

DEVELOPING A SYSTEM OF ELECTRONIC EDUCATIONAL TOOLS FOR TEACHING CHEMISTRY USING SIMULATION METHODS: A MILITARY-PROFESSIONAL COMPETENCE PERSPECTIVE

Maftuna Sharofiddinovna Islamova

Associate Professor, Department of Psychology and Pedagogy, ISFT Institute, Uzbekistan
Doctor of Philosophy (PhD) in Pedagogical Sciences, Associate Professor

Abstract: Chemistry learning in military-oriented professional preparation requires learners to connect conceptual chemical knowledge with safe, time-sensitive, accountable decisions. Digital platforms provide access to representations and repeated practice, yet fragmented use of simulations does not in itself produce an integrated competence-based curriculum. Objective: This article develops and critically examines a system of electronic educational tools for simulation-supported chemistry teaching oriented toward transferable military-professional competence. Methods: A conceptual design-research approach combines an analytical synthesis of established scholarship on virtual chemistry laboratories, multimedia learning, inquiry, experiential learning and formative analytics with constructive alignment of tasks, outputs and assessment. No student experiment or institutional implementation is claimed. Results: The proposed SIM-CHEM framework integrates a learning management layer, a chemical simulation layer, a scenario and decision layer, an evidence and analytics layer, and a governance and safety layer. A six-stage learning cycle, an illustrative eight-week curricular sequence, contextualized cases, a multidimensional analytic rubric and a feasible validation protocol are provided. Conclusions: Simulation can support conceptual reasoning, procedural preparation and evidence-based decisions when paired with authentic supervision, safe physical practice where appropriate, feedback and transparent assessment. The article offers a testable pedagogical design rather than an empirically demonstrated effectiveness claim.

Keywords: chemistry education; electronic educational tools; simulation-based learning; military-professional competence; virtual laboratory; scenario-based instruction; learning analytics; instructional design.

1. Introduction

The teaching of chemistry in professionally oriented higher education should extend beyond the recall of reactions, formulae and laboratory definitions. A learner may reproduce a chemical equation accurately while struggling to interpret a material-safety label, distinguish an observation from an assumption or communicate uncertainty during a practical task. Military-professional education adds the expectation of disciplined decision-making under constraints: clear procedural sequencing, communication within a team, consistent documentation, respect for safety boundaries and responsibility for the consequences of error. These expectations should be addressed educationally without converting chemistry classes into unsupervised operational instruction. A defensible curriculum therefore foregrounds scientific reasoning, prevention, protective awareness and the responsible transfer of classroom knowledge to professional situations.

Electronic educational tools may expand what instructors can make visible. Dynamic particle models display microscopic processes that cannot be seen directly; virtual laboratories permit repeatable manipulation of selected variables; learning management systems distribute resources and capture progression; assessment tools provide immediate explanatory feedback; and scenario interfaces ask students to justify choices rather than click toward a correct answer. Yet these tools are not interchangeable. A simulation that is excellent for explaining equilibrium may be inadequate for evaluating a learner's ability to notice a mislabeled vessel, follow a supervision protocol or communicate the limits of available evidence. Technological availability therefore must be distinguished from educational adequacy.

Research on virtual chemistry laboratories gives a cautious foundation for innovation. The systematic review by Chan and colleagues (2021) reports that virtual laboratories generally outperform passive media on cognitive outcomes and can produce outcomes comparable with or better than hands-on formats in some studies; the authors also identify weaknesses in evidence for practical skills and underline the benefits of combining methods. Ali and Ullah (2020) compare virtual chemistry laboratories and highlight variability in realism, flexibility and educational functionality. These findings invite structured selection of tools rather than the assumption that any digital activity is inherently innovative. Similarly, learning analytics studies show that digital traces can help examine progression, although interpretation of those traces requires theoretical and assessment discipline (Herodotou et al., 2023).

A second gap concerns professional transfer. A student may perform successfully inside a visually engaging exercise because the interface highlights the next action. Such success does not guarantee that the student could explain the chemical principle, recognize missing data or identify an unsafe instruction in a new context. Transfer requires deliberate variation in scenarios, reflective explanation and assessment beyond completion scores. Military-professional competence is used here as a broad educational construct encompassing chemistry-informed risk awareness, reliable procedure, collaborative communication and reflective judgment. It does not refer to weapon design, deployment or operational exploitation of hazardous chemical agents.

