



Tipping Point in the Future Readiness of Artificial Intelligence and Chemistry Education

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Abstract

The potential for artificial intelligence (AI) to make a transformative impact in the chemistry research and education field begins with the contributions of university administrators, instructors, and students. As a team of international authors from 9 global regions representing these 3 roles in the university, we use public data to argue for a re-thinking and update to the chemistry curriculum to train the next generation of scientists. To prepare researchers for the future with AI, chemistry education must be designed for new approaches to problem-solving and ways of thinking. Analysis of higher education AI chemistry courses was extracted from publicly available information based on the 2024 QS World University Ranking and separated into two categories: “computational coursework” and “AI/ML coursework”. The data revealed that institutions with existing computational coursework also tend to offer AI/machine learning coursework. The paucity of these courses may reflect different funding priorities or a shortage of faculty trained in AI chemistry. Overall, immediate users such as university teachers can apply the Technological Pedagogical Content Knowledge (TPACK)-AI framework, originally proposed by Mishra and Koehler (2006) to describe the synergistic intersection of teachers’ technological, pedagogical, and content knowledge, and recently extended to encompass AI (Mishra et al., 2023), for instructional design, inspiring curriculum material and pedagogies to be conducive to learning chemistry. While novel approaches to teaching and learning can face significant implementation challenges due to various cultures, pedagogical innovation must continue to remain a priority to ensure our training remains relevant for future students. In this paper, we encourage the development of normative frameworks within higher education that avoid unequal workloads on academic staff and ensure all stakeholders have a voice in the creation of curriculum and training of our students for the future.

Keywords Artificial intelligence · Chemistry education · Critical thinking · Future-readiness · TPACK · Chemistry curriculum · Machine learning · Computational thinking · AI chemistry

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Introduction

Artificial intelligence (AI) is becoming increasingly relevant in both research and education (Gasteiger, 2020; Grzybowski et al., 2024; Roser, 2022). The advancement of AI has spurred chemical industries and researchers to take advantage of the opportunities provided by digital tools. Students have also experienced shifts in learning from the introduction in research as they begin to navigate a future with AI. In 2023, Investment in generative AI (GenAI) increased tremendously, reaching \$25.2 billion in funding. In Ireland, €370 million has been allocated to date via the Disruptive Technologies Innovation Fund, aimed to accelerate collaboration and innovation in the latest fields of technology (Government of Ireland, 2024). Beginning in 2024, CeADAR, Ireland's National AI Hub and part of the European Digital Innovation Hub network was allocated €1.9 million each year, to provide support for businesses to utilize AI (Government of Ireland, 2024). In Singapore, more than \$500 million in funding has been allocated for the country's Research, Innovation, and Enterprise 2020 and 2025 plans (Ministry of Communications And Information, 2023).

With more higher education institutions releasing computational thinking and AI in chemistry courses, there is an urgent need to analyze and evaluate the possible opportunities enabled by AI and ensure that future students and researchers can best utilize and prepare for a future in chemistry. Changes to the assessment regime have been shown to impact student achievement (Fung & Watts, 2019). Immediate and future users are prompted to contemplate on the extent to which chemistry curriculum should change to account for the moving trends of AI. The way that students use AI will shape how they learn – students have ultimate responsibility for learning and deserve to develop appropriate lifelong skills to effectively make use of the benefits AI brings.

With the chemistry community's attention on AI, computational chemistry (CC) has become indispensable for scientists involved in frontier chemistry research fields. University courses delivering AI enable students to adopt computational thinking (CT), CC, and cheminformatics knowledge relevant to the field of chemistry. These processes and methods can be translated into real-life scenarios students face in their future professional careers.

This study will discuss the historical milestones of AI influencing the progression of AI in the industry and academia sectors. Based on the current state of use of AI, the paper will move on to discuss relevant preparation required to effectively take advantage of the opportunities AI brings. The current state of adoption/delivery of computational and AI skills in chemistry will be investigated in higher

education institutions to provide insight into how the early adopters have been successful in getting started into building AI coursework in institutions. The article ends by discussing the necessary steps forward for immediate users and higher education governance.

Artificial Intelligence and its Influence of Scientific Thinking: Historical Developments

While the public's fascination with AI has skyrocketed in recent years, the field itself has been steadily evolving for almost a century (Grzybowski et al., 2024; Roser, 2022). More deliberate application of these tools in chemistry carries immense potential for accelerating research breakthroughs. In order to better comprehend the future of chemistry, one requires an understanding of the future of AI and its potential.

The introduction of AI demonstrates the mindsets researchers employ while acquiring knowledge. The main foundation of chemical calculations rests on “Deductive Learning”, a concept explaining how calculations are derived based on existing theories (Gasteiger, 2020). In 1965, the DENDRAL project was started by Edward Feigenbaum, Bruce Buchanan, Joshua Lederberg, and Carl Djerassi with a team of research associates and students (Alasadi & Baiz, 2023; Feigenbaum & Buchanan, 1990; Gasteiger, 2020). Written in the LISP programming language, the software program automated the decision-making and problem-solving processes for organic chemists. By analyzing the uploaded mass spectra data and identifying unknown organic molecules, the DENDRAL project possessed the ability to synthesize new information (Feigenbaum & Buchanan, 1990).

With a suite of modern scientific tools, chemists today now are equipped with more means to research and possess more opportunities to collect data and make discoveries. The retrosynthetic analysis is an organic chemistry concept founded by Elias James Corey and changed the way chemists construct and solve organic pathways (The Nobel Prize in Chemistry 1990, 2025). To synthesize a desired target compound, a series of reaction steps tracing back to the starting material needs to be identified. This milestone in 1990 reflects the starting point of computer-assisted synthesis planning, which subsequently transitioned to more involvement of AI in organic chemistry (Coley et al., 2017). As such, a black star between 1990 and the 2000s is included in Fig. 1 to reflect this important transition.

