

Developing the Mathematical Competence of Future Chemists Through an Adaptive–Integrative Approach

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Abstract

Mathematical preparedness is a recurring bottleneck in undergraduate chemistry programmes, where students are expected to move fluently between abstract mathematical reasoning and discipline-specific representations of chemical phenomena. This paper proposes and conceptually examines an adaptive–integrative approach to developing the mathematical competence of future chemists, in which “adaptive” denotes the systematic orientation of mathematical content toward the professional field of chemistry, and “integrative” denotes the meaningful embedding of mathematical concepts within authentic chemical contexts. Drawing on a structured review of research in chemistry education, competence-based mathematics instruction, and integrated STEM pedagogy, the study identifies four design principles: (i) discipline-anchored selection of mathematical content; (ii) context-based and modelling-oriented tasks; (iii) differentiated, adaptive support of learners with heterogeneous mathematical backgrounds; and (iv) authentic, competence-oriented assessment. A pedagogical model linking these principles to the cognitive, operational, motivational, and reflective components of mathematical competence is presented. The discussion outlines testable hypotheses for future quasi-experimental studies in chemistry teacher education and industrial chemistry programmes.

Keywords: mathematical competence; chemistry education; adaptive learning; integrative STEM; context-based learning; higher education.

1. Introduction

Mathematics functions as both an instrument and a language of the chemical sciences. Stoichiometric calculations, equilibrium expressions, kinetic laws, quantum-

mechanical descriptions of bonding, and the statistical treatment of experimental data all require students to perform mathematical operations while simultaneously interpreting them in chemical terms. Despite this, the so-called “mathematics problem” — the persistent gap between the mathematical preparedness students arrive with and the mathematical demands of their university courses — remains a well-documented concern in chemistry and the wider physical-science disciplines [1]. The problem in chemistry is qualitatively different from that in mathematics or engineering, because chemistry students frequently need not more mathematics but a deeper conceptual grasp of how familiar mathematics encodes chemical meaning [1].

Empirical work confirms that the gap is not a marginal issue. A recent intervention study with incoming chemistry doctoral students at the University of California, Berkeley reports that insufficient mathematical fluency depresses first-semester performance and erodes students’ sense of belonging in their programmes [2]. Other authors note that even capable undergraduates struggle to translate the abstract mathematics taught in service courses into chemical reasoning [3]. At the same time, large-scale evidence from general chemistry suggests that prior mathematical knowledge predicts where students start more strongly than how quickly they learn during the course itself [4], implying that early, well-targeted interventions are particularly valuable.

From a pedagogical standpoint, the established response has shifted from purely remedial support toward structural reforms in how mathematics is taught to students of the natural sciences. The competence-based paradigm reframes mathematical preparation as the development of professional mathematical competence: the ability to deploy mathematical knowledge to solve problems that arise in a specific professional field [5]. In parallel, the context-based learning tradition has shown that anchoring scientific concepts in authentic, professionally meaningful situations improves

motivation, conceptual understanding and transfer [6]. When mathematics is reorganised around chemical contexts — the “chemistry-first” principle [7] — these gains can be brought to bear directly on the preparation of future chemists.

The present paper synthesises these strands of research into a coherent adaptive–integrative approach to the mathematical preparation of future chemists. In this framework, “adaptive” refers specifically to the orientation of mathematics instruction toward the professional field of chemistry — that is, the deliberate selection, sequencing, and contextualisation of mathematical content according to the cognitive demands of chemical reasoning. “Integrative” refers to the horizontal coupling of mathematical and chemical concepts within tasks, modules, and assessments, so that students experience the two disciplines as a single epistemic practice rather than as two parallel courses.

The objectives of the study are threefold: (1) to articulate the theoretical foundations of the adaptive–integrative approach; (2) to formulate design principles and a pedagogical model linking the approach to the structural components of mathematical competence; and (3) to outline empirically testable propositions that can guide subsequent quasi-experimental research. The paper is structured according to the IMRaD convention.

2. Methods

2.1 Research design

The study is conceptual–analytical in character. It develops a pedagogical model on the basis of a structured narrative review of the research literature on (a) the mathematical preparation of chemistry students, (b) the competence-based approach to mathematics education, and (c) integrative and context-based STEM pedagogy. The objective of the review was not to provide an exhaustive bibliometric mapping but to identify recurrent design principles that converge across these three traditions and that can be combined into a unified instructional framework.

2.2 Source selection

Sources were identified through searches in Google Scholar, ERIC, Scopus and ScienceDirect using combinations of the terms “mathematical competence”, “chemistry education”, “competence-based approach”, “integrated STEM”, “context-based learning” and “mathematical modelling”. Priority was given to peer-reviewed journal articles and monographs published by established academic publishers between 2007 and 2024. Sources were screened in two stages: an initial title-and-abstract screening for thematic relevance, followed by a full-text reading aimed at extracting design principles, assessment models and reported empirical effects.