The central objective of this paper is to design a coherent system of electronic educational tools for chemistry instruction using simulation methods, to make the components and their pedagogical relationships explicit, and to propose an evaluation strategy suitable for future empirical investigation. Four research questions guide the work: RQ1, which learning functions must be coordinated for a competence-oriented simulation ecosystem? RQ2, how can chemical conceptual reasoning be connected to professional decision scenarios without sacrificing safety and scientific validity? RQ3, which indicators can provide meaningful evidence of competence rather than mere platform activity? RQ4, what implementation conditions and research procedures are required before effectiveness can be established?

The contribution is a design artifact, not an experimental report. It combines tool architecture, a learner workflow, mapped outcomes, exemplars, an assessment instrument and quality safeguards in one reproducible proposal. Because the publication target is an international scholarly journal, methodological boundaries are stated explicitly: the tables and scenarios are author-developed proposals; they are not statistical findings from students, and numerical weights used for assessment are illustrative design parameters requiring local validation.

2. Materials and Methods

2.1. Research design and epistemic scope

This study adopts a conceptual design-and-development methodology informed by design-based research, constructive alignment and literature-grounded framework building. The unit of analysis is the educational system rather than individual learners. The analytical procedure consisted of specifying outcomes, extracting design principles from the relevant scholarship, translating principles into platform functions, mapping functions to observable learner evidence, and stress-testing the resulting framework against constraints characteristic of military-oriented chemistry instruction. This procedure supports a plausible and inspectable model; it cannot estimate causal effect sizes or demonstrate implementation fidelity.

Sources were selected purposively for conceptual relevance: peer-reviewed studies and reviews on virtual chemistry laboratories, guided inquiry with interactive simulations, multimedia learning, laboratory learning outcomes and digital activity traces, supplemented by established frameworks for aligned assessment and experiential instruction. Searches and bibliographic verification focused on the chemistry education and virtual-laboratory literature; the work does not

present a comprehensive systematic review or claim a PRISMA-compliant sampling procedure. Therefore, its conclusions should be read as theoretically substantiated design propositions rather than an exhaustive synthesis of all available research.

Five assumptions delimit the framework. First, students have access to at least a basic computer or shared device and a controlled institutional learning environment. Second, a qualified chemistry instructor remains responsible for selecting scientifically valid materials and for feedback. Third, the system targets routine educational scenarios such as identifying hazards, evaluating water-quality evidence, checking storage compatibility at a general level and documenting safe laboratory conduct. Fourth, dangerous real-world procedures, restricted operational details and specific harmful-agent instructions are excluded. Fifth, any physical laboratory component occurs under the institution's established safety rules and supervision.

2.2. Conceptual foundations

Constructive alignment provides the organizing logic: intended learning outcomes, learning activities and assessment tasks must refer to the same underlying performances (Biggs, 1996). Instead of starting with a fashionable application, an instructor first specifies what a student should explain, recognize, perform or justify. This outcome determines the form of representation, interaction, feedback and evidence required. For example, recognizing the difference between a concentration and a total amount is best assessed by interpreting multiple representations, whereas a judgment about a doubtful measurement calls for a scenario with missing or conflicting information.

Cognitive theory of multimedia learning suggests that carefully coordinated verbal and visual representations can support understanding when irrelevant information is minimized (Mayer, 2021). In simulation design, this means that visual sophistication is not an independent educational goal. Students need legible axes, meaningful units, explicit changes in controlled variables and prompts that direct attention to scientifically productive patterns. Guided inquiry research with PhET simulations similarly demonstrates the value of environments enabling exploration while sustaining disciplinary discussion (Moore et al., 2014). For novice learners, prompts should offer support without mechanically revealing the answer.

Experiential learning provides a cycle of action, reflection, conceptualization and renewed application (Kolb, 1984). In an electronic environment, experience is necessarily mediated by an interface; reflection must be explicitly elicited so that repeated clicks become evidence-based learning. Virtual and physical settings should be viewed as complementary environments with different affordances. A simulation is suitable for rehearsing observation and causal prediction, whereas tactile handling, authentic instrument calibration and safety behavior may demand supervised physical work.

