

THE ESSENCE, OBJECTIVES, TYPES, AND DIDACTIC POTENTIAL OF THE COMPETENCY-BASED APPROACH IN CHEMISTRY EDUCATION

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Abstract

This article examines the theoretical essence, educational objectives, principal types and didactic potential of the competency-based approach in chemistry education. The study uses an integrative conceptual review of educational frameworks and selected peer-reviewed research, combined with didactic comparison and model construction. Competence is interpreted as an observable ability to mobilize chemical knowledge, experimental procedures, reasoning and responsible attitudes in meaningful contexts. The analysis distinguishes eight mutually connected competency domains: conceptual-representational, experimental-safety, inquiry-critical, quantitative-analytical, digital-information, communication-collaboration, environmental-ethical and self-regulatory-pedagogical.

Keywords: Chemistry education; competency-based approach; scientific literacy; inquiry-based learning; laboratory competence; contextual tasks; formative assessment; didactic model.

Introduction

In contemporary chemistry education, the central question is no longer limited to how much disciplinary information students can reproduce. It is also concerned with whether students can interpret chemical phenomena, justify an experimental procedure, communicate evidence and make scientifically defensible decisions in unfamiliar circumstances. This change reflects a broader educational understanding of competence as the contextual integration of knowledge, skills and attitudes, rather than the possession of isolated facts. The European framework of key competences explicitly connects science with observation, experimentation, evidence-based conclusions and responsible citizenship.¹

The competency-based approach (CBA) therefore signifies a transition from content coverage to demonstrable learning outcomes. It does not diminish the importance of chemical theories or

calculations. Instead, it requires the learner to mobilize them in the course of solving a meaningful problem. Biggs's concept of constructive alignment provides an important pedagogical principle: intended outcomes, learning activities and assessment tasks must demand the same kinds of intellectual performance.² For chemistry, an intended outcome such as 'evaluate water quality using chemical evidence' cannot be assessed adequately by recalling only the definition of water hardness. The aim of the present article is to clarify the essence and objectives of CBA in chemistry education, systematize its principal competency domains and identify its didactic possibilities. The article also offers an original analytical framework linking competencies, instructional activities, assessable evidence and feedback. It addresses the following research question: how can competence-oriented chemistry instruction connect theoretical understanding, experimental practice and contextual problem solving in a coherent assessment system?

MATERIALS AND METHODS

The study adopts a conceptual and methodological research design based on an integrative, non-systematic review of authoritative educational frameworks and selected peer-reviewed studies. Sources were chosen for their relevance to competency definitions, chemistry-specific representations, inquiry-based learning, active learning, contextualized instruction and formative assessment. The review covers foundational works and recent synthesis research; it is not presented as an exhaustive systematic search or a meta-analysis.

Three analytical procedures were applied. First, conceptual comparison was used to distinguish competence from knowledge, skill and measurable performance. Second, didactic mapping connected major chemistry competencies with instructional methods and observable indicators. Third, model construction was employed to develop a five-stage instructional sequence and an example of performance-based assessment. Findings therefore consist of a reasoned taxonomy and a proposed methodological model; no student experiment, survey or institutional dataset was conducted or analyzed for this article.

RESULTS

1. Essence of the competency-based approach in chemistry education

Within a competency-based paradigm, chemical competence can be defined as a student's context-sensitive capacity to select, combine and apply relevant chemical concepts, procedures, reasoning strategies and responsible attitudes to explain phenomena and resolve problems with justifiable evidence. This operational definition contains five interdependent dimensions: a disciplinary knowledge base; practical action; contextual transfer; evaluation of evidence; and reflection on limitations, safety and consequences. Competence is demonstrated through performance, not inferred automatically from course attendance or a high score on recall questions.

Chemistry possesses a distinctive cognitive structure that makes integration particularly demanding. Johnstone identified the difficulty learners encounter when simultaneously processing different levels of scientific explanation.² Talanquer subsequently examined the macroscopic, submicroscopic and symbolic chemistry triplet as a crucial, though conceptually complex, structure of chemical knowledge.³ At the macroscopic level, a learner observes a precipitate or color change; at the submicroscopic level, the learner reasons about ions, particles and interactions; at the symbolic level,

the phenomenon is represented by equations and quantitative relationships. A competent explanation connects all three without treating symbols as substitutes for understanding.