Retrosynthetic analysis can also be perceived as a form of critical thinking to problem-solve “backwards”, spurring the relevance of creativity in research and transforming the way scientists approach various challenges (Choo

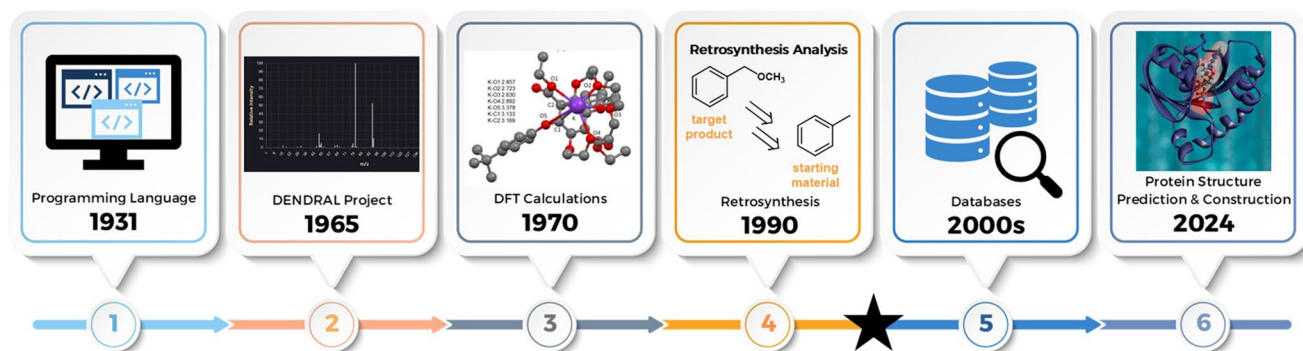


Fig. 1 Historical milestones of the progression of chemistry

et al., 2025). At this point, the foundation and mindset of chemical research have shifted from “Deductive Learning” to “Inductive Learning” (Gasteiger, 2020). Through inductive learning, new theories can be proposed from existing data, a concept that still currently serves as one of the main modes of thinking in chemistry.

Over time, we see that milestones in artificial intelligence have paved the way for the present state of chemistry research we are seeing today. The future possibilities in store for scientists extend beyond research, reaching into industry and the education of young chemists. The transformation of foundational modes of thinking and important skills required should thus inform how we prepare our future chemistry majors and scientists (Walter, 2024). Within this context, this paper will highlight the impacts of AI in chemistry education, particularly the key advances in these domains and the major indicators determining how prepared educators and researchers are for the future. This framework allows us to gauge the future readiness of our current chemistry undergraduates.

How will Teaching and Learning be Impacted by Artificial Intelligence?

Table 1 summarizes the major opportunities enabled by AI in both chemistry education. Each of these sectors presents various key opportunities that individual groups can best utilize. Questions for reflection for different audiences have been presented in the table below, as points of consideration to help them determine the priorities they wish to focus on. University administrators can question if there are sufficient avenues for instructors to use AI to achieve specific opportunities enabled by AI, whereas the instructors can reflect if they are designing assignments to help learners develop these skills, and for students, they should reflect by asking themselves the ‘how’ in solving problems, rather than focusing on the goal of finding solutions to problems.

Virtual reality and augmented reality represent such a modern approach to teaching and learning in the field of chemistry, where digital virtual platforms are simulated for students to experience and access a more interactive learning experience (An et al., 2020; Ananikov, 2024). Immersive learning environments with head-mounted displays have been found to yield positive outcomes as compared to other media types such as videos and presentation slides, with immersive virtual reality more appropriate as a teaching and learning tool for “action-oriented environments” to increase student engagement in learning (Han & Fung, 2025; Ziatdinov et al., 2024).

Utilizing digital platforms for chemistry learning, including game-based learning software and virtual reality simulations, can increase engagement and solidify foundational chemistry knowledge in students. Furthermore, the incorporation of AI including multimedia elements such as interactive animations and videos facilitates the acquisition of knowledge by accommodating students of diverse learning styles and enhancing conceptual understanding (Ananikov, 2024; Sui et al., 2023).

Artificial Intelligence and its Importance to Creativity and Critical Thinking

Computational chemistry is now indispensable for scientists involved in frontier chemistry research fields of drug discovery (Öztürk et al., 2020). In the future with AI, scientists can investigate reaction mechanisms, identify potential drug molecules and predict more complex calculations at more sophisticated levels (Fung et al., 2024; Luo et al., 2024). To prepare scientists to be well-equipped for such a future, it is vital that students now develop problem-solving abilities suitable to build and operate digital systems (Walter, 2024). The concept of chemical thinking can be defined as the development and application of chemical knowledge and practices with the main intent of analyzing,

Table 1 Summary of impacts of artificial intelligence and questions for reflection in chemistry education and research

Opportunities enabled by AI	Questions for Reflection		
	For University Administrators	For Instructors	For Students
Personalized Learning Experience Visualization (3D, Data, etc.)	What systems of support should be in place to enable instructors and students to take advantage of the opportunities?	What assignments, assessments, or tools should I design for my students to educate them into becoming future-ready graduates?	What tools/courses do I need to learn/enroll so that I am prepared to join the workforce for a better graduate outcome?
	Are there opportunities for instructors to support self-directed learning in class?	Am I creating opportunities for self-directed learning?	How can I utilize my resources to support my learning?
	Are there appropriate infrastructures and resources to handle visualization tools utilized by instructors and students?	Am I providing sufficient resources to train students to handle cases of hallucination by AI while using it to visualize molecules?	How can I prepare myself to handle potential hallucination situations by AI if I do not have sufficient prior knowledge in this domain?
Drug Discovery	Are there opportunities for instructors to impart foundational computational chemistry to students?	Am I providing students the necessary training for them to be equipped with foundational computational chemistry knowledge?	How can I prepare myself to learn foundational computational chemistry knowledge?
	Are there appropriate avenues for students to explore evolving and emerging domains using big data?	Am I creating opportunities for students to be exposed to evolving and emerging domains using big data?	How can I utilize my resources to expose myself to evolving and emerging domains using big data?
Big Data and Cheminformatics Laboratory Automation	Are there opportunities and resources for instructors to teach flow chemistry/adopt AI in chemistry education?	Am I providing opportunities for students to prepare for maneuvering lab robots in the future?	What courses/tools can I enroll/learn to program software with the aim to automate lab procedures using robots?
		Am I adopting AI resources and tools in chemistry education?	

synthesizing, and transforming matter for practical purposes (Sevian & Talanquer, 2014). At present, the dominant approach to teaching chemistry in most institutions involves delivering chemistry concepts as isolated topics, such as quantum chemistry separate from spectroscopy (Sevian & Talanquer, 2014). When taking the future of chemistry and AI into perspective, future scientists may be required to go beyond experimentation and transition into being designers, creating and evaluating methods and strategies to analyze, synthesize and transform research (Sevian & Talanquer, 2014). Hence, students need to be equipped with *computational thinking* (CT). CT describes the processes and methods used to operate a system (Hsu et al., 2018). It focuses on how people solve or research problems using computers, rather than the computer hardware or code (Hsu et al., 2018). By adopting CT through foundational computational chemistry or AI courses, students can translate skills learned from CT into real-life problems and scenarios faced during drug discovery processes along their professional career.