2.3. Design procedure and evidence mapping

The design process was organized into six steps. In the first step, broad military-professional expectations were decomposed into teachable educational performances, including conceptual explanation, laboratory-safety awareness, data interpretation, cooperative communication and justified decision-making. In the second, chemistry topics were screened for safe, meaningful simulations. The third step assigned each performance to a tool layer. Fourth, scenario prompts were drafted with explicit information constraints and anticipated misconceptions. Fifth, an analytic rubric and supporting trace indicators were constructed. Finally, constraints involving digital access, privacy, simulation fidelity and instructor workload were assessed in order to identify implementation risks.

A crosswalk table was developed to distinguish what can be measured automatically from what requires teacher judgment. Platform completion, time spent and repeated attempts are useful process indicators, but cannot alone certify a complex professional competence. Written explanations, annotated graphs, reasoned decisions, peer dialogue and supervised performance provide more

defensible outcome evidence. This distinction also limits misuse of predictive analytics: a learner should not be penalized simply for exploring a simulation slowly or repeatedly.

3. Results: Proposed System and Instructional Model

3.1. Five-layer SIM-CHEM architecture

The principal design result is SIM-CHEM (Simulation-Integrated Military-Professional Chemistry Education Model), an interoperable pedagogical architecture comprising five functional layers. The layers describe educational responsibilities rather than a claim that a new software platform has already been programmed. Existing technologies can fulfill different layers if integration and data governance are adequate.

Layer	Primary purpose	Illustrative functions	Primary evidence
1. Learning management	Coordinate learning sequence	Lessons, prerequisites, scheduling, feedback, access controls	Submission history and learning portfolio
2. Scientific simulation	Represent chemical phenomena	Variable manipulation, molecular/solution models, repeatable virtual experiments	Predictions, parameter records, explanations
3. Scenario and decision	Situate chemistry in professional judgment	Branching cases, team roles, incomplete-information prompts	Justified choices and documented alternatives
4. Assessment and analytics	Gather defensible learning evidence	Rubrics, low-stakes quizzes, reflective prompts, dashboards	Outcome profiles and feedback history
5. Governance and safety	Protect learners and assure quality	Content review, accessibility, privacy, instructor approval	Audit trail and revision records

The first layer uses a learning management system such as Moodle or a functionally equivalent institutional platform to present a clear sequence. It stores reading resources, embeds accessible simulation links, organizes group assignments and preserves feedback. Its function is not to produce deep learning by itself, but to reduce fragmentation: students should encounter a consistent workflow in which a simulation, its explanatory tasks and a later decision exercise are visibly connected. A platform that records only attendance or file downloads would not provide adequate competence evidence.

The second layer comprises interactive chemistry simulations, virtual laboratory environments and selected molecular visualizations. PhET-style resources can demonstrate changing concentration, molecular polarity and interactions at an appropriate conceptual level. More complex laboratory environments can simulate measurement choices, equipment selection and consequences of ordinary experimental errors. Selection must prioritize chemical correctness, explicit units, editable parameters, accessibility and transparency about simplifications. An instructor should document whether a model represents an idealized solution, whether concentrations are approximate and what sources of physical laboratory uncertainty are absent.

The third layer is what converts a generic electronic laboratory into professionally situated instruction. A scenario might present conflicting descriptions of an unlabeled classroom sample, a table of water-quality measurements or a decision about how to communicate a doubtful result. Students are asked to identify relevant chemical principles, list data still needed, select a safe authorized next step and provide a brief rationale. Branching options should reward well-reasoned

uncertainty and requests for supervision, not risk-taking or speed for its own sake. An effective case includes more than one plausible distraction and makes evidence quality visible.

The fourth layer separates learning analytics from competence judgment. Automated indicators include completed activities, revision count, explanation length and patterns of answer change. These traces become useful only when interpreted alongside content validity, rubric-based instructor evaluation and peer feedback. A student who revises an explanation after evidence may be showing strong metacognition rather than weakness. Likewise, high simulation scores can coexist with a flawed safety rationale. Dashboards should display formative trends and source evidence rather than opaque rankings.

The fifth layer governs access, pedagogical quality and safety. Institutional review should establish permitted chemistry content, mechanisms for removing inaccurate simulations, retention rules for student records and alternatives for learners with limited bandwidth or accessibility needs. A technically feasible option is not automatically an ethical or educationally legitimate choice. Sensitive professional context should be represented only at the level necessary for learning objectives; confidential or operational details need not enter the system. The architecture consequently supports both instructional effectiveness and accountable institutional deployment.

