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Research Progress of Generative Artificial Intelligence in Secondary School Chemistry Teaching

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Abstract:

As a cutting-edge branch of artificial intelligence technology, generative artificial intelligence (GenAI) is effecting a profound transformation in secondary - school chemistry education. This study undertakes a systematic review of 31 related research papers to analyze the current application of GenAI in chemistry teaching. Through discussing four key dimensions—homework and assessment optimization, experimental teaching innovation, instructional design empowerment, and personalized learning support—the research not only unveils the underlying mechanisms of technological empowerment but also grapples with practical challenges such as data security and algorithmic bias. It ultimately proposes development paths including building human-machine collaborative teaching paradigms and cultivating critical thinking. The findings demonstrate that GenAI bolsters the personalization and efficacy of chemistry instruction via intelligent content generation, contextualized interaction design, and precise data feedback. However, the study emphasizes the necessity to address time constraints in technology application while preserving the rational essence of education.

Keywords: generative artificial intelligence; secondary school chemistry teaching; educational application; research progress

1. Introduction

In this era of swift technological progress, emerging technologies like artificial intelligence are reshaping the education ecosystem. Generative AI, in particular, is increasingly infiltrating educational settings.

Chemistry, a cornerstone of secondary education, is an experimental science that links macroscopic phenomena with microscopic principles. It poses distinct challenges in fostering students' abstract thinking and practical skills.. Traditional teaching approaches frequently struggle to meet the demand for personalized, tangible learning experiences when dealing with the subject's complexity. The advent of generative AI technology has brought about a revolutionary change in chemistry education.

Current research on generative AI applications in secondary school chemistry education has shifted from theoretical hypothesis to practical innovation. From the early rule - based Q&A systems to the contemporary intelligent teaching assistants powered by large language models, the extent and depth of generative AI integration in chemistry education keep expanding..

Through a literature review, this paper systematically discusses the core application scenarios of generative AI in secondary school chemistry education, its technological enabling of teaching practices, existing challenges, and future prospects. The study aims to provide educators with a reference that combines theoretical profundity with practical value, fostering deeper integration and sustainable development of generative AI in chemistry teaching.

2. The technological empowerment of generative artificial intelligence in secondary school chemistry teaching

2.1 Multi-dimensional and Visual Representation of Knowledge

Generative AI effectively bridges the cognitive divide between macroscopic phenomena and microscopic principles in chemistry education through multimodal knowledge representation. For instance, when teaching atomic structure, AI transforms abstract quantum mechanical models into intuitive electron cloud distribution animations. By utilizing different colors and transparency levels to vividly illustrate electron probability distributions,[1] it deepens students'understanding of the abstract concept of "electron orbitals". In the instruction on chemical equilibrium shifts, the system-generated dynamic models allow students to independently adjust parameters like temperature and concentration, facilitating real - time observation of equilibrium constant curves.[2] This approach not only enhances students' grasp of Le Chatelier's principle but also reinforces their mastery of the fundamental concept.

The generative AI's capability to construct knowledge graphs enable students to build structured chemical cognition systems. During the "elements and compounds" review, the system automatically generates an element-centered knowledge network. For example, the "iron element" node links its properties to elemental forms, oxides, hydroxides, salts, and their inter - transformations. Reaction conditions and types are clearly indicated by arrows between nodes,[3] significantly enhancing students' knowledge extraction speed. In "organic chemistry" learning, AI-generated reaction-type mind maps such as the "substitution reaction" include halogenation, nitration, esterification subtypes and typical reaction formulas,[4] assisting students in establishing a systematic organic chemistry knowledge framework.

2.2 Personalization and adaptability of cognitive processes

Generative AI, powered by precise cognitive diagnostics, provides personalized learning support that precisely caters to the diverse needs of chemistry education. By analyzing students' problem-solving processes in "redox reactions", the AI accurately identifies cognitive challenges. For example, while some students grapple with "oxidation state determination", others encounter difficulties in "electronic conservation application".[5] Subsequently, the system offers customized learning resources for each group, which significantly boosts the efficiency of error correction across diverse learning patterns.