For example, when an aqueous solution of calcium chloride is mixed with sodium carbonate, a white solid forms. A competence-oriented explanation requires students to identify the observation, infer the formation of poorly soluble calcium carbonate and express the net ionic reaction $\text{Ca}^{2+}(\text{aq}) + \text{CO}_3^{2-}(\text{aq}) \rightarrow \text{CaCO}_3(\text{s})$. More advanced students can relate the result to solubility equilibria, ion concentrations and limitations of qualitative observation. Thus, chemical literacy emerges through coordinated reasoning rather than memorization alone.

2. Objectives and expected educational outcomes

The general objective of CBA is to develop learners capable of using chemical knowledge accurately, independently, safely and ethically in educational, professional and social contexts. At the instructional level, this objective entails conceptual understanding and transfer; competence in planning and conducting investigations; mathematical treatment of measurements and uncertainty; evidence-based argumentation; responsible handling of chemicals and waste; effective scientific communication; and self-directed improvement. The objectives should be expressed as assessable actions—for example, 'compare two experimental designs and justify the more reliable one'—rather than vague intentions such as 'know titration well'.

A second objective is to reduce the distance between disciplinary coursework and real decisions. Students should be able to distinguish an experimentally supported conclusion from an unsupported claim about food additives, corrosion prevention, pharmaceutical substances or environmental pollution. A third objective is pedagogical agency: future chemistry teachers should be able to transform subject knowledge into inquiry questions, contextualized tasks, valid assessment criteria and productive feedback.

3. Principal types of competencies in chemistry education

Competency categories are presented here as an analytical classification proposed for curriculum design, not as a single universally mandated taxonomy. They overlap in real chemical activity, but distinguishing them helps teachers make learning outcomes and assessment criteria explicit.

These domains should not become isolated modules. In a single lesson on sulfur dioxide and atmospheric pollution, students may simultaneously use knowledge of acidic oxides, interpret sensor data, evaluate source reliability, discuss environmental responsibility and communicate policy options. The most productive approach integrates several competency domains through one scientifically manageable context.

4. Didactic possibilities and instructional technologies

The first didactic possibility is to transform laboratory work from procedural repetition into authentic inquiry. In traditional confirmation experiments, learners often follow a fixed recipe and report the expected result. In competency-oriented laboratory work, they identify variables, make predictions, consider controls, evaluate measurement uncertainty and defend conclusions. Hofstein and Lunetta's review underscores the central role of laboratory environments while highlighting the importance of inquiry, assessment and the thoughtful design of practical work.⁵ Laboratory safety remains a non-

negotiable instructional outcome: risk assessment, personal protective equipment, chemical compatibility and waste disposal must be included in performance criteria.

The second possibility is active and collaborative learning. Students can compare explanatory models, solve multistep calculations, critique a chemical claim or defend competing experimental plans. A large meta-analysis across university STEM fields reported higher examination performance and lower failure rates under active-learning conditions than under traditional lecturing.⁶ This evidence supports the use of active learning as a general instructional strategy, although its magnitude cannot be assumed to be identical in every chemistry course or institutional context.

A third possibility is inquiry-based and contextualized instruction. A recent systematic review specifically addressing inquiry-based chemistry education examines how inquiry is conceptualized and implemented across chemistry teaching settings.⁷ Research synthesizing context-based and science–technology–society instruction has also identified benefits for student attitudes, alongside scientific understanding comparable to conventional teaching in the studies reviewed.⁸ Context must nevertheless serve a clear chemical learning objective. An attractive environmental story without accurate chemistry or sufficient conceptual support is not equivalent to competence development.

A fourth possibility is formative assessment. The instructor can use diagnostic questions, prediction–observation–explanation tasks, laboratory notebooks, oral defense, concept maps, peer review and analytic rubrics to identify which aspects of performance require improvement. Black and Wiliam's review of formative assessment provides a theoretical foundation for feedback that changes subsequent teaching and learning rather than merely recording scores.⁹ Competency evidence should be collected at different points in the learning process, with opportunities for revision and transfer to new contexts.