2.3 Analytical procedure

The selected sources were coded along four analytical dimensions corresponding to the structural components of mathematical competence as articulated in the contemporary mathematics-education literature [8]: the cognitive component (mathematical knowledge and conceptual understanding), the operational component (procedural and modelling skills), the motivational–value component (interest, self-efficacy, professional identification), and the reflective component (metacognitive monitoring and transfer). For each source, pedagogical design features were classified according to whether they primarily addressed the adaptive dimension (orientation toward the chemical profession), the integrative dimension (structural coupling of mathematics and chemistry), or both. Recurring patterns were then synthesised into a small set of design principles and into a pedagogical model linking the approach to learning outcomes.

2.4 Limitations of the method

Because the present study is conceptual rather than empirical, its conclusions take the form of testable propositions rather than verified findings. The reviewed literature is dominated by studies conducted in North American, Western European and East Asian contexts; transfer to other educational systems requires cultural and curricular

adaptation. A formal systematic-review protocol was not adopted, which means that selection bias cannot be fully excluded. These limitations are discussed further in section 4.

3. Results

3.1 The construct of mathematical competence in chemistry

Across the reviewed literature, the mathematical competence of a future chemist emerges as a multi-componential construct rather than as a unidimensional measure of computational skill. Building on the competence-based formulation in [5] and on the framework articulated in [8], the construct can be described as the integrated readiness and ability of a student to use mathematical knowledge, procedures, and reasoning strategies to identify, formulate and solve problems that arise in the practice of chemistry. Four interrelated components are consistently distinguished: a cognitive component (conceptual mathematical knowledge and its disciplinary interpretations), an operational component (procedural fluency and the ability to construct and manipulate mathematical models of chemical systems), a motivational–value component (interest in mathematics-as-tool, self-efficacy, and identification with the chemical profession), and a reflective component (metacognitive awareness, error analysis, and transfer to novel contexts).

This decomposition is consistent with the argument that conceptual rather than purely procedural mathematical understanding is most strongly associated with chemistry performance [1], and with research on modelling-based instruction showing that students' ability to construct, interpret and critique mathematical models of chemical phenomena is a distinct learning outcome that should be assessed alongside computational fluency.

3.2 Design principles of the adaptive–integrative approach

The synthesis of the reviewed sources yields four mutually reinforcing design principles. They are summarised in Table 1 and elaborated below.

Table 1. Design principles of the adaptive–integrative approach and their primary targets in the mathematical-competence construct.

No	Design principle	Pedagogical mechanism	Primary competence target
1	Discipline-anchored content selection	Mathematical topics and tasks are chosen on the basis of their explanatory role in chemical theories and laboratory practice.	Cognitive component
2	Context-based and modelling-oriented tasks	Each mathematical concept is introduced through, or immediately applied to, an authentic chemical context (kinetics, equilibrium, spectroscopy, data analysis).	Cognitive & operational
3	Differentiated, adaptive support	Diagnostic assessment, tiered tasks, scaffolded modelling, and small-group peer learning accommodate heterogeneous mathematical backgrounds.	Operational & motivational
4	Authentic, competence-oriented assessment	Performance tasks, project-based modelling assignments, and reflective portfolios complement traditional written examinations.	Operational & reflective

Principle 1 — Discipline-anchored content selection. The mathematics curriculum for future chemists is not a generic service course but a deliberately reorganised body of content whose selection and sequencing follow the conceptual structure of chemistry. The chemistry-first perspective [7] exemplifies this idea: mathematical tools are introduced as responses to recognisable chemical problems rather than as decontextualised abstractions. This principle responds to the observation that even mathematically capable students often fail to see mathematics as relevant to chemistry, which depresses both motivation and transfer [1].

Principle 2 — Context-based and modelling-oriented tasks. A meta-analytic synthesis of research on context-based and STS approaches shows that situating new

concepts in authentic contexts improves both motivation and conceptual understanding without compromising performance on traditional measures [6]. When applied to mathematics-for-chemistry, the principle implies that mathematical concepts — derivatives in kinetics, integrals in thermodynamics, matrices in molecular symmetry, statistics in analytical chemistry — are introduced through modelling tasks that begin with a chemical question, proceed through mathematical formulation, and return to chemical interpretation.

Principle 3 — Differentiated, adaptive support. The heterogeneity of incoming students' mathematical backgrounds, documented at scale in general-chemistry cohorts [4], demands a differentiated pedagogical response. Practical manifestations include diagnostic pre-tests, tiered problem sets that calibrate difficulty to demonstrated proficiency, scaffolded modelling worksheets, and small-group active-learning sessions of the type evaluated by Clune and colleagues, whose week-long bootcamp produced measurable gains in students' confidence and sense of belonging [2]. Computer-algebra environments — such as the Maple-supported practical sessions described in [3] — offer complementary technological means to individualise the learning trajectory.

Principle 4 — Authentic, competence-oriented assessment. If competence is the goal, then assessment must elicit and evaluate performance in tasks that resemble the genuine intellectual work of a chemist. Context-based testing models implemented at the university level demonstrate that assessment items grounded in real laboratory scenarios can validly probe both mathematical and chemical reasoning while complementing traditional written examinations [6]. Project-based modelling assignments, reflective portfolios, and oral defences extend this principle to the operational and reflective components of competence.