3.2. Six-stage simulation-based teaching cycle

The instructional cycle begins with diagnosis. Short questions and a prediction exercise surface prior knowledge of the relevant chemical ideas, especially misconceptions about concentration, reaction evidence and uncertainty. The purpose is not gatekeeping but adaptive support: learners who need foundational explanations receive additional resources, while those ready for further challenge encounter richer interpretations. The second stage is orientation, in which the instructor clarifies the learning outcome, the relation between an idealized simulation and the material world, the safety boundaries and the evidence to be submitted.

Third comes guided experimentation. Learners manipulate one factor at a time, record their predictions, and compare modeled outcomes. Worksheets emphasize controls and causal claims rather than screenshots of an interface. The fourth stage is professional contextualization: students receive a case requiring chemistry-informed choices, identify relevant and irrelevant information and defend an action consistent with safe institutional practice. During the fifth stage, they reflect and triangulate: they compare explanations, consider counterexamples, and document how a revised conclusion differs from an initial guess. The sixth stage uses assessment and transfer tasks to examine whether knowledge survives altered conditions.

The cycle is intentionally recursive. When a learner cannot explain a virtual observation, the educator returns to the relevant conceptual representation; when a case reveals a faulty assumption, the instructor models a safer reasoning process. Teacher facilitation remains important because inaccurate intuitions can become more confident with repetition. A scenario should therefore contain purposeful feedback explaining the chemical and procedural basis of an answer rather than merely indicating “correct” or “incorrect.”

3.3. Illustrative eight-week curriculum map

Week	Chemical focus	Simulation task	Professional competence evidence
1	Laboratory safety and evidence	Interpret labels and simulated observation logs	Explain escalation and documentation
2	Solutions and concentration	Change dilution variables within virtual model	Distinguish concentration from volume

3	Acids, bases and pH	Compare model outcomes and graph pH trends	Interpret measurements and limits
4	Chemical equilibrium	Predict response to variable changes	Justify uncertainty in forecasts
5	Corrosion and materials	Compare simplified environmental factors	Evaluate prevention rationale
6	Water chemistry	Review simulated quality data and anomalies	Recommend further verification
7	Multi-stage workplace scenario	Integrate measurements and safety cues	Collaborative decision record
8	Capstone transfer	Apply principles to unfamiliar safe case	Evidence portfolio and defense

This sequence is an illustrative curriculum proposal, not a record of an eight-week course already taught. Individual institutions should determine the appropriate chemistry depth, legal requirements, language of instruction and accessibility accommodations. The map can also be compressed for professional-development programs or extended for laboratory-rich university modules.

3.4. Scenario A: Water-quality reasoning under uncertainty

An educationally safe scenario presents a hypothetical field-support team receiving routine water-quality indicators from several collection points. The electronic worksheet shows plausible differences in reported pH and conductivity, an incomplete measurement log and a note that one instrument has not been verified. The scenario does not ask students to treat unsafe water or devise field operations; instead, it asks what the available chemical measurements can and cannot establish. The associated simulation demonstrates how ion concentration can affect conductivity in an idealized solution and how pH measures a distinct property. Learners must distinguish measurement interpretation from a premature declaration of safety.

Assessment prompts ask students to identify missing information, construct a short evidence table, explain one possible measurement error and propose a cautious, authorized response: verify sampling and measurement processes, seek qualified laboratory confirmation and avoid treating a single indicator as proof of potability. Working in pairs, students defend why a visually convincing virtual result must not override procedural requirements. The competency focus is evidence literacy, collaboration and escalation under uncertainty, with chemistry used to support disciplined reasoning.

3.5. Scenario B: Corrosion prevention and scientific explanation

A second scenario uses a simplified model of corrosion to explore how moisture, dissolved ions and material conditions influence a generic metal surface. The instructor supplies several hypothetical maintenance observations and asks learners to compare the evidence with the model's assumptions. Students first predict which environmental factor could accelerate an observed trend, then test changes in a safe educational simulation and document why correlations in a simplified model are not identical to outcomes in diverse real equipment. The task avoids specialized vulnerabilities of military systems and addresses only general chemistry and maintenance literacy.