Critical thinking skills are crucial in learning AI (as students) and utilizing AI (as scientists). Computational thinking and computational chemistry and cheminformatics provide strong avenues for chemists to further their research, but critical thinking skills required for building chemistry-tailored technology are necessary to combine foundational technical skills with fresh ideas. The delivery of computational thinking or computational chemistry knowledge therefore involves the training and refinement of personal critical thinking skills, which can only be honed through individual effort and dedication. Guidance is paramount to lead future scientists and guide individual and unique development of critical thinking and problem-solving abilities.

How Higher Education has been Supporting the Advent of Artificial Intelligence

Analysis of Higher Education Artificial Intelligence Chemistry Courses

With AI tools like ChatGPT, Gemini and Claude becoming widely used, their role in scientific education and research is growing (Baytas & Ruediger, 2024). These new tools, together with established ML methods and computational simulations, are reshaping research, data analysis, and problem-solving, and they hold promises for improving educational outcomes and accessibility in higher education (Haraldsrud & Odden, 2025).

To see how higher education is supporting these advances, we analyzed publicly available course catalogs

and study plans from 51 top universities worldwide (Table S1). The selection of universities is based on the 2024 QS World University Rankings for the subject Chemistry (QS World University Rankings for Chemistry, 2024). In addition to the top 20 universities, we included 31 more, ensuring regional representation by selecting the highest-ranked university in each region within the top 150. Furthermore, University College Dublin, University of Zurich, and Xiamen University were included due to the authors' affiliation with these institutions. The public study plans and course catalogs from those selected universities were searched for classes within their bachelor's or master's degrees programs in chemistry that fit either computational or AI/ML related coursework. The classes were grouped according to their titles. If available, descriptions or syllabi were used to help categorize the classes.

Courses training CT, computational chemistry, or cheminformatics are labeled "Computational Coursework". While not directly teaching the use of AI, these courses suggest universities' openness to integrating AI topics and the importance of CT in using AI tools. Classes focusing on computational chemistry and cheminformatics also directly relate to the CT skills of students and thus are an important factor in preparing students for a future with AI (Weng et al., 2024).

Courses explicitly teaching AI or ML in chemistry are labeled "AI/ML Coursework". Although the syllabi or descriptions were not always insightful or available, these classifications can still help with understanding the trends in the introduction of AI related classes in higher education. Table 2 summarizes available offerings, also specifying the degree level with the date on which each of these universities was analyzed and accessed stated in Table S1 (Supporting Information).

Of the 51 universities, 38 offer computational coursework, with most focusing on computational chemistry (CC) or cheminformatics (CI), and only an eighth on CT (Fig. 2a). Nearly half the universities (23 of 51) offer AI or ML classes within a chemical context (Fig. 2b), with most classes in this category focusing on ML. For example, UCLA's "CHEM 151: Machine Learning for Chemistry" explores methods for modeling large and complex data sets, including neural networks and deep learning (Machine Learning for Chemistry, 2024). Encouragingly, over a third of AI/ML courses focus specifically on AI. For example, NTU Singapore offers the undergraduate class "CM4044: Artificial Intelligence in Chemistry," which teaches how AI can be applied in chemical contexts (CM4044 Course Description, n.d.). Notably, Imperial College London offers a master's degree titled "Digital Chemistry with AI and Automation" where all relevant topics are covered (Imperial College London, 2025).

Almost all universities offering AI/ML also offer computational coursework suggesting that a foundation in computational classes supports the integration of AI/ML. This aligns with literature identifying ML as a growing pillar of computational chemistry (Kuntz & Wilson, 2022). These courses are often driven by faculty research. At Stanford University, for instance, strong theoretical chemistry research has spurred curriculum growth for computational and AI chemistry. Additionally, institutional discussions, such as ones at Stanford, are shaping how AI is integrated into education more broadly, making it possible to introduce new classes and expand the curriculum (Stanford University, Office of the Provost, 2025).

Given that only a few years have passed since the introduction of more user-friendly AI in the form of large language models like ChatGPT has been made available to the public, it is both surprising and encouraging how quickly many universities have created courses focused on teaching students how to use AI and ML. As these students move forward in their careers and presumably incorporate more AI/ML tools and technologies into their own research, one would anticipate that a broader range and number of AI/ML-based courses be offered.

Necessary Steps Forward in Chemistry Education

The following section offers some questions to encourage stakeholders to assess the various supporting rationales and goals, followed by key alternative curricular implementations of AI. A conscious and transparent implementation, regardless of the changes made and the strategies employed for their deployment, is paramount for the subsequent assessment of whether pedagogical and curricular innovations truly produce the desired learning outcomes.

For Immediate Users of AI

When considering how higher education curricula must be adapted to better prepare students for the workplace of tomorrow, teachers and learners are, as the main actors and beneficiaries of the learning outcomes, the two stakeholders that warrant more attention. While the effectiveness of most teaching and learning practices, especially those occurring in the classroom, depend on the interaction of teachers and learners, it is important to be mindful that these and other relevant stakeholders (such as those in charge of education policy and governance or in-the-job training) do not engage with curricular and pedagogical resources, including AI, in the same way and to the same extent and that specific arrangements or frameworks of teaching and learning lead to interesting asymmetries in the interaction and control of these resources.

