



ARTIFICIAL INTELLIGENCE IN CHEMISTRY EDUCATION: OPPORTUNITIES, CHALLENGES, AND FUTURE DIRECTIONS

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The rapid development of artificial intelligence (AI) has become one of the most significant technological transformations of the 21st century. In recent years, AI-powered tools have increasingly entered educational environments, influencing how knowledge is accessed, processed, and communicated. Generative AI systems, particularly large language models such as ChatGPT, have attracted considerable attention due to their ability to generate human-like responses, support problem-solving, create educational materials, and facilitate communication between learners and educators (Araujo & Saude, 2024; Clark et al., 2023). As these technologies become more accessible, educational institutions face an important challenge: how can AI be integrated into teaching and learning in ways that enhance educational quality while preserving the fundamental goals of education?

The discussion surrounding AI in education extends beyond technological innovation. AI is increasingly viewed as a tool capable of supporting personalized learning, improving accessibility, and fostering student engagement (Araujo & Saude, 2024). Unlike traditional digital resources, generative AI systems can interact with users, adapt explanations to individual needs, and provide immediate feedback. Consequently, they have the potential to transform educational practices across different disciplines and educational levels.

Chemistry education represents a particularly relevant context for examining the educational potential of AI. Learning chemistry is inherently challenging because students are required to connect observable phenomena with invisible particulate processes and symbolic representations. According to Johnstone's triplet model, meaningful understanding of chemistry depends on successful integration of macroscopic, submicroscopic, and symbolic levels of representation (Johnstone, 1991; Talanquer, 2011). Students frequently experience difficulties in establishing these connections, which often results in fragmented understanding and persistent misconceptions. Therefore, educational innovations capable of supporting conceptual understanding are of particular interest in chemistry education.

One of the most frequently discussed advantages of AI is its capacity to support personalized learning. Students differ considerably in their prior knowledge, learning pace, motivation, and preferred learning strategies. Traditional classroom instruction often struggles to address these differences effectively. AI-powered systems can provide individualized explanations, generate additional practice tasks, offer adaptive feedback, and modify the complexity of learning materials according to student needs (Araujo & Saude, 2024; Yik & Dood, 2024). Such support may be particularly valuable in chemistry, where abstract concepts and complex problem-solving procedures often require repeated explanations and alternative instructional approaches.

The application of AI also offers new possibilities for developing students' problem-solving skills. Modern AI systems can guide learners through complex calculations, explain individual solution steps, and provide alternative approaches to solving chemical problems

(Araujo & Saude, 2024; Clark et al., 2023). When used appropriately, these tools can help students focus on conceptual understanding rather than solely on procedural execution. Furthermore, AI-generated explanations and examples may contribute to reducing cognitive barriers that frequently accompany the learning of chemistry.

Laboratory instruction constitutes another area in which AI may provide substantial educational benefits. Practical work remains one of the most important components of chemistry education because it enables students to connect theoretical knowledge with experimental evidence. However, laboratory activities are frequently constrained by limited resources, equipment availability, safety considerations, and time restrictions. AI tools can assist educators in designing laboratory activities, adapting experimental procedures to available resources, and creating context-based learning scenarios that enhance student engagement (Araujo & Saude, 2024; Trčková et al., 2024). In addition, AI may support students in preparing laboratory reports, interpreting experimental results, and reflecting on their findings.

Beyond supporting student learning, AI offers numerous opportunities for educators and researchers. Teachers may use AI to assist in lesson planning, assessment design, rubric development, and preparation of instructional materials (Clark et al., 2024; Fernández et al., 2024). Researchers can employ AI-powered tools for literature exploration, data analysis, and organization of scientific information (Wang et al., 2023; Zheng et al., 2023). Such applications may reduce administrative workload and allow educators to devote greater attention to pedagogical decision-making, mentoring, and direct interaction with students.

Despite these opportunities, the educational use of AI should not be approached uncritically. One of the most significant concerns involves the reliability and scientific accuracy of AI-generated content. Generative AI models occasionally produce inaccurate explanations, fabricated references, or scientifically incorrect information while presenting these outputs in a highly convincing manner (Exintaris et al., 2023; Ruff et al., 2024). In chemistry education, where precision and scientific rigor are essential, even minor inaccuracies may contribute to the development of misconceptions and misunderstanding. Consequently, both teachers and students must develop the ability to critically evaluate AI-generated information rather than accepting it uncritically.

