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Practical Dilemmas and Breakthrough Paths for Integrating Scientific Thinking into Chemistry Teaching

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Abstract. Cultivating scientific thinking is a key objective in competency-focused education reform. Chemistry, with its empirical nature, reliance on models, and macro-micro-symbolic representational system, offers a natural context for fostering such thinking. However, current chemistry instruction often integrates scientific thinking in a superficial or fragmented manner, disconnecting it from substantive knowledge acquisition. Through theoretical analysis and literature review, this paper examines the practical challenges in embedding scientific thinking into chemistry teaching—across objectives, content design, instructional processes, assessment, and teacher readiness—and analyzes contributing factors rooted in educational philosophy, evaluation systems, teacher development, and resource availability. Proposed pathways for improvement include redefining teaching goals, enriching instructional activities, shifting pedagogical approaches, innovating evaluation mechanisms, and strengthening teacher support, with the aim of informing deeper reform in chemistry education and advancing students' scientific reasoning abilities.

Keywords: chemistry teaching, scientific thinking, practical dilemmas, causal analysis, breakthrough paths

1. Introduction

As education shifts toward a focus on core competencies, the development of scientific thinking has become central to cultivating students' scientific literacy and capacity for innovation [1]. Such thinking encompasses not only critical reasoning and empirical analysis but also higher-order abilities such as systems thinking, model construction, and creative problem-solving [2]. Against this backdrop, the goal of science education has expanded beyond knowledge acquisition to include the fostering of inquiry skills and cognitive development.

Chemistry, as an experimental science grounded in observation and modeling, offers a natural platform for nurturing scientific thinking. Its practices—including hypothesis generation, experimental testing, and data interpretation—closely align with core elements of scientific reasoning [3]. For instance, laboratory work trains students in observation and evidence-based reasoning; the use of molecular and reaction models develops modeling competence; and transitions among macroscopic, microscopic, and symbolic representations foster abstract and systemic thought [4]. These features make chemistry particularly suited to developing students' scientific habits of mind.

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Nonetheless, integrating scientific thinking into classroom practice remains challenging. Instructional emphasis often remains on knowledge transmission, with thinking skills treated as secondary or addressed only superficially [5]. Common issues include the marginalization of thinking-related objectives, inquiry tasks lacking genuine intellectual engagement, and mechanistic use of models without critical reflection [6]. This disconnect between content and reasoning not only limits chemistry's educational potential but also constrains students' development as innovative thinkers.

A systematic analysis of these obstacles, their underlying causes, and possible pathways forward is therefore of both theoretical and practical importance. This study examines the chain connecting problems, reasons, and solutions, with the aim of supporting chemistry educators and researchers in meaningful instructional renewal.

2. Theoretical perspective: the theoretical basis for integrating chemistry teaching and scientific thinking

2.1. The nature and constituent elements of scientific thinking

Scientific thinking encompasses higher-order cognitive abilities—from foundational critical thinking to more complex processes like model construction, evidence evaluation, and systems analysis [2]. At its heart, it represents a reasoned approach to understanding nature: developing knowledge through hypothesis generation, experimental design, and evidence-based inference.

In chemistry, this thinking takes concrete form. It is reflected in the precise control of experimental variables, the ability to move flexibly between macroscopic, microscopic, and symbolic representations, and the critical evaluation of chemical models [4]. These competencies reveal the multidimensional character of scientific thinking and underscore the unique capacity of chemistry education to develop students' systemic and analytical reasoning.

2.2. Learning theory and the development of scientific thinking

From a learning theory perspective, constructivism posits that learners actively build knowledge and cognitive patterns through inquiry and participation—not by passively receiving information, but by restructuring mental frameworks through interaction with their environment [7]. Sociocultural theory emphasizes how social interactions—such as peer argumentation, collaborative inquiry, and classroom discourse—help develop scientific reasoning [8]. At the same time, cognitive development theory suggests that thinking-oriented tasks should match students' developmental readiness and zone of proximal development, making the cultivation of reasoning both accessible and appropriately challenging [9].

