Innovation in A-level Chemistry Teaching from the AI-TPACK Perspective: Reconstructing Cognition, Deep Interaction, and Whole-person Education

Lu Wan[1,*], Sanchuan Peng[2], Xiaohan Lei[1]
[1]Chongqing Depu Foreign Language School, Chongqing 401320, China
[2]Imperial College London, London SW7 2AZ, England
*Corresponding email: 317635463@qq.com

Abstract

This research report examines the deep application and teaching-paradigm innovation of digital technology in A-level Chemistry instruction at international high schools. In response to three persistent challenges in international chemistry education, namely cognitive overload, cross-language learning barriers, and limited personalization, this study draws on an expanded technological pedagogical content knowledge (TPACK) framework to design a coherent, technology-supported teaching system. Rather than focusing only on classroom tools, the report emphasizes the redesign of the wider learning ecosystem, including how instruction, materials, assessment, and student support can work together more effectively. The study explains how well-structured resources and instructional routines can function as “cognitive scaffolds” at the heart of A-level Chemistry, helping students manage complex concepts and connect macroscopic observations with microscopic models and symbolic representations. With particular attention to multilingual classrooms and the development of higher-order thinking, the report proposes practical, forward-looking strategies that teachers can implement and adapt. Using detailed teaching cases, careful comparative data analysis, and reflection on educational ethics, the research ultimately argues for a return to the core purpose of education: Helping students build strong scientific understanding while developing responsibility, judgment, and humanistic concern.

Keywords

AI-TPACK, A-level Chemistry, Chemistry education, Digital technology, Teaching innovation, Cognitive load

Introduction

The shift in educational ecology

International high schools currently sit at a friction point between secondary instruction and university expectations. The pressure isn’t simply abstract “digital transformation”. It is a tangible crisis of engagement. For modern cohorts, access to information is trivial - they are drowning in it. The actual scarcity is cognitive focus. Old-fashioned “chalk-and-talk” sessions are losing the battle against the digital noise in students’ lives. In this context, generative AI ceases to be just a disruption. Instead, we must treat it as necessary infrastructure, as vital as the laboratory fume hood itself, capable of converting abstract theory into something students can see and grasp.

Pedagogical pain points and challenges in A-level Chemistry

While academics label Chemistry the central science for the student sitting in the classroom, it often feels more like the invisible science. The unique difficulty of the A-level syllabus lies in the cognitive leap it demands. Students are forced to construct mental models of realities that are completely divorced from their sensory experience. Examples include the probability density of an electron or the fleeting nature of a transition state. This disconnects between macroscopic observation and microscopic theory creates several distinct cognitive bottlenecks.

Theoretical framework: From TPACK to AI-TPACK

The evolution of technological pedagogical content knowledge

The TPACK framework proposed by Mishra and Koehler has long guided the integration of educational technology [1]. However, with the advent of generative AI, it is essential to incorporate AI literacy into this framework, giving rise to AI-TPACK.

In chemistry education, this means that teachers must not only understand chemistry content knowledge, pedagogy, and technology knowledge, but also comprehend how AI represents chemical knowledge and how AI simulates human chemical reasoning [2].

For example, when using AI to explain hybrid orbital theory, teachers need integrated knowledge across multiple dimensions. They need content knowledge, understanding that sp^3 hybridization arises from the linear combination of atomic wave functions. They need pedagogical knowledge, recognizing students' difficulties in visualizing orbital transformations and the need for analogies and visualization. They need technological knowledge, knowing which 3D modeling software or AI tools can effectively render orbitals [3]. They also need AI knowledge, understanding how prompt engineering can guide AI to generate explanations appropriate for high school cognition rather than graduate level mathematical derivations.

Digital extensions of constructivism and cognitive load theory

Vygotsky's social constructivist theory posits that learning occurs through social interaction. In the AI era, AI increasingly assumed the role of a More Knowledgeable Other (MKO). Unlike static textbooks, AI can engage students in Socratic dialogue and provide interactive scaffolding.

Meanwhile, according to Sweller's Cognitive Load Theory (CLT), the high conceptual density of A-level Chemistry often results in cognitive overload [4]. AI technologies can reduce extraneous load through dual coding and increase germane load by generating varied practice tasks, thereby optimizing learning efficiency.

Innovation in physical chemistry teaching: Breaking the barrier of abstraction

Physical chemistry is the most logically demanding and mathematically intensive component of the A-level curriculum, encompassing atomic structure, thermodynamics, kinetics, and chemical equilibrium. AI applications in this domain primarily focus on visualizing abstract concepts and dynamically simulating mathematical models [5].

Immersive learning of atomic structure and electron configuration

In traditional A-level instruction, students often struggle with the counter intuitive reality of transition metals. They question why the 4s orbital fills before the 3d but loses electrons first during ionization. Standard textbooks present this merely as a rule to be memorized, creating a disconnect between mathematical logic and physical reality.

The AI enabled instructional process involves several steps. First, scenario construction uses AI based molecular dynamics simulations combined with VR interfaces to create an atomic exploration environment. Second, dynamic rendering allows students to input atomic numbers. AI numerically solves the Schrödinger equation to render electron probability density clouds in real time. Third, interactive inquiry lets students remove electrons using controllers, visually observing that 4s electrons are more diffuse and higher in energy than 3d electrons. This explains their preferential loss. Fourth, visual feedback shows energy level diagrams updating dynamically alongside microscopic images. This links abstract graphs with intuitive visuals.

Visualizing invisible energy flow in thermodynamics

Entropy and Gibbs free energy are major conceptual hurdles at the A_2 level. Students may memorize the formula without grasping its physical meaning.