Table 2 Selection of universities which offer a class either in computational chemistry (CC), computational thinking (CT), cheminformatics (CI), machine learning (ML) or artificial intelligence (AI). Existing classes are marked ● for undergraduate/bachelor's and ○ for graduate/masters. Note that the date on which each of these universities was analyzed and accessed is stated in Table S1 (Supporting Information)

University	Region	CC	CT	CI	ML	AI
California Institute of Technology	United States	●○				
EPF Lausanne	Switzerland	○		●	○	○
ETH Zurich	Switzerland	●		●	○	○
Fudan University	China (Mainland)	●		●	●	●
Harvard University	United States	●				○
Imperial College London	United Kingdom	○	○	○	○	○
Indian Institute of Technology Bombay	India	●○		●		●
Karlsruhe Institute of Technology	Germany		●		●	
KU Leuven	Belgium	○				
Massachusetts Institute of Technology	United States	●○				
Nanyang Technological University	Singapore		●		●	●
National University of Singapore	Singapore	○	●	○	○	○
Northwestern University	United States	○				
Peking University	China (Mainland)	●			●	
Seoul National University	South Korea	●				●
Stanford University	United States	●○			●	
Technical University of Denmark	Denmark	●				
Technical University of Munich	Germany			●○		
The Hong Kong University of Science and Technology	Hong Kong SAR			●	●	
The University of Manchester	United Kingdom	●				
The University of Tokyo	Japan	●				
Trinity College Dublin	Ireland	●				
Universidad Nacional Autónoma de México	Mexico	●				
Universidade de São Paulo	Brazil				○	
Universitat de Barcelona	Spain	●				
Université de Strasbourg	France	○	○	●○	○	○
Universiti Malaya	Malaysia	●				
University College Dublin	Ireland	●				
University College London	United Kingdom	●				
University of Bologna	Italy			○		
University of California, Berkeley	United States	●○			●○	
University of California, Los Angeles	United States	●○			●	
University of Cambridge	United Kingdom			●		
University of Groningen	Netherlands				●	●
University of Helsinki	Finland	○				
University of Oxford	United Kingdom				○	
University of Toronto	Canada				○	
University of Vienna	Austria	○			○	
University of Zurich	Switzerland			●		
Uppsala University	Sweden	●	●			
Xiamen University	China (Mainland)	●○		●	●	●
Yale University	United States	●			○	

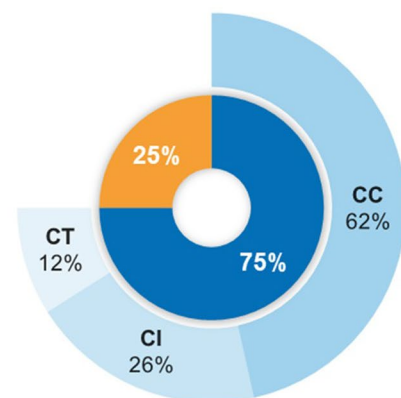
How Should the Curriculum Change to Account for AI?

The incorporation of AI into the higher education chemistry curriculum could pursue goals that could be grouped along two intertwined yet still independent dimensions: those seeking to enhance teaching and learning practices and those seeking to

provide professionally relevant knowledge and skills. In the former, the use of AI is subordinate to other learning goals. AI, for example, could be employed to design class contents and materials that facilitate learning, such as novel visualization of relevant chemical phenomena. It could also help deliver a more personalized learning, among others, by providing real-time answers to students' questions (Zawacki-Richter et al., 2019).

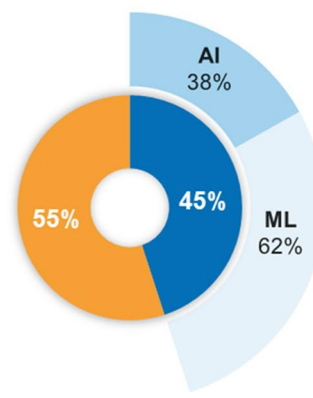
Fig. 2 (a) Number of universities offering computational coursework and the corresponding distribution of computational chemistry (CC), cheminformatics (CI) and computational thinking (CT) related classes. (b) Number of universities offering AI/ML coursework and the corresponding distribution of artificial intelligence (AI) and machine learning (ML) related classes

(a) Computational Coursework



■ Universities that offer
■ Universities that don't offer

(b) AI/ML Coursework



■ Universities that offer
■ Universities that don't offer

Alternatively, AI could be incorporated into teaching and learning practices with the intention to help learners develop skills and knowledge that are believed to be fundamental for the workplace of today (or tomorrow). GenAI, for instance, has proved successful in tasks such as coding. Given the ubiquity of computer programming in the professional practice of chemistry (Gill, 2022), curricular changes accounting for the development of knowledge and skills pertaining to the use of AI for coding might be warranted.

Curricular deployments of AI informed by the professional practice of chemistry are, perhaps, more essential. Because of the novelty and thereby relatively less regulated nature of GenAI, the future is also bound to be more uncertain. Although chemistry education and the contemporary workplace have already been changed by AI, decisions about what students should learn are bound by high uncertainty pertaining, most prominently, to future regulation in the use of AI and its overall social impact and to the progress in the cognitive capabilities of these technologies. For instance, given the current cognitive limitations of GenAI, teaching and learning practices in which AI is employed to support coding should encourage students and give them an opportunity to critically review the AI's output (Wu et al., 2025). The effectiveness of this instructional design with AI has yet to be determined, and it is worth evaluating.

What is true, however, is that the emerging trend to standardize and automate traditional manual experiments brings a new concern about how to connect the chemistry knowledge to the lab robot. To ensure current chemistry students are future-ready, teaching them some basic concepts of automation and organization skill of an automated experiment will be essential. Entry-level courses of mechanical

and information technology would arguably augment the availability of newly transited automation of chemistry and bring students with an advanced understanding of AI in chemistry.

Who is Responsible for Teaching AI-related Knowledge and Skills?

Because of the novelty of GenAI, most curricular changes so far have been made at the course level. Part of the challenge when considering the curriculum-wide incorporation of AI is that responsibilities, especially for complex knowledge and skills, are not always easy to assign. Extensive teaching on prompting can hardly be provided without heavily affecting the time and resources available for subject-specific chemistry materials. Possible alternatives, such as distributing this knowledge across several courses or creating new courses centered on AI, involve curricular trade-offs that require being mindful of a variety of contextual determinants. Coordinated or centralized efforts are probably needed to avoid a situation in which AI-related content is neglected or only superficially addressed to prevent major disruptions in the existing curriculum (Baker et al., 2019; Southworth et al., 2023).