2.3. The alignment points between chemistry discipline characteristics and scientific thinking cultivation

Chemistry, as an experimental science, provides authentic contexts for developing scientific thinking. Laboratory work, for example, cultivates empirical reasoning and inductive-deductive skills by training students in precise observation, hypothesis building, variable control, and evidence-based conclusion drawing [10]. The subject also relies on models—from molecular structures to reaction mechanisms—engaging students in model construction, application, and revision, which strengthens model-based reasoning [11]. Furthermore, shifting across macro, micro, and symbolic representations helps students develop abstraction and symbolic competence.

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Complex concepts like chemical equilibrium and reaction kinetics promote systems thinking, enabling learners to grasp multi-factor interactions and dynamic processes [3].

2.4. Theoretical principles for effective integration

To effectively integrate scientific thinking into chemistry instruction, four principles prove essential: explicitness, contextualization, process focus, and reflective practice [12,13]. Explicitness means defining thinking methods as explicit learning goals and using modeling and think-aloud strategies to develop students' metacognitive awareness.Contextualization grounds thinking skills in meaningful chemical or real-world situations, strengthening relevance and engagement.Process focus values the progression of student reasoning—not just correct answers—by emphasizing questions, drafts, and conceptual development.Reflective practice guides students to examine and adjust their own thinking, fostering self-regulation and deeper cognitive growth [14].

3. Practical dilemmas of integrating scientific thinking into chemistry teaching

3.1. Deviation in teaching objective positioning and vague formulation

In current chemistry teaching practice, teaching objectives still significantly favor the memorization and reproduction of basic knowledge and factual content. In contrast, the formulation of scientific thinking objectives generally suffers from being vague, lacking operability and progressive hierarchy [6]. In many teaching cases, thinking objectives and knowledge objectives are mechanically separated, failing to achieve organic integration in depth and structure. Teachers often also lack the instructional design ability to systematically deconstruct higher-order thinking skills and integrate them into specific knowledge units.

3.2. Fragmentation of teaching content and insufficient thinking challenge

The organization of teaching content still clearly continues the arrangement pattern based on disciplinary knowledge points, failing to systematically construct high-quality question chains or challenging learning tasks that can stimulate students' sustained and in-depth thinking [15]. Students face significant cognitive obstacles when converting between the triplet representations of macro phenomena, micro particles, and symbolic expressions. Model teaching also mostly focuses on applying ready-made models to explain phenomena, lacking guidance for students to critically reflect on the model establishment process, applicable conditions, and inherent limitations [4].

3.3. Teacher dominance in the teaching process and lack of inquiry

The classroom teaching model is still dominated by teacher lecturing and control, with students having severely insufficient opportunities to initiate inquiry actively, participate in scientific argumentation, and collaboratively solve problems [16]. Teacher-student interactions and classroom dialogues mostly revolve around factual knowledge or low-level questions, failing to effectively promote students' engagement in higher-order thinking activities such as comparative prediction, hypothesis testing, and evidence evaluation [17]. Furthermore, in the experimental teaching component, there is a phenomenon of being replaced by demonstration experiments, virtual experiments, or "cookbook-style" operations, leading to students lacking complete, open inquiry experiences and thinking training [18].

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3.4. Singularity of teaching evaluation methods and lack of focus on thinking

The teaching evaluation system still relies heavily on traditional paper-and-pencil tests, which are difficult to capture and measure the complexity, dynamics, and individual differences displayed by students in the process of scientific thinking [19]. Evaluation content overemphasizes the examination of disciplinary conclusions and knowledge mastery, relatively neglecting the assessment of thinking quality, reasoning logic, and problem-solving processes [20]. Simultaneously, there is a scarcity of process-oriented evaluation tools for thinking development, making it difficult for students to receive timely and effective feedback to promote self-adjustment of their thinking modes [21].