The AI enabled instructional process for this involves several components. First, microscopic simulation uses an AI driven particle simulator to model gas systems at different temperatures. Second, variable control allows students to issue natural language commands. This prompts real time recalculation of microstates. Third, data visualization plots the free energy temperature curves dynamically. This allows students to observe spontaneity changes at critical temperatures. Fourth, conceptual deepening helps students develop an intuitive understanding of entropy driven processes rather than relying on rote criteria.

Inorganic and analytical chemistry: Building systemic thinking and spectral logic

Inorganic chemistry requires mastery of periodic trends, while analytical chemistry, particularly spectroscopy, represents one of the most cognitively demanding components of A-level Chemistry [6].

Dynamic knowledge graphs of the periodic table

This approach helps students move from fragmented facts to an interconnected understanding of periodicity and element behavior.

The technology supported instructional process includes two main parts. First, interactive concept mapping allows students to click on an element and explore a structured element in the universe. This links its key chemical properties to common uses, industrial applications, extraction methods, and typical reactions. Knowledge is learned in context rather than as isolated notes. Second, trend-based prediction lets students investigate hypothetical elements by fitting periodic trends with simple modelling tools. They then use those patterns to predict likely properties. This strengthens inductive reasoning and the habit of justifying predictions with evidence and trends rather than guesses [7].

"Detective mode" in organic spectroscopy

Interpretation of mass spectrometry, IR, and proton NMR is a frequent source of errors. This is largely because students struggle to connect spectral clues into a coherent structural argument.

The technology supported instructional process involves three strategies. First, individualized practice sets allow the system to produce different simulated spectra for each student. Practice is authentic and copying is minimized. Second, structured, step by step prompting provides students with staged prompts that support the reasoning process without giving away the final answer. Third, reverse checking for self-correction allows the system to generate expected spectra for a student's proposed structure. Students can compare, spot inconsistencies, and refine their reasoning.

Innovation in organic chemistry teaching: Reconstructing mechanistic and synthetic logic

Organic chemistry constitutes nearly half of the A-level syllabus, emphasizing reaction mechanisms and synthetic planning [8].

Dynamic visualization of reaction mechanisms

Reaction mechanisms, particularly the spatial inversion in SN2 reactions, represent a significant cognitive barrier. On a 2D whiteboard, the "curly arrow" is merely a symbol. Students often fail to perceive it as a representation of physical electron flow.

AI-assisted retrosynthetic analysis

The AI enabled instructional process for retrosynthetic analysis includes several steps. First, target setting involves teachers assigning target molecules. Second, AI guided disconnections provide feedback on unstable synthons. Third, multidimensional evaluation assesses routes using radar charts covering atom economy, step count, green metrics, and cost. This cultivates engineering and sustainability awareness.

Assessment and feedback: from outcome-oriented to process-focused

Automation and intelligence of formative assessment

Traditional weekly or monthly tests provide delayed feedback. AI technology makes high frequency, low risk formative assessment regular practice. Adaptive testing can automatically adjust question difficulty based on student performance. If a student consistently makes mistakes on a certain type of question, the system lowers the difficulty to help them fill in the gaps. If they perform well, they are pushed by advanced challenge questions.

Intelligent grading and thinking diagnosis of subjective questions

We developed a mark scheme aligned grading support system for A-level Chemistry. It goes beyond spotting isolated keywords. It checks whether students use clear cause effect reasoning and logical links. When marks are lost, it flags the exact missing step. For example, it might note that a student referred to intermolecular forces but did not state that van der Waals forces increase with the number of electrons.

In addition, teachers receive an aggregated class overview in the form of a topic heatmap. This highlights recurring misconceptions and weak knowledge points across the cohort and helps target revision more precisely.

Ethics, risk, and the return of the teacher's role

Avoiding technological dependency and cognitive outsourcing

If students get used to asking AI questions, they may lose their ability to think independently. We advocate setting up "AI-free zones" and stipulating that certain classroom activities (such as basic calculations and hand-drawn mechanism diagrams) must be completed completely without electronic devices. At the same time, we design "spot the error" courses to allow students to find errors (illusion phenomena) in AI-generated content and train their critical thinking.

A new definition of academic integrity

Schools should develop clear guidelines for the use of AI. When using AI assistance, students must retain the dialogue records as attachments and clearly state the proportion of AI's contribution to the work. This transforms "anti-cheating" into "responsible use of tools" [9].

Reshaping the teacher's role

In the AI era, the value of teachers as "knowledge transmitters" is diminishing, but their value as "engineers of the soul" is rising. Emotional connection: AI cannot perceive the confusion in a student's eyes, nor can it offer warm encouragement when an experiment fails.

Moral mentor: In discussions about the dual uses of chemicals and drug ethics, the humanistic guidance provided by teachers is irreplaceable by AI.

Classroom conductor: Teachers design complex PBL activities, organize debates and collaborations - these high-level socialization activities are the soul of education.

Conclusion

Innovation in international high school chemistry teaching is far more than swapping chalkboards for screens or updating classroom hardware. It reflects a deeper shift in how we understand learning itself. The real goal is to make the invisible microscopic world intelligible. It is to turn abstract symbols and mathematical logic into thinking tools students can use. Within shared curriculum standards, it is better to respect different starting points, learning speeds, and ways of understanding.

At the same time, improvements in tools and methods also remind us that chemistry education cannot revolve only around efficiency and test scores. It has to return to the growth of the learner: Nurturing curiosity and creativity through inquiry and experimentation, strengthening safety awareness and ethical judgment through scientific practice, and building communication and empathy through collaboration and discussion.

A future oriented chemistry classroom should feel like a learning community with both structure and energy. Resources should serve understanding. Teachers should offer expertise and care as steady guidance. Students should develop solid scientific literacy while keeping a sense of responsibility toward society and the world.

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Conflicts of Interest

The authors declare no conflicts of interest.

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