3.3 A pedagogical model

The four design principles can be organised into a four-stage pedagogical cycle that operates at the level of a single instructional unit (lecture–seminar–laboratory–assessment) and is iteratively replicated across the curriculum. The cycle consists of: (a) a contextualisation stage, in which a chemical phenomenon is introduced and the need for mathematical description is made apparent; (b) a mathematisation stage, in which the mathematical content is developed in explicit dialogue with the chemical context; (c) a modelling-and-practice stage, in which students construct, manipulate and critique mathematical models of chemical systems with scaffolded support calibrated to their diagnosed level; and (d) a reflection-and-assessment stage, in which authentic tasks elicit evidence of the four components of mathematical competence and inform the next iteration of the cycle.

Within this cycle, the adaptive dimension manifests primarily in the calibration of content selection and scaffolding to the professional field and to the individual learner, while the integrative dimension manifests in the systematic coupling of mathematics and chemistry at every stage. The model thus articulates how the two dimensions, often discussed separately in the literature, can be operationalised together within a coherent instructional sequence.

3.4 Anticipated effects on the components of mathematical competence

On the basis of the reviewed evidence, the model is expected to produce differentiated gains across the four components of mathematical competence. The context-based and modelling-oriented tradition [6] supports gains in conceptual understanding and in the construction of mathematical models of chemical phenomena. The competence-based tradition [5] supports improvements in students' ability to apply mathematical knowledge to professional problems. The active-learning intervention reported in [2] provides evidence that such formats can increase self-efficacy and strengthen students' sense of belonging in the discipline. The reflective component is

the least studied empirically; the model treats it as a hypothesised outcome of authentic assessment and structured peer discussion, to be tested in subsequent empirical work.

4. Discussion

The adaptive–integrative approach articulated above brings together strands of research that are frequently treated separately. The competence-based tradition [5] has clarified what mathematical competence should consist of for a future specialist, but has only partly addressed the discipline-specific structure of mathematics instruction for chemistry students. The chemistry-education literature — from synthetic reviews of context-based teaching [6] to the contemporary debate on conceptual mathematical understanding [1] — has produced rich evidence on the mathematics problem and on context-based and modelling-based remedies, yet has not consistently framed these remedies in terms of a single competence construct. By proposing four design principles and a four-stage pedagogical model that explicitly couples adaptation to the chemical profession with integration of mathematics and chemistry, the present study contributes a unified instructional framework whose components are individually grounded in prior empirical work.

Several aspects of the approach deserve closer scrutiny. First, the discipline-anchored selection of mathematical content raises the question of which mathematics is genuinely necessary for contemporary chemistry. Recent curriculum analyses suggest that the answer increasingly involves linear algebra, differential equations, probability and statistics, and computational methods, alongside the classical calculus core [2, 3]. The adaptive–integrative approach is compatible with such a reorientation but does not by itself prescribe a specific topical inventory; this remains a matter for curriculum-level decisions informed by the chemistry programmes' graduate-profile documents.

Second, the integrative coupling of mathematics and chemistry depends on institutional conditions that are frequently absent: close cooperation between

mathematics and chemistry faculty, co-designed teaching materials, and shared assessment practices. Implementation studies of the proposed model would need to attend explicitly to these organisational dimensions.

Third, the role of digital tools deserves emphasis. Computer-algebra systems, statistical software, and discipline-specific simulations make it feasible to engage students in mathematical modelling of chemical phenomena at a level of authenticity that was previously inaccessible. The technology-supported pedagogy described in [3] illustrates how digital environments can carry the integrative principle, but their integration must itself be adaptive: technology choices should follow the professional practices of the chemical sciences rather than precede them.

The principal limitation of the present work is its conceptual nature. The propositions developed here are based on a triangulation of well-established research traditions but have not yet been tested in a coordinated empirical design. Subsequent work should pursue at least three lines of investigation: (i) quasi-experimental comparison of cohorts taught under the adaptive–integrative model versus parallel mathematics and chemistry courses, with outcomes measured on all four components of mathematical competence; (ii) longitudinal tracking of the transfer of mathematical competence into upper-division chemistry courses and capstone projects; and (iii) design-based research on the institutional conditions that make sustained adaptive–integrative implementation possible.

5. Conclusion

The mathematical preparation of future chemists is best conceived not as a remedial supplement but as the cultivation of a multi-componential professional competence whose development requires a deliberate alignment of mathematics teaching with the epistemic practices of chemistry. The adaptive–integrative approach proposed in this paper specifies this alignment along two axes: an adaptive axis that orients mathematical

content and pedagogical scaffolding toward the chemical profession, and an integrative axis that couples mathematical and chemical reasoning within shared tasks and assessments. Translated into four design principles — discipline-anchored content selection, context-based and modelling-oriented tasks, differentiated adaptive support, and authentic competence-oriented assessment — and a four-stage pedagogical cycle, the approach offers a coherent framework that consolidates established findings from chemistry-education, competence-based mathematics didactics, and integrated STEM research. Its empirical validation, particularly through quasi-experimental and longitudinal designs, constitutes a promising agenda for further research and a practical resource for the reform of mathematics teaching in chemistry programmes.

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