3.5. Teachers' cognitive bias and professional ability limitations

Some teachers' understanding of the connotation of scientific thinking remains relatively superficial, often equating it with problem-solving skills or logical reasoning steps, and failing to fully grasp its multidimensional characteristics including critical, creative, and systems thinking [22]. In actual teaching, teachers generally lack systematic and effective strategies for cultivating thinking, while also facing multiple practical constraints such as their own insufficient scientific thinking literacy and the lack of relevant teaching cases and training resources [5].

4. Causal analysis of practical dilemmas in integrating scientific thinking into chemistry teaching

4.1. Educational culture inertia and conceptual cognition limitations

The current education system is still deeply influenced by the tradition of exam-oriented education, whose significant inertia leads teaching practice to significantly focus on the transmission and mastery of disciplinary knowledge, while insufficient attention is paid to the cultivation of scientific thinking [23]. The traditional view of knowledge transmission still dominates among teachers and public perception. Many educators have not yet fully understood and embraced the "thinking-oriented" teaching philosophy, and their recognition of the long-term value of students' cognitive development and thinking quality is limited [1]. Additionally, utilitarian educational values widely pursue short-term visible results and college entrance effects, neglecting the long-term cultivation of higher-order literacies such as critical thinking, systems analysis, and innovation awareness, further weakening the internal motivation for thinking orientation in teaching reform [24].

4.2. Vagueness of curriculum standards and disconnection from the evaluation system

Although current curriculum standards propose requirements for cultivating scientific thinking, they generally lack clear guidance on the specific manifestations of thinking development and ability level gradations, making it difficult for teachers to grasp the implementation path and hierarchy in actual teaching [6]. At the same time, because high-stakes exams such as the Zhongkao and Gaokao still focus on knowledge reproduction and formulaic problem-solving as key assessment points, failing to effectively integrate the measurement of higher-level scientific thinking like hypothesis construction, model evaluation, and evidence reasoning, a significant disconnect arises between curriculum objectives, teaching practice, and evaluation methods, further hindering the effective implementation of thinking teaching [19].

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4.3. Absence in teacher education and insufficient professional support

During the pre-service teacher training stage, teacher education courses generally lack systematic training on the connotation of scientific thinking and its cultivation strategies, resulting in significant shortcomings in the core ability of new teachers to implement thinking teaching in actual classrooms [12]. In post-service professional development activities, relevant training often emphasizes theoretical explanations, lacking practical case analysis and operational guidance combined with disciplinary content. School-based teaching research activities also fail to deeply touch upon the design and reflection aspects of thinking teaching, limiting the continuous improvement of teachers' related teaching abilities [5].

4.4. Scarcity of teaching resources and implementation condition constraints

Current textbooks still do not provide sufficient support for the explicit cultivation of scientific thinking in their content arrangement and activity design, lacking targeted modules and prompts to guide students in questioning, reasoning, and model construction [25]. Furthermore, high-quality resources suitable for thinking teaching, such as typical teaching case libraries, process-oriented evaluation tools, and dedicated learning platforms, are still relatively scarce, restricting teachers' effective use of relevant teaching strategies [21]. Simultaneously, the implementation level also faces practical constraints, including the tight class hours stipulated by the curriculum standards making it difficult to conduct in-depth inquiry, and large class sizes preventing teachers from fully attending to each student's thinking process [8].