In the realm of learning path planning, generative AI demonstrates remarkable dynamic adaptability. The system automatically customizes personalized learning paths for students according to their pre - test outcomes. Students with relatively weaker foundations progress through a "basic calculation-comprehensive calculation-experimental calculation" sequence,[6] Conversely, those with

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stronger capabilities can directly proceed to advanced training. This approach significantly enhances the rationality of the learning progression. When delving into experimental design concepts, AI incrementally raises the design complexity in accordance with the quality of students' experimental proposals. It guides them from "single - variable experiments" to "multi - factor optimization experiments".[7] This method effectively promotes students' cognitive development in a step-by-step manner.

2.3 Processual and Diagnostic Learning Evaluation

Generative AI has brought revolutionary transition to chemical learning assessment by shifting from traditional summative evaluation to formative assessment, thereby enabling dynamic diagnosis and feedback throughout the learning process. In laboratory operations, the system employs video analysis technology to evaluate students' procedural compliance in real time, offering specific scores and improvement suggestions for each step.

When it comes to evaluating cognitive abilities, generative AI showcases profound analytical capabilities. During short-answer tests, the system evaluates both the correctness of answers and students' analytical thinking patterns. For example, if a student responds to "the effect of temperature on reaction rate" by simply stating "higher temperature accelerates reactions" without elaborating on the microscopic mechanism of "increased percentage of activated molecules," the AI automatically flags "enhanced microscopic analysis required" and provides relevant cognitive frameworks,[8] This makes the development of thinking skills more targeted.

The value-added assessment feature of generative AI focuses on tracking students' learning progress trajectories rather than static academic performance. When students are learning chemical notation, the system meticulously records each student's improvement in symbol writing. For example, it documents the change from a 30% error rate in chemical formula writing to a 10% rate,[9] generating a 'progress curve' that effectively motivates students.

2.4 Naturalization and contextualization of teaching interaction

The natural language interaction feature of generative AI fosters an immersive dialogue environment for chemistry learning. In in-depth chemistry history studies, students can engage in conversations with the AI - simulated "Lavoisier". By asking questions like "How did you discover oxygen?" they can obtain responses generated by the system, which are grounded in detailed historical materials,[10] which greatly enhances the learning experience.

In problem-solving instruction, generative AI adopts a step - by - step guidance approach that effectively prompts deep thinking. When students ask, "How can we distinguish between sodium carbonate and sodium bicarbonate?" the system leads them through a series of follow-up questions: "What are the differences in their chemical properties?", "Which properties can be used for identification?", and "What should be considered when designing the experiment?"[11] This method significantly enhances problem-solving skills compared to merely providing the answer.

Virtual scenarios developed by generative AI can substantially strengthen the translation of chemical knowledge into real - world applications. In the "Chemistry and Life" unit, the system creates virtual "home experiments" like "testing water scale composition". Here, students can independently select reagents and design experimental procedures within a simulated kitchen environment. Concurrently, AI generates experimental phenomena based on authentic chemical principles.[12] This effectively improves students' knowledge-transfer capabilities.

3. Challenges and prospects of applying generative artificial intelligence in middle school chemistry teaching

3.1 Challenges

The application of generative artificial intelligence in middle school chemistry teaching encounters numerous technical challenges, encompassing image - recognition accuracy, data privacy, algorithms, knowledge updates, and more.

Firstly, the inadequate accuracy of image recognition results in misidentifications of experimental instruments. For example, in complex laboratory setups, the misidentification rates for equipment like “fractionating flasks” and “long-necked funnels” remain high,[13] indicating future improvement in recognizing similar instruments. Secondly, the scientific validity of molecular model generation needs to be enhanced. Some AI tools produce ethanol molecular structure models with bond angle deviations,[14] which may cause cognitive misunderstandings among students. Concerning data - privacy protection, sensitive student information such as answer trajectories and learning preferences poses risks of leakage. A case in point is the AI homework system of a middle school that experienced a security breach, resulting in unauthorized access to a large number of student answer records [15]. Furthermore, algorithmic biases impact educational equity. When designing exercises on the “metal activity series”, certain generative AI tools disproportionately emphasize specific metals while neglecting others,[16] causing imbalanced knowledge acquisition. Additionally, virtual lab operations differ significantly from real-world experiments. Students’ habits formed in virtual environments often do not transfer effectively to physical lab settings,[17] leading to notable discrepancies in operational accuracy between virtual and real experiments. Finally, large language models exhibit a lag in the update of chemical knowledge, with inadequate coverage of recent research findings, such as “room-temperature superconducting material synthesis” after 2023[18].