Another challenge relates to the risk of passive learning. The educational value of AI depends largely on how it is used. If students rely on AI primarily as a source of ready-made answers, opportunities for independent reasoning, problem-solving, and knowledge construction may be diminished (Exintaris et al., 2023; Guo & Lee, 2023). Excessive dependence on AI could potentially reduce students' motivation to engage deeply with scientific concepts and weaken the development of critical thinking skills. Therefore, educational practices should encourage learners to evaluate, critique, and improve AI-generated responses rather than merely consuming them.

Particularly valuable educational opportunities may emerge when AI is used as an object of critical analysis. Students can be asked to identify errors, evaluate the validity of explanations, compare AI-generated responses with scientific sources, and justify their conclusions. Such activities transform AI from a simple information provider into a catalyst for critical thinking and metacognitive development (Clark et al., 2024; Exintaris et al., 2023; Guo & Lee, 2023). In this context, AI becomes a tool for learning about knowledge construction rather than merely acquiring information.

Additional concerns involve issues of accessibility, ethics, and safety. Advanced AI systems often require paid subscriptions, potentially creating inequalities among learners and educational institutions (Emenike & Emenike, 2023; Jaroonchokanan & Sirisathitkul, 2025). Furthermore, AI-generated laboratory suggestions may occasionally overlook important safety considerations or propose procedures that require careful professional verification (Araujo & Saude, 2024; Ruff et al., 2024). These limitations emphasize the continuing necessity of human supervision and professional responsibility in educational settings.

Perhaps the most important educational question raised by AI is not whether students will use AI, but how its presence will reshape the goals of chemistry education. For decades, chemistry instruction has focused heavily on the acquisition and reproduction of knowledge, requiring students to recall concepts, solve calculations, and apply established procedures. However, generative AI systems are now capable of providing explanations, solving quantitative problems, generating laboratory protocols, and even producing scientifically sounding reports within seconds. AI will not transform chemistry education simply because it can provide answers. Rather, it will transform chemistry education because it forces educators to redefine what it means to understand chemistry. If students can instantly obtain explanations, calculations, and laboratory protocols from AI systems, chemistry education can no longer focus primarily on information transmission. Consequently, future chemistry education may place greater emphasis on scientific reasoning, critical evaluation of information, interpretation of evidence, the ability to distinguish scientifically valid explanations from plausible but incorrect ones, and the responsible use of digital technologies (Emenike & Emenike, 2023; Exintaris et al., 2023; Guo & Lee, 2023; Ruff et al., 2024). In this context, the educational value of AI does not lie in replacing human thinking but in creating new opportunities for its development. Students should be encouraged to question AI-generated responses, identify inaccuracies, compare alternative explanations, and justify their conclusions using scientific evidence. Such practices can transform AI from a provider of answers into a catalyst for deeper learning, critical thinking, and metacognitive development.

The future of chemistry education may therefore depend less on the capabilities of AI itself and more on educators' ability to design learning environments in which technology supports, rather than substitutes, meaningful scientific inquiry in ways that promote understanding, curiosity, scientific literacy, and lifelong learning. From this perspective, the role of teachers becomes even more important rather than less significant. AI cannot replace the pedagogical expertise, ethical judgment, and professional experience required to support meaningful learning. Instead, it should be viewed as a complementary tool that enhances educational practice while leaving essential educational decisions in human hands. Teachers remain responsible for ensuring scientific accuracy, promoting critical thinking, fostering student motivation, and creating safe learning environments.

The central question is therefore no longer whether AI will become part of chemistry education. Its presence in educational practice is already a reality. Its greatest potential lies in supporting human expertise and enriching educational experiences. When combined with sound pedagogical principles and critical evaluation, AI may become a valuable partner in advancing chemistry education and preparing students for the increasingly complex scientific and technological challenges of the future. In this new educational landscape, the teacher remains indispensable—not as a source of answers, but as a guide who helps students transform information into understanding and understanding into knowledge.

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