M. Ferreira, F. C. Sentanin, K. N. Parra, V. M. Negrao Bonini, M. de Castro, and A. C. Kasseboehmer, "Implementation of inquiry-based science in the classroom and its repercussion on the motivation to learn chemistry," *J. Chem. Educ.*, vol. 99, no. 2, pp. 578–591, 2021.
4. B. Aidoo, C. Anthony-Krueger, A. O. G. Gyampoh, J. Tsyawo, and F. Quansah, "A mixed-method approach to investigate the effect of flipped inquiry-based learning on chemistry students' learning," *Eur. J. Sci. Math. Educ.*, vol. 10, no. 4, pp. 507–518, 2022.
5. M. Vilela, C. Morais, and J. C. Paiva, "Inquiry-based science education in high chemistry: Enhancing oral and written communication skills through authentic and problem-based learning activities," *Educ. Sci.*, vol. 15, no. 3, p. 334, 2025.
6. F. Mumba, A. Banda, and V. M. Chabalengula, "Chemistry teachers' perceived benefits and challenges of inquiry-based instruction in inclusive chemistry classrooms," *Sci. Educ. Int.*, vol. 26, no. 1, pp. 180–194, 2015.
7. D. Cheung, "Facilitating chemistry teachers to implement inquiry-based laboratory work," *Int. J. Sci. Math. Educ.*, vol. 6, no. 1, pp. 107–130, 2008.
8. P. U. B. Xayrullo o'g and T. M. Umurzokovich, "Inquiry-based learning in chemistry education: Exploring its effectiveness and implementation strategies," *Fan va ta'lim integratsiyasi*, vol. 2, no. 1, pp. 74–79, 2024.
9. T. Gupta, K. A. Burke, A. Mehta, and T. J. Greenbowe, "Impact of guided-inquiry-based instruction with a writing and reflection emphasis on chemistry students' critical thinking abilities," *J. Chem. Educ.*, vol. 92, no. 1, pp. 32–38, 2015.
10. M. Juntunen and M. Aksela, "Life-cycle analysis and inquiry-based learning in chemistry teaching," *Sci. Educ. Int.*, vol. 24, no. 2, pp. 150–166, 2013.
11. J. A. Luft and G. H. Roehrig, "Inquiry teaching in high school chemistry classrooms: The role of knowledge and beliefs," *J. Chem. Educ.*, vol. 81, no. 10, p. 1510, 2004.
12. J. de Dieu Kwitonda, A. Sibomana, E. Gakuba, and C. Karegeya, "Inquiry-based experimental design for enhancement of teaching and learning of chemistry concepts," *Afr. J. Educ. Stud. Math. Sci.*, vol. 17, no. 2, pp. 13–25, 2021.