3.2 Development

When implementing generative AI, we must be vigilant against technological alienation, uphold the essence of education, and revert to educational rationality. Over-reliance on AI explanations may undermine students’ independent thinking abilities. Students who receive AI-guided instruction throughout the learning process show significantly weaker performance in tasks requiring independent reasoning compared to those in traditional - teaching groups[19]. The virtual experiments may lead to a decline in students’ experimental operation skills. Some students perform well in virtual experiments but frequently encounter basic operational problems in real - world experiments[20]. Meanwhile, the quantitative bias inherent in AI-based evaluations often overlooks the emotional dimensions embedded in chemistry learning. Assessments of “chemical inquiry reports” place excessive emphasis on data accuracy while failing to adequately address the depth of students’ reflective processes and innovative thinking during the inquiry process[21].

Furthermore, the algorithmic logic underlying generative AI tends to conflict with the disciplinary thinking inherent in chemistry AI’s problem-solving approach based on “pattern matching” could stifle students’ innovative thinking, especially in organic synthesis route design tasks where system-recommended solutions often follow conventional pathways.[22] This restricts students’ exploration of novel approaches. Data-driven teaching decisions may not adequately consider the complexity of chemical learning. Adjusting the instruction pace solely based on answer accuracy rates risks overlooking students’ cognitive development rhythms. Moreover, AI’s standardized feedback might homogenize students’ learning processes.

4. Conclusion

The application of generative artificial intelligence in secondary school chemistry education has evolved from experimental stages to deep integration. Through innovative methods such as tiered homework design, virtual experiment simulations, intelligent teaching innovations, and personalized learning support, this technology has significantly improved the relevance and effectiveness of chemistry instruction. Research suggests that generative AI, through multimodal knowledge representation, adaptive cognitive support, and naturalized teaching interactions, can surmount the challenges of abstraction,

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risk, and individual differences in chemistry learning, providing technological support for cultivating core subject competencies. However, challenges persist in technology implementation. Maintaining educational integrity while innovating, and keeping deepening research efforts are of great significance.

Firstly, we should achieve deep integration between generative AI and the chemical discipline. For example, developing specialized AI tools with distinct chemical - discipline characteristics, incorporating reasoning models and standard chemical - language processing modules that embody chemical thinking, to enhance AI's accuracy in dealing with chemical problems. Additionally, exploring the integration of generative AI with brain-science technology by leveraging learning neural mechanisms for adaptive learning path planning. This can help establish a generative AI-supported model for cultivating innovative chemical talents.

Secondly, we should establish a new paradigm for human-machine collaborative chemistry education by clarifying the roles of AI and teachers. Teachers should concentrate on cultivating disciplinary thinking and providing emotional guidance, while AI tackles technical tasks such as model generation and data visualization. This gives rise to a three-tiered interaction mechanism: AI initially conducts a preliminary grading of student assignments and identifies common errors, after which teachers provide in - depth guidance to address personalized issues.

Thirdly, AI literacy should be cultivated among teachers and students to boost technical proficiency and specialized training should be conducted for educators on "Generative AI + Chemistry Teaching" to improve their AI-integrated instructional skills. Then integrating AI-powered cognitive content and inquiry-based activities into chemistry courses is significant to foster scientific understanding of AI technology. Finally, AI can be utilized for designing and optimizing original experiments, while human should establish guidelines and standards for AI-assisted chemistry learning.

Fourth, strengthening the application safeguard system for generative AI is necessary to ensure its healthy development. Establishing access standards and ethical review mechanisms for generative AI teaching tools are also significant in chemistry education. Relevant authorities should exercise comprehensive oversight over the entire data lifecycle of AI applications—encompassing data collection, utilization, and storage. Furthermore, research community for AI-driven chemistry education that integrates the expertise of educational researchers, frontline chemistry teachers, and AI developers can be built, thereby advancing the in-depth integration of digital transformation in chemistry education.

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