5. Constructing practical breakthrough paths for integrating scientific thinking into chemistry teaching

5.1. Reconstruct the teaching objective system to achieve multiple integration of knowledge, thinking, and literacy

A multidimensional objective framework integrating knowledge understanding, thinking development, and competency enhancement should be systematically implemented in chemistry teaching. Specifically, it is necessary to combine learning progression theory to stratify, refine, and explicitly formulate scientific thinking objectives, clarifying the focus of thinking development and expected performance levels for each learning stage and theme [6]. For example, in conceptual learning and experimental inquiry, teachers should explicitly set observable and evaluable thinking objectives such as "establishing awareness of variable control" and "conducting evidence-based reasoning," thereby achieving organic unity between knowledge transmission and thinking cultivation at the instructional design level [10]. Some regions in China have begun exploring the specific implementation of incorporating thinking objectives into curriculum standards. For instance, Shanghai's "Thinking Literacy Grading Guide" for chemistry subject teaching divides scientific thinking into three levels: basic thinking, comprehensive applied thinking, and innovative thinking, providing specific behavioral representations for each level, offering teachers a highly operable reference for designing teaching objectives. Zhejiang Province, in deepening curriculum reform, explicitly proposed the "knowledge, ability, thinking, value" integrated teaching objective design concept, emphasizing the infiltration of classification and comparison thinking in chemical concept teaching, and strengthening variable control and inductive reasoning thinking in chemical experiment teaching, achieving deep integration of thinking objectives and disciplinary content.

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5.2. Optimize teaching content and activity design to strengthen the thinking process experience

Teaching should move beyond the traditional approach of simply listing knowledge points. Instead, it should create authentic, open, and cognitively challenging problem situations, using driving questions and project-based tasks to stimulate students' higher-order thinking [15].

In terms of content delivery, the Claim–Evidence–Reasoning (CER) framework can be introduced to help students develop rigorous evidence-based reasoning and logical expression. Model-based instruction should also be strengthened—not only focusing on the application of models, but also guiding students to understand how models are constructed, their applicable conditions, and limitations [11].

Moreover, teachers should consciously support students in flexibly shifting between macro phenomena, micro explanations, and symbolic expressions. Through structured inquiry activities and timely scaffolding, students can overcome cognitive barriers [4].

Chinese teaching practices have demonstrated the effectiveness of Project-Based Learning (PBL) in chemistry education. For example, the "Water Quality Monitoring and Treatment" project developed by the Chemistry Education Team of Beijing Normal University engages students in field investigations, experimental testing, and data analysis—guiding them through the complete scientific inquiry process while fostering systems thinking and social responsibility.

Another case from Nantong Middle School in Jiangsu Province centers on core concepts such as chemical equilibrium and reaction mechanisms. Their "Model Construction and Evaluation" series encourages students to build models independently and participate in peer evaluation and debate, effectively enhancing model-based reasoning and critical thinking.

These approaches not only diversify instructional formats but also provide meaningful contexts for deep student thinking.

5.3. Transform teaching methods and teacher-student roles to create a thinking-friendly classroom

Teaching methods should shift from teacher-dominated to teacher-student collaborative inquiry, actively promoting heuristic, inquiry-based, and dialogic teaching methods. By improving the quality of classroom dialogue, encourage students to raise questions, express opinions, and engage in rational argumentation, making the classroom a place for clash of ideas and meaning construction [16]. Teachers need to deliberately "leave blanks," giving students sufficient time and space for thinking, trial and error, and reflection, tolerating and rationally viewing the "thinking detours" that occur during student inquiry, and transforming them into valuable teaching resources [21]. In Chinese classrooms, many teachers promote students' deep thinking through the design of "question chains." For example, in teaching "Galvanic Cells," teachers can design a series of questions: Why can a lemon light up an LED? How are electrons generated? How to design a more efficient battery? These questions progress layer by layer, guiding students from macro phenomena to the micro essence. Addressing the current situation of large class sizes, some schools have explored the "Thinking Mutual Aid Group" model, such as the "Group Debate-Style Learning" in Shandong Dulangkou Middle School, allowing students to fully express their views and engage in thinking collisions within small groups, while teachers play the role of guides and facilitators, effectively enhancing student participation and thinking quality.