It is also necessary to acknowledge the key role that external stakeholders play in helping students develop relevant AI-specific skills and knowledge. Students interact with external stakeholders primarily through internships and a variety of pedagogical practices relying on work-integrated learning. Since these stakeholders are experiencing in real-time how AI is reshaping the profession, they are able to provide students with insights that can readily be made actionable in the currently changing workplace (Ajjawi et al., 2024).

How can AI-related Knowledge and Skills be Harmonized with and Boosted by Other Pedagogical and Curricular Innovations?

While command of AI could be achieved by breaking down knowledge and skills that are becoming professionally relevant and incorporating them into diverse areas of the curriculum, a more robust and effective expertise requires being mindful of and accommodating to a variety of pedagogical innovations that have been taking place in the last few decades. Developing skills that foster adaptiveness are fundamental, considering that AI will not only change how chemists work, but, as mentioned above, will likely reshape entire professional domains in the upcoming years.

How can a Renewed Sense of Scientific Integrity be Developed?

The discussion about GenAI in education has disproportionately centered on the negative effects of these technologies, particularly in take-home assessments (Baron, 2023; Fazackerley, 2023; Stokel-Walker, 2022). Because of the extent of the disruption generated by AI, some solutions have revolved around the availability and efficacy of software to detect AI-generated content and around the adoption of AI-proof teaching and learning practices (e.g., going back to in-person hand-written assignments). This approach might work locally in a few courses, learning activities, and assessment tasks, but it is untenable for entire programmes, for, ultimately, the desire to prevent the use of AI often trumps considerations of how to better fulfil the expected learning outcomes. Failing to equip students with the skills and knowledge needed to navigate an AI-dominated job market could have significant negative consequences.

Against the backdrop of this tension, an important question arises about what should be prioritized when incorporating AI in the curriculum. While it could be argued that teaching and learning practices that allow students to completely defer the completion of a task to AI should be avoided, there might be a need to reassess how students engage with their learning process. With the possibility of AI developing increasingly complex cognitive capabilities, there is a need to encourage students to adopt a model of scientific integrity where the use of AI in their learning process is not motivated by considerations of whether AI can be used, but of whether it *should* be used (Stanford University, Office of Community Standards, 2023).

Such renewed model of scientific integrity requires, on the one hand, an honest conversation with students about how the education system is changing and how different stakeholders should contribute to the development of a

model that adequately meets the needs of the workplace of the future and, on the other hand, developing awareness in students about how, in a context of widespread availability of cognitive technologies, they should actively engage in acquiring knowledge and skills that prove professionally advantageous, while remaining mindful of what constitutes an ethical use of these technologies (UNESCO, 2024).

For Higher Education Governance

As immediate users of AI, both teachers and students have a crucial role to play. After them, the various stakeholders involved in the management of higher education institutions are key in the process of getting students to be future-ready, since they are responsible for curriculum design and coordination and for the formulation and adoption of various types of education policy.

Higher education institutions can greatly support their teachers by setting a normative framework that clearly stipulates duties, roles, and responsibilities for different stakeholders. For example, a teacher cannot incorporate AI in the curriculum if it is banned or might be hesitant to do so if there are no institutional mechanisms to handle improper misuse of AI technologies.

Institutions should, as well, develop a normative and physical infrastructure that robustly supports the use of AI. Teachers, for example, should be extensively trained on AI, first to acquire enough understanding of AI technologies (especially because some relevant elements are neglected in typical discussions e.g., the often overlooked difference between transformer and diffusion models is fundamental for visualization, a prominent potential application of AI in chemistry education) and, second, to update their teaching and learning practices accordingly (Mishra et al., 2023). Similarly, in some cases, the curricular incorporation of AI will require novel physical infrastructure and support, for example, in terms of software, which creates further training needs and regulation. Ideally, institutions should deliberately decide whether they provide students with access to AI technologies that do not use their data for training.

Learning about AI and incorporating it into the teaching and learning practices could be very demanding for some teachers, having to quickly invest time, first, for upskilling and reskilling and, second, for the update of class contents and materials. Higher institutions should be mindful of the burden this implies for their academic staff and make sure the curricular transition is adequately managed and properly rewarded, especially if the burden falls disproportionately on specific members of the staff, to prevent demanding and unequal workloads that negatively impact well-being (Bakker et al., 2005).

Faculty Professional Development and the Pedagogical Dimension of TPACK-AI

While much of the foregoing discussion has charted what students should learn, the success of any AI-integrated chemistry curriculum hinges on instructors who themselves possess the technological, pedagogical, and content knowledge required to teach with AI. Many current chemistry faculty completed their graduate training before computational thinking, machine learning, or generative AI tools became part of mainstream chemical research. Their transition into AI-augmented teaching constitutes a significant but yet often under-resourced institutional challenge that warrants more explicit attention than the broader discussion of curricular redesign typically affords.

The TPACK framework, originally formulated by Mishra and Koehler (2006) and substantially elaborated over the past decade by Chai et al. (2010, 2013), identifies the synergistic intersection of three knowledge domains required for effective technology-integrated teaching. In their study of preservice teachers' development of TPACK, (Chai et al., 2010) reported that pedagogical knowledge exerts the largest direct effect on overall TPACK, suggesting that AI training for chemistry faculty cannot be reduced to a tool tutorial. Instructors need to (re)develop pedagogical strategies for designing learning activities that genuinely exploit the affordances of AI, from molecule visualisation to retrosynthesis prediction, rather than bolting these tools onto existing instructional designs. Tsai and Chai (2012) describe this challenge in terms of a “third-order barrier” to technology integration: beyond access to tools (first-order) and personal beliefs or skills (second-order), teachers face a deficit of design thinking, that is, the creative capacity to reorganise pedagogy around new technological possibilities. For chemistry departments, addressing this third-order barrier is arguably more demanding than acquiring the AI tools themselves: it requires sustained pedagogical experimentation, peer observation, and iterative redesign of lessons and assessments.