The professional performance expected is not a tactical recommendation but a reasoned maintenance report. Students should differentiate preventive inspection from causal certainty, recommend consultation of relevant approved procedures and show how evidence supports a limited conclusion. A strong answer explicitly states the boundary between modeled chemical mechanisms

and material-specific engineering decisions. Instructors may assess conceptual accuracy alongside concise communication and the ability to acknowledge data limitations.

3.6. Scenario C: Safe laboratory communication

A third case begins with a virtual bench containing ordinary educational materials, labels and an intentionally incomplete observation sheet. Rather than requiring hazardous combinations or real mixing instructions, the simulation asks learners to recognize which information would be needed before any authorized laboratory procedure could occur. Learners practice reading standardized hazard communication, identifying a missing label, recording unexpected observations and notifying the supervising instructor. A branching dialogue allows a student to choose between proceeding despite uncertainty, inventing missing data and stopping to request clarification; feedback makes the safety and evidentiary reasoning explicit.

The case helps separate procedural obedience from informed responsibility. Merely remembering a symbol is not the same as using the symbol within a reliable decision sequence. The same task can be adapted for learners with little experience or for experienced students asked to explain their judgment to peers. When implemented, an institution should review all instructions against its chemical safety rules and replace generic prompts with locally authorized terminology without adding operationally sensitive material.

3.7. Competency rubric and performance indicators

The proposed rubric contains five constructs scored from 1 (emerging) to 4 (well demonstrated). Scores should be anchored in observable evidence, accompanied by narrative feedback and validated before summative use. Equal weights provide a transparent starting point; programs may revise weights through expert consensus and empirical evidence, rather than treating the values as natural constants.

Construct (20% each)	Score 1: emerging	Score 4: well demonstrated
Chemical conceptual reasoning	Makes unsupported or inconsistent claims	Explains mechanisms with appropriate limits
Evidence interpretation	Confuses observations and assumptions	Integrates data and identifies uncertainty
Safety-oriented judgment	Overlooks authorization or missing data	Prioritizes verification and safe escalation
Communication and teamwork	Records unclear rationale or excludes peers	Provides clear, traceable collaborative reasoning
Reflection and transfer	Repeats a memorized answer unchanged	Revises reasoning and applies it to a novel case

At an intermediate level (score 2), a learner may identify a relevant principle but explain it incompletely or overlook one important limitation. At score 3, the learner applies the correct principle and produces a mostly defensible explanation, although it may require prompting or contain small omissions. Specific descriptors should be elaborated through annotated example responses. Raters can score anonymized products independently; agreement statistics and moderation discussions would then reveal rubric ambiguity. The rubric is designed to support diagnostic dialogue, not to label learners as permanently competent or incompetent.

Formative indicators should be triangulated. Suggested measures include pre/post conceptual tests, scenario-based written decisions, a supervised practical checklist when facilities allow, a reflective learning portfolio and an instructor rating of collaborative argumentation. Analytics data may support evaluation of process, for example whether learners use feedback to correct

misunderstandings, but are subordinate to demonstrated reasoning. Reporting should distinguish engagement from achievement and near-transfer from performance in an unfamiliar professional situation.

4. Discussion

4.1. Educational advantages and realistic boundaries

The proposed framework contributes a shift from tool-centered digitization to competence-centered instructional engineering. Many educational projects begin by choosing a simulation platform and subsequently searching for a pedagogical purpose. SIM-CHEM reverses the sequence: competence evidence is specified first, then chemical representations and scenarios are chosen to elicit that evidence. This position follows the principle of constructive alignment and addresses a recurring problem in digital education, namely the conflation of access, engagement and learning. The framework also explicitly documents the points at which a human instructor must make an expert judgment.

Virtual laboratories provide opportunities that are difficult to reproduce in a short lesson. Variables can be altered and restored quickly, microscopic entities visualized and counterfactual hypotheses tested repeatedly. Those affordances matter for chemistry because students often need to coordinate symbolic equations with particulate models and observable phenomena. When used judiciously, animations and model outputs may reduce extraneous cognitive burden and allow attention to focus on causal relationships. However, weak simulation fidelity, confusing interaction design and excessive visual decoration can generate new misconceptions. A vivid display should therefore be accompanied by a statement of what the representation omits.