A fifth possibility lies in digital and self-directed learning. Interactive molecular visualizations can help students coordinate particulate and symbolic representations; spreadsheets can support calibration graphs and uncertainty calculations; simulations can permit the safe investigation of otherwise impractical conditions. The National Academies' synthesis on learning draws attention to the role of motivation, self-regulation and thoughtful technology integration.¹⁰ Digital tools are pedagogically justified when they make reasoning visible, allow feedback or expand access—not simply because they are technologically novel.

5. Proposed five-stage competency-development model

On the basis of this conceptual synthesis, a five-stage instructional model is proposed. Stage 1, contextual diagnosis, presents a chemically relevant problem and elicits prior conceptions through a short diagnostic activity. Stage 2, conceptual construction, explicitly links observations with particle-level explanations and symbolic representations. Stage 3, guided inquiry, engages students in selecting methods, gathering or analyzing data, controlling variables and documenting safety decisions. Stage 4, transfer and argumentation, introduces an unfamiliar but structurally related problem and requires a justified solution. Stage 5, reflective assessment, applies an analytic rubric, targeted feedback, peer dialogue and a revised performance task.

The model aligns four components: the target competence, the learning action, the observable product and the criterion for judging its quality. For instance, the target 'interpret titration data' should be taught through measured or simulated titration records, evidenced through a worked calculation and



judged by the correctness of the chemical ratio, unit conversions, uncertainty discussion and evidence-based conclusion. This alignment reduces the risk that a curriculum advertises higher-order competencies but rewards only rote recall.

DISCUSSION

The analysis indicates that the principal didactic value of CBA is the integration of chemistry content with the practices through which chemical knowledge is produced, scrutinized and used. Its contribution is therefore not the replacement of disciplinary teaching by generic 'soft skills'. Without reliable knowledge of stoichiometry, bonding, equilibria and reaction mechanisms, contextual problem solving becomes superficial. Equally, conceptual mastery alone does not establish whether a learner can design a reasonable test, criticize a graph or communicate uncertainty.

The proposed model is consistent with constructive alignment and inquiry-oriented instruction, but it should be regarded as a design proposition awaiting classroom validation. Contextual tasks may increase cognitive demands, and insufficient scaffolding can disadvantage students with weaker prior knowledge. Moreover, practical conditions—including laboratory equipment, student numbers, time allocation and the availability of teacher feedback—shape what can be implemented. Digital simulations may complement, but cannot automatically replace, the motor, procedural and safety competencies developed in supervised laboratory settings.

The sustainability dimension is especially important for chemistry, which is implicated in resource use, pollution prevention, materials production and responsible consumption. UNESCO's roadmap for education for sustainable development emphasizes learning for informed and responsible action.¹⁰ The article's principal limitation is methodological: it reports a conceptual synthesis and a designed task, not an intervention trial. No claims of increased competency scores, statistical significance or effect sizes are made. Further studies should pilot the rubric, document fidelity of implementation and evaluate change using pre- and post-assessment tasks that measure transfer, not merely repetition of practiced examples. Where feasible, comparable groups, assessor blinding, reliability estimates and analysis of student work could strengthen the validity of subsequent conclusions.

CONCLUSION

The competency-based approach in chemistry education is best understood as a systematic organization of learning around observable, context-sensitive performances that integrate chemical knowledge, investigative methods, reasoning, communication and responsible action. Its central purpose is to enable learners to explain chemical phenomena and apply evidence beyond familiar textbook exercises. The proposed taxonomy identifies conceptual, experimental, inquiry-based, quantitative, digital, communicative, environmental and self-regulatory competency domains. Their separation is useful for curriculum planning, but authentic chemistry problems require their integration.

The five-stage model—contextual diagnosis, conceptual construction, guided inquiry, transfer and argumentation, and reflective assessment—offers a practical route from intended competence to observable evidence. To implement the approach, instructors should formulate measurable learning outcomes, align them with active and laboratory tasks, teach across chemical representational levels and use analytic rubrics with actionable feedback.

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