Empirical evidence reinforces the urgency of this investment. Lee and Tsai (2010) reported that teachers' self-efficacy in integrating Web-based technology was, counter-intuitively, lower among those with more years of teaching experience, therefore implying that senior faculty, who often shape departmental curricula and graduate training, may be among those most in need of structured support. More recent work on AI-TPACK (Celik, 2023; Mishra et al., 2023; Ning et al., 2024) emphasises that effective AI integration further requires ethical and evaluative competencies: judging when AI output is reliable, when its use is pedagogically appropriate, and how to scaffold students' critical engagement with it. Wu et al. (2025) similarly argue

that instructors must cultivate students' epistemic agency in human–AI partnerships, which is a goal that presupposes the instructors themselves have first developed such agency through their own engagement with these tools.

Several practical mechanisms can support faculty upskilling at the departmental and institutional level. Drawing on self-determination theory, Chiu and Chai (2020) argue that sustainable AI curriculum planning depends on supporting teachers' autonomy, competence, and relatedness. The implication for chemistry departments is that mandated, top-down AI training is likely to be less effective than communities of practice in which faculty co-design AI-augmented chemistry activities and openly share what works and what does not. Concrete strategies that departments may consider include: (i) protected time and workload credit for AI-related course redesign; (ii) faculty learning communities pairing computationally trained chemists with experimentalists, so that pedagogical and content expertise are jointly developed; (iii) micro-credentials or certificate pathways recognising the upskilling effort in promotion and tenure processes; (iv) institutional partnerships with educational technology and teaching-and-learning centres for pedagogical design support; and (v) mentoring schemes that pair early-career faculty fluent in AI/ML with senior colleagues who hold deep disciplinary expertise. Without such mechanisms and the recognition and reward structures that make them sustainable, the burden of curricular transition is liable to fall disproportionately on a small number of motivated individuals, reproducing the unequal workloads we cautioned against earlier.

Ultimately, the pedagogical dimension of TPACK-AI is what differentiates a curriculum that uses AI from one that teaches with and about AI. Strengthening this dimension through deliberate, well-resourced faculty professional development is therefore not an optional complement to the broader curricular reforms outlined in this paper, but a precondition for them.

How Should Departments Support Faculty Upskilling?

Higher education institutions could equally support students in a variety of ways. They should, first, engage with students through transparent communication and training regarding what constitutes proper use of AI and appropriate sanctions for misuse. It also requires, as previously discussed, to create awareness in them about their responsibility towards their learning process and align institutional changes with students' perceptions, needs, and expectations (Chan & Hu, 2023; UNESCO, 2024).

Finally, higher education institutions should make external stakeholders aware of curricular changes seeking to

incorporate AI-related knowledge and skills, especially if these are embedded in further curricular and pedagogical innovations. They also should, if appropriate, explicitly involve these stakeholders in the modification of the curriculum, for as mentioned, they have real-time experience of the effect of AI on the workplace and are increasingly interacting with students through several work-integrated learning strategies. It will be easier for different stakeholders to be on the same page and for AI-related curricular innovation to prove effective if changes occur at the programme level, rather than as a collection of individual uncoordinated efforts by some teachers. Institutions must be aware, however, that current curriculum structures partially determine the nature and the scope of the changes that could be reasonably made (Binkley et al., 2012). For example, highly rigid and structured programmes, with several prerequisites and corequisites and few options for students to personalize their learning, make curricular changes more demanding, for these changes need to be more widely coordinated and most people must be involved.

Awareness of current teaching and learning practices is equally important. The desire to incorporate AI into the curriculum adds to an ongoing and wider push for curricular and pedagogical innovations in higher education. As previously mentioned, AI-related skills and knowledge could be more broadly linked to skills and knowledge that contemporary curricular and pedagogical innovations are equally emphasizing, such as computational and critical thinking, creativity, collaboration, problem-solving, or communication skills (Binkley et al., 2012).

Conclusion

This perspective discussed the historical evolution of AI and overcoming the limitations of manual computations to provide more opportunities for data prediction and data mining in research. The evolutionary shift from deductive learning to inductive learning also indicates the need to adopt relevant skills that meet the problem-solving and critical thinking rigor of more complex, interdisciplinary problems. To do so, university administrators, instructors and students all have individual roles that they can partake in to take advantage of the new opportunities that AI brings to the chemistry scene.

The analysis of higher education AI chemistry courses revealed that institutions with existing computational coursework are more likely to introduce AI/ML coursework. The lack of AI-related courses could possibly suggest a difference in funding directions, lack of faculty staff proficient in AI chemistry, or the priority to focus on the industrial relevance of chemistry courses for chemical and pharmaceutical industries present in the country.

It is also necessary to acknowledge how external stakeholders assist in the development of AI-specific skills in students, such as through internships and work-integrated learning, thereby providing insights that can be readily applied in the fast-moving trends in the workplace. For higher education governance, support through normative frameworks that stipulate duties, roles and responsibilities for different stakeholders prevents demanding and unequal workloads on academic staff. Creating awareness in staff about the responsibility towards student learning processes and the need for institutional changes with students' perceptions, needs and expectations is also essential. However, novel approaches to teaching and learning may face significant design and implementation difficulties.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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References

- Ajjawi, R., Tai, J., Dollinger, M., Dawson, P., Boud, D., & Bearman, M. (2024). From authentic assessment to authenticity in assessment: Broadening perspectives. *Assessment & Evaluation in*