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5.4. Innovate the teaching evaluation system, focusing on the thinking process and developmental performance

Evaluation reform is a key lever for promoting the implementation of thinking teaching. It should break through the limitations of traditional paper-and-pencil tests and introduce multiple evaluation methods such as performance assessment, observation records, learning portfolios, and project reports to comprehensively capture students' performance in thinking activities [19]. When formulating evaluation criteria, not only the correctness of conclusions should be concerned, but also the rigor of thinking logic, the rationality of the reasoning process, and the depth of reflection and revision. Strengthen process-oriented evaluation and provide timely, targeted feedback to help students achieve self-monitoring and optimization of their thinking [26]. Some regions in China have conducted beneficial explorations in evaluation reform. For example, the "Scientific Thinking Evaluation Scale" developed by Haidian District in Beijing quantitatively evaluates students' thinking processes from dimensions such as problem posing, evidence collection, reasoning logic, and reflection ability. Shanghai added question types like "Experimental Design and Evaluation" in the chemistry academic proficiency test, requiring students to analyze the rationality of experimental schemes and propose improvement suggestions, effectively guiding teaching to focus on the thinking process. Some schools have also tried using electronic portfolios to record students' thinking growth trajectories, such as the "Chemistry Thinking Growth Portfolio" developed by Shenzhen Middle School, which collects students' thinking works from different stages, including experimental design diagrams, argumentation drafts, and model construction processes, providing rich process evidence for evaluating students' thinking development.

5.5. Strengthen teacher professional development and support systems, building sustainable practice communities

Teachers are the key agents for realizing the cultivation of scientific thinking. Through practice-focused activities such as case studies, thematic workshops, and lesson study, deepen teachers' understanding of the connotation of scientific thinking and its teaching strategies [12]. Simultaneously, actively build regional or school-based resource sharing platforms, develop and provide practical resources such as teaching strategy toolkits, typical design cases, and evaluation rubrics that are easy for teachers to use [5]. The evaluation of the effectiveness of thinking teaching implementation should also be included in the teacher professional evaluation system to incentivize teachers' related teaching innovations [22]. In the Chinese context, teacher development programs at all levels have begun to focus on cultivating the ability for thinking teaching. The Ministry of Education's "National Training Plan" has added a special topic on "Scientific Thinking Teaching Design and Implementation," organizing university experts and frontline teachers to jointly develop training courses. The "Scientific Thinking Teaching Research Center" established by East China Normal University regularly holds national teaching case collection and seminar activities, promoting the dissemination and promotion of excellent practices. Many regions have also established regional teaching research communities, such as Jiangsu Province's "Chemistry Thinking Teaching Research Alliance," which helps teachers improve their design and implementation capabilities for thinking teaching through collective discussions by regularly conducting activities like "different lessons on the same topic" and teaching salons. The establishment of these support systems provides a solid professional guarantee for teachers to carry out thinking teaching.

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6. Conclusion

This study identifies several core challenges in integrating scientific thinking into chemistry education: instructional goals that prioritize factual knowledge over cognitive development, learning content with low cognitive demand, assessments that neglect higher-order thinking, and limited teacher awareness and expertise. These issues are rooted in misaligned educational philosophies, restrictive examination systems, insufficient teacher training, and resource limitations.

To counter these challenges, a five-dimensional framework is proposed—reorienting goals, redesigning content, transforming pedagogy, innovating assessment, and enhancing teacher support. Effectively fostering scientific thinking requires a fundamental shift from knowledge transmission to thinking development. This entails not only changes in classroom practice but also systemic coherence across educational philosophy, curriculum design, implementation, and evaluation [2]. Teachers are central to this transformation. Their ability to nurture scientific thinking depends on systematic professional growth, supported through theoretical training, case studies, instructional resources, and collaborative reflection [12].

Looking forward, persistent barriers include the dominance of exam-oriented culture, the need for scalable assessment tools, and delivering individualized support in large-class settings. Addressing these will require coordinated efforts among researchers, policymakers, teacher educators, and school practitioners to build an enabling ecosystem for thinking-oriented education. Future research should explore domain-specific thinking strategies, technology-supported developmental pathways, and the long-term impacts of teaching focused on scientific thinking—further realizing the educational value of chemistry.

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