A crucial boundary concerns procedural competence. The literature on virtual chemistry laboratories does not justify an unconditional claim that simulated success equals safe laboratory performance. Physical handling, response to unexpected tactile or sensory cues, instrumentation and authentic coordination can depend on settings absent from a virtual environment. The model thus favors blended sequences: simulations prepare conceptual understanding and procedural anticipation, while supervised exercises verify skills that actually require real equipment. Where physical activity is unavailable, educators should describe the learning outcomes honestly as preparatory or cognitive rather than certifying unobserved manual proficiency.

Another issue is the definition of military-professional competence. Broad labels may hide heterogeneity between military engineering, medical support, logistics, environmental monitoring and other specializations. This article therefore offers a transferable core of safe chemistry-informed reasoning, not a universal occupational standard. Institutions need a local occupational analysis to identify permissible, relevant tasks and distinguish general chemical education from role-specific operational certification. The instructional unit of professional competence should be observable judgment in a lawful and safe scenario, not an unverified claim of readiness for deployment.

4.2. Accessibility, equity and digital governance

International implementation must accommodate differences in internet capacity, devices, language proficiency and accessibility. Some immersive environments require high-performance computers or headsets and can exclude learners who do not have them. A tiered design is preferable: a low-bandwidth browser simulation, static alternatives with comparable conceptual questions and optional higher-fidelity visualization where accessible. Accessibility should be planned from the start, including readable contrast, keyboard navigation, transcripts for narration, alternatives to color-only distinctions and sufficient time for reflection. These provisions are relevant not only to disability inclusion but also to instructional reliability.

Data governance is equally important. Electronic platforms can record detailed learner actions, but the technical possibility of collection does not establish legitimate educational use. Instructors should minimize identifiable data, explain the purpose of collection, restrict access and

define retention and deletion procedures. Sensitive professional identities and unnecessary location or operational information should not be inserted into external educational services. Analytics should support feedback and curricular revision; high-stakes automated profiling based on uncertain behavioral proxies should be avoided. The governance layer should define responsibilities for content accuracy, security review, appeals and human oversight.

Teacher preparation is an implementation determinant. Lecturers need sufficient familiarity with chemical models to detect misleading outputs, enough digital competence to integrate activities and enough assessment literacy to judge reasoning rather than speed. Professional development should involve the instructor completing the same simulation and scenario as a learner, documenting misconceptions, revising feedback prompts and practicing rubric calibration. It is also useful to establish a small institutional repository of vetted simulations, scenario templates and accessibility notes so that every teacher does not have to independently reconstruct the quality assurance process.

4.3. Proposed empirical validation protocol

Future research should evaluate SIM-CHEM through a staged mixed-methods design. Stage one would use an expert panel of chemistry educators, instructional designers, military-professional education specialists and ethics or safety officers to assess content relevance, scenario realism at the appropriate educational level, technological feasibility and rubric clarity. Expert ratings could be used to revise the model; qualitative comments should be retained to identify disagreements rather than reduced to a single numerical approval threshold. A pilot usability study should then test device access, navigation, reading load and comprehension of safety boundaries with a small voluntary learner group.

Stage two could compare the proposed blended instruction with a pedagogically credible comparison condition that receives equivalent chemistry content, instructor contact and assessment time. A quasi-experimental pretest–posttest design may be practical where classes already exist, while cluster randomization would reduce some selection problems when ethically and organizationally feasible. Researchers should predefine the primary outcome, establish comparability at baseline and account for classroom-level clustering, instructor effects and missing data. Reporting only statistically significant changes would be inadequate; confidence intervals and effect sizes are necessary for evaluating educational importance.

An assessment battery should distinguish four outcomes. Conceptual achievement may be examined with a validated chemistry test; contextual decision quality with unfamiliar, safe scenario prompts assessed by blinded raters; procedural preparation with a supervised checklist in authorized laboratory activities; and learner experience with appropriately validated usability and perceived-support measures. Follow-up measurement after several weeks would be valuable for retention and transfer. Inter-rater agreement, internal consistency, construct validity and possible ceiling effects should be checked. If the proposed rubric fails to distinguish learners meaningfully, it must be revised before claims about competence development are made.