- Higher Education*, 49(4), 499–510. <https://doi.org/10.1080/02602938.2023.2271193>
- Alasadi, E. A., & Baiz, C. R. (2023). Generative AI in education and research: Opportunities, concerns, and solutions. *Journal of Chemical Education*, 100(8), 2965–2971. <https://doi.org/10.1021/acs.jchemed.3c00323>
- An, J., Poly, L.-P., & Holme, T. A. (2020). Usability testing and the development of an augmented reality application for laboratory learning. *Journal of Chemical Education*, 1, 97–105. <https://doi.org/10.1021/acs.jchemed.9b00453>
- Ananikov, V. P. (2024). Top 20 influential AI-based technologies in chemistry. *Artificial Intelligence Chemistry*, 2(2), Article 100075. <https://doi.org/10.1016/j.aichem.2024.100075>
- Baker, T., Smith, L., & Anissa, N. (2019). *Educ-AI-tion rebooted? Exploring the future of artificial intelligence in schools and colleges*. Nesta. Retrieved May 16, 2026 from <https://www.nesta.org.uk/report/education-rebooted/>
- Bakker, A. B., Demerouti, E., & Euwema, M. C. (2005). Job resources buffer the impact of job demands on burnout. *Journal of Occupational Health Psychology*, 10(2), 170–180. <https://doi.org/10.1037/1076-8998.10.2.170>
- Baron, N. (2023). *How ChatGPT robs students of motivation to write and think for themselves*. The Conversation. <https://theconversation.com/how-chatgpt-robs-students-of-motivation-to-write-and-think-for-themselves-197875>
- Baytas, C., & Ruediger, D. (2024). Generative AI in Higher Education. *Ithaka S + R*. <https://doi.org/10.18665/sr.320394>
- Binkley, M., Erstad, O., Herman, J., Raizen, S., Ripley, M., Miller-Ricci, M., & Rumble, M. (2012). Defining Twenty-First Century Skills. In P. Griffin, B. McGaw, & E. Care (Eds.), *Assessment and teaching of 21st century skills* (pp. 17–66). Springer. https://doi.org/10.1007/978-94-007-2324-5_2
- Celik, I. (2023). Towards Intelligent-TPACK: An empirical study on teachers' professional knowledge to ethically integrate artificial intelligence (AI)-based tools into education. *Computers in Human Behavior*, 138, Article 107468. <https://doi.org/10.1016/j.chb.2022.107468>
- Chai, C. S., Koh, J. H. L., & Tsai, C.-C. (2010). Facilitating preservice teachers' development of technological, pedagogical, and content knowledge (TPACK). *International Forum of Educational Technology & Society*, 13(4), 63–73. <http://www.jstor.org/stable/jedu techsocio.13.4.63>
- Chai, C. S., Koh, J. H. L., & Tsai, C. C. (2013). A review of technological pedagogical content knowledge. *Educational Technology & Society*, 16(2), 31–51. <http://www.jstor.org/stable/jedutechso ci.16.2.31>
- Chan, C. K. Y., & Hu, W. (2023). Students' voices on generative AI: Perceptions, benefits, and challenges in higher education. *International Journal of Educational Technology in Higher Education*, 20, Article 43. <https://doi.org/10.1186/s41239-023-00411-8>
- Chiu, T. K. F., & Chai, C. (2020). Sustainable curriculum planning for Artificial Intelligence education: A Self-Determination Theory perspective. *Sustainability*, 12(14), Article 5568. <https://doi.org/10.3390/su12145568>
- Choo, Y. S. L., Kolanowski, J. L., Milić, J. V., & Fung, F. M. (2025). The retrosynthesis mindset: A problem-solving tool. *Synlett*, 36(06), 714–718. <https://doi.org/10.1055/s-0043-1775406>
- CM4044 *Artificial Intelligence in Chemistry Course Description*. (n.d.). Nanyang Technological University. Retrieved May 16, 2026 from https://www.ntu.edu.sg/docs/librariesprovider123/obt l/cbc/cm4044-obtl.pdf?sfvrsn=673517a8_2
- Coley, C. W., Rogers, L., Green, W. H., & Jensen, K. F. (2017). Computer-assisted retrosynthesis based on molecular similarity. *ACS Central Science*, 3(12), 1237–1245. <https://doi.org/10.1021/acscentsci.7b00355>
- Fazackerley, A. (2023). AI makes plagiarism harder to detect, argue academics – in paper written by chatbot. *The Guardian*. Retrieved May 16, 2026 from <https://www.theguardian.com/technology/2023/mar/19/ai-makes-plagiarism-harder-to-detect-argue-academic s-in-paper-written-by-chatbot>
- Feigenbaum, E. A., & Buchanan, B. G. (1990). (Hosts). *25th Anniversary of the DENDRAL Project—Buchanan, Barr, Friedland, Clancy, Bennett, Dietterich, Kunz, Englemore—Session #3* [Video recording]. <https://exhibits.stanford.edu/ai/catalog/wr759qp9369>
- Fung, F. M., & Watts, S. F. (2019). Bridges to the future: Toward future ready graduates in chemistry laboratories. *Journal of Chemical Education*, 96(8), 1620–1629. <https://doi.org/10.1021/acs.jchem ed.8b00771>
- Fung, F. M., Lederbauer, M., Choo, Y. S. L., Gehring, T., Jablonka, K. M., Jorner, K., Schwaller, P., Sullivan, M. B., Volkamer, A., Sigman, M. S., Liao, K., & Windle, C. (2024). Chemical education in digital chemistry. *Chem*, 10(12), 3519–3525. <https://doi.org/10.1016/j.chempr.2024.10.010>
- Gasteiger, J. (2020). Chemistry in times of Artificial Intelligence. *ChemPhysChem*, 21(20), 2233–2242. <https://doi.org/10.1002/cp hc.202000518>
- Gill, M. L. (2022). The rise of the machines in chemistry. *Magnetic Resonance in Chemistry*, 60(11), 1044–1051. <https://doi.org/10.1002/mrc.5304>
- Government of Ireland (2024). *Ireland's National AI Strategy: AI - Here for Good Refresh 2024*. Retrieved May 16, 2026 from <https://enterprise.gov.ie/en/publications/publication-files/national-ai-strategy-refresh-2024.pdf>
- Grzybowski, A., Pawlikowska-Lagód, K., & Lambert, W. C. (2024). A history of Artificial Intelligence. *Clinics in Dermatology*, 42(3), 221–229. <https://doi.org/10.1016/j.clindermatol.2023.12.016>
- Han, J. Y., & Fung, F. M. (2025). Spatial reality in education – Approaches from innovation experiences in Singapore. *Chemistry Teacher International*, 7(2), 287–302. <https://doi.org/10.1515/cti-2024-0088>
- Haraldsrud, A., & Odden, T. O. B. (2025). Bridging Artificial Intelligence and real intelligence: Self-scaffolding computational modeling with generative AI in chemistry. *Journal of Chemical Education*, 102(10), 4255–4266. <https://doi.org/10.1021/acs.jchemed.5c00657>
- Hsu, T.-C., Chang, S.-C., & Hung, Y.-T. (2018). How to learn and how to teach computational thinking: Suggestions based on a review of the literature. *Computers & Education*, 126, 296–310. <https://doi.org/10.1016/j.compedu.2018.07.004>
- Imperial College London (2025). *Digital Chemistry with AI and Automation*. Retrieved May 16, 2026 from <https://www.imperial.ac.uk/study/courses/postgraduate-taught/digital-chemistry/>
- Kuntz, D., & Wilson, A. K. (2022). Machine learning, artificial intelligence, and chemistry: How smart algorithms are reshaping simulation and the laboratory. *Pure and Applied Chemistry*, 94(8), 1019–1054. <https://doi.org/10.1515/pac-2022-0202>
- Lee, M.-H., & Tsai, C.-C. (2010). Exploring teachers' perceived self efficacy and technological pedagogical content knowledge with respect to educational use of the World Wide Web. *Instructional Science*, 38(1), 1–21. <https://doi.org/10.1007/s11251-008-9075-4>
- Luo, S., Gao, W., Wu, Z., Peng, J., Coley, C. W., & Ma, J. (2024). Projecting molecules into synthesizable chemical spaces. *arXiv Article arXiv:2406.04628*. <https://doi.org/10.48550/arXiv.2406.04628>
- Machine Learning for Chemistry*. (2024). University of California, Los Angeles. Retrieved May 16, 2026 from <https://catalog.registr ar.ucla.edu/course/2024/CHEM151?year=2024>
- Ministry of Communications and Information (2023). *NAIS 2.0 Singapore National AI Strategy—AI for the Public Good For Singapore and the World*. Government of the Republic of Singapore. Retrieved May 16, 2026 from <https://file.go.gov.sg/nais2023.pdf>

- Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A framework for teacher knowledge. *Teachers College Record: The Voice of Scholarship in Education*, 108(6), 1017–1054. <https://doi.org/10.1111/j.1467-9620.2006.00684.x>
- Mishra, P., Warr, M., & Islam, R. (2023). TPACK in the age of ChatGPT and generative AI. *Journal of Digital Learning in Teacher Education*, 39(4), 235–251. <https://doi.org/10.1080/21532974.2023.2247480>
- Ning, Y., Zhang, C., Xu, B., Zhou, Y., & Wijaya, T. T. (2024). Teachers' AI-TPACK: Exploring the relationship between knowledge elements. *Sustainability*, 16(3), Article 978. <https://doi.org/10.3390/su16030978>
- Öztürk, H., Özgür, A., Schwaller, P., Laino, T., & Ozkirimli, E. (2020). Exploring chemical space using natural language processing methodologies for drug discovery. *Drug Discovery Today*, 25(4), 689–705. <https://doi.org/10.1016/j.drudis.2020.01.020>
- QS World University Rankings for Chemistry 2024. (2024). Top Universities. Retrieved May 16, 2026 from <https://www.topuniversities.com/university-subject-rankings/chemistry/2024>
- Roser, M. (2022). *The brief history of artificial intelligence: The world has changed fast — what might be next?* Our World in Data. Retrieved May 16, 2026 from <https://ourworldindata.org/brief-history-of-ai>
- Sevian, H., & Talanquer, V. (2014). Rethinking chemistry: A learning progression on chemical thinking. *Chemical Education Research and Practice*, 15(1), 10–23. <https://doi.org/10.1039/C3RP00111C>
- Southworth, J., Migliaccio, K., Glover, J., Glover, J., Reed, D., McCarty, C., Brendemuhl, J., & Thomas, A. (2023). Developing a model for AI across the curriculum: Transforming the higher education landscape via innovation in AI literacy. *Computers and Education: Artificial Intelligence*, 4, Article 100127. <https://doi.org/10.1016/j.caeai.2023.100127>
- Stanford, University, & Office of the Provost. (2025). *Report of the AI at Stanford Advisory Committee*. Retrieved May 16, 2026 from <https://provost.stanford.edu/news/report-ai-stanford-advisory-committee>
- Stanford, University, & Office of Community Standards. (2023). *Generative AI Policy Guidance*. Retrieved May 16, 2026 from <https://communitystandards.stanford.edu/generative-ai-policy-guidance>
- Stokel-Walker, C. (2022). AI bot ChatGPT writes smart essays—Should professors worry? *Nature*. <https://doi.org/10.1038/d41586-022-04397-7>
- Sui, C. J., Chen, H. C., Cheng, P. H., & Chang, C. Y. (2023). The Go-Lab Platform, an inquiry-learning space: Investigation into students' technology acceptance, knowledge integration, and learning outcomes. *Journal of Science Education and Technology*, 32, 61–77. <https://doi.org/10.1007/s10956-022-10008-x>
- The Nobel Prize in Chemistry 1990. (2025). NobelPrize.Org. Retrieved May 16, 2026 from <https://www.nobelprize.org/prizes/chemistry/1990/core/facts/>
- Tsai, C. C., & Chai, C. S. (2012). The third-order barrier for technology-integration instruction: Implications for teacher education. *Australasian Journal of Educational Technology*, 28(6). <https://doi.org/10.14742/ajet.810>
- UNESCO. (2024). AI competency framework for students. *UNESCO*. Retrieved May 16, 2026 from <https://doi.org/10.54675/JKJB9835>
- Walter, Y. (2024). Embracing the future of artificial intelligence in the classroom: The relevance of AI literacy, prompt engineering, and critical thinking in modern education. *International Journal of Educational Technology in Higher Education*. <https://doi.org/10.1186/s41239-024-00448-3>
- Weng, X., Ye, H., Dai, Y., & Ng, O. (2024). Integrating artificial intelligence and computational thinking in educational contexts: A systematic review of instructional design and student learning outcomes. *Journal of Educational Computing Research*, 62(6), 1420–1450. <https://doi.org/10.1177/07356331241248686>
- Wu, J. Y., Lee, Y. H., Chai, C. S., & Tsai, C. C. (2025). Strengthening human epistemic agency in the symbiotic learning partnership with generative artificial intelligence. *Educational Researcher*, 54(6), 358–368. <https://doi.org/10.3102/0013189X251333628>
- Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education – Where are the educators? *International Journal of Educational Technology in Higher Education*, 16, 39. <https://doi.org/10.1186/s41239-019-0171-0>
- Ziatdinov, R., Atteraya, M. S., & Nabiye, R. (2024). The fifth industrial revolution as a transformative step towards Society 5.0. *Societies*, 14(2), 19. <https://doi.org/10.3390/soc14020019>

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