Stage three should focus on implementation mechanisms rather than only overall scores. Learning analytics may show which feedback sequences accompany improved explanations, and interviews may identify why some students benefit less. Nevertheless, correlations between the number of actions and scores should not be described as causal evidence. Researchers should examine whether a specific simulation affordance helps conceptual development, whether the professional scenario adds transfer value and whether instructor facilitation moderates results. Such component-level questions make the findings more actionable than a general comparison between “technology” and “traditional teaching.”

Ethical governance should include appropriate institutional review where required, transparent consent procedures, voluntary participation in research and protections against disadvantaging students who decline data analysis. A control class should not be denied necessary

safety teaching. De-identified academic records and carefully specified learning outcomes are preferable to collecting extensive personal data. A multi-institutional study could assess generalizability across chemistry programs and professional settings, but cross-institutional differences in curriculum and regulations should be described rather than assumed away.

4.4. Implications for theory and practice

Theoretically, this paper situates simulation-based chemistry education between three distinct claims: visualization can help make an abstract chemical mechanism intelligible; a carefully designed scenario can elicit evidence-based judgment; and professional competence must be demonstrated under appropriately authentic conditions. These propositions are related but not identical. A person who understands a dynamic particle representation might still struggle with situational communication. The model therefore recommends layered outcomes rather than one aggregate “simulation effectiveness” score. Its assessment design makes those layers visible and theoretically interpretable.

Practically, academic departments could begin implementation without commissioning an expensive proprietary platform. A secure institutional course space, carefully evaluated open simulations, instructor-written cases, a portable analytic rubric and a coherent assessment portfolio form a viable first version. More advanced environments may then be added only when they address a documented learning gap. This incremental strategy provides a path for resource-constrained institutions and supports sustainability: faculty can improve tasks and evidence collection independently of vendor-specific interfaces. At the same time, interactivity alone is not a quality metric, and low-cost resources still require scientific and accessibility review.

For professional educators, a useful criterion is whether a student can explain why a decision was warranted, what uncertainties remain and who has authority to authorize the next step. Those habits are relevant across many lawful professional roles and align naturally with sound chemical reasoning. They also discourage hazardous overconfidence: an educationally successful learner may sometimes be the one who refuses to infer more than the evidence permits. In that sense, simulation should cultivate epistemic discipline as well as knowledge and efficiency.

5. Limitations

This article has several limitations. It is a conceptual design study and includes no recruited participants, experimental manipulation, observed learning outcomes or statistical analysis. The architectural layers, eight-week sequence and assessment weights are proposals, not validated interventions. The targeted literature was selected for theoretical relevance rather than through a comprehensive systematic review, and the framework necessarily abstracts from specialization-specific rules, language needs and local infrastructure. Moreover, commonly available simulations differ significantly in accuracy, pedagogical support and accessibility. These limitations restrict any claim of measured effectiveness and indicate the need for transparent, context-specific empirical testing.

Future authors using this framework should be explicit about which software version and chemistry modules were deployed, which teacher prompts were delivered, what learning outcomes were measured, how competence judgments were moderated and whether any observed gains persist beyond familiar tasks. The distinction between modeled phenomena and authentic procedures is especially important in safety-related professional training. Without this transparency, educational technology studies risk producing impressive interfaces but insufficiently interpretable evidence.

6. Conclusion

The development of electronic educational tools for chemistry should be understood as the construction of a coordinated learning system rather than a collection of digital resources. The SIM-CHEM framework specifies the responsibilities of learning management, scientific simulation, contextual decision cases, evidence and analytics, and safety-oriented governance. Its six-stage cycle

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and illustrative curriculum map link fundamental chemical understanding with cautious, documented professional judgment. The proposed rubric operationalizes conceptual reasoning, evidence use, safety awareness, communication and reflective transfer.

For military-professionally oriented education, the central value of simulation lies in providing repeatable, low-risk opportunities to reason through chemistry-relevant problems and to practice responsible explanation under uncertainty. Simulations should complement rather than automatically replace supervised laboratory instruction and institutional procedures. A rigorous research agenda involving expert content validation, usability review, fair comparison conditions, multi-source assessment and longitudinal follow-up is required before claims of effectiveness can be made. The framework thus supplies a practical foundation for curriculum development and a falsifiable basis for subsequent empirical scholarship.

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