Generative AI-Empowered Multimodal Intelligent Teaching Assistants for Physical Chemistry Education: Practice, Innovation, and Pedagogical Exploration

Hongyan Li*, **Zhiwang Liu, Wei Wen**
School of Chemistry and Materials Science, Jinan University, Guangzhou, Guangdong, China
**Corresponding Author*

Abstract: As a basic course with deep theoretical knowledge, abstract ideas and complicated experimental steps, Physical Chemistry is quite difficult for students to master both in terms of concept and practical application. The conventional teaching methods usually have some shortcomings in arousing the interest of the learners and giving individualized teaching assistance. In this research, a multimodal intelligent teaching assistant based on generative artificial intelligence (AI) has been developed by combining various educational resources such as textual materials, visual contents, instructional videos and virtual simulation experiments. The system is intended to solve some important problems in Physical Chemistry teaching, for example, the difficulty in understanding concepts, the lack of chance to do experiments, the few learning routes and the insufficient personalized instruction. The results show that the proposed framework can not only improve the students' learning enthusiasm and concept attainment, but also enhance the teaching efficiency and promote the fair distribution and sharing of educational resources.

Keywords: Generative AI; Physical Chemistry; Multimodal Teaching; Virtual Experiments; Personalized Learning

1. Course Overview

Physical Chemistry is a basic course in chemistry and related fields, including main subjects like thermodynamics, electrochemistry, chemical kinetics and quantum chemistry. This course not only builds up solid theoretical foundations but also highlights its practical uses. As a multidisciplinary subject combining the principles of chemistry, physics and mathematics, Physical Chemistry has a high level of abstraction and logical difficulty, which usually makes it a challenging subject for the students during the learning process.

In the usual teaching methods, the main activities are lectures and practical demonstrations. Due to the abstractness of the subject and the wide range of disciplines, students usually have difficulty in forming a systematic cognitive structure, especially in grasping the microscopic processes such as thermal energy transformation and electrochemical electron transfer. Moreover, practical instruction is often restricted by the availability of experimental equipment, time and financial resources. This problem is particularly noticeable in electrochemistry and new energy materials, where the laboratory teaching is mainly based on theoretical demonstrations, thus providing little chance for direct practice and inquiry-based investigation. Recently, some universities have tried to use online learning systems and virtual simulation experiments in the teaching of Physical Chemistry. However, the present approaches are still mainly based on video instruction or presentation materials, with little interactivity and inadequate intelligent assistance. Therefore, these methods are not able to meet the requirements of individualized learning and explorative involvement effectively.

Therefore, it is important to solve the conceptual difficulty in Physical Chemistry teaching and improve both the theoretical understanding and experimental skills of the students. This need is especially urgent in the developing areas such as new energy and environmental science, where a good background in Physical Chemistry is necessary for scientific research and technological progress. Under such circumstances, the integration of modern information technologies, particularly AI, into the teaching procedure is considered a significant way to establish intelligent, interactive and individualized learning conditions [1].

2. Research Status and Analysis

With the fast development of information technology and AI, the teaching methods in the educational field are undergoing significant changes [2,3]. As a subject which requires solid theoretical basis and much practical work, Physical Chemistry has become an important part of the educational reform. The present teaching of Physical Chemistry is moving from the traditional lecture-based method and the demonstration of experiments to the integration of digital and intelligent technologies. However, the existing problems that students find it hard to understand the abstract theoretical knowledge and to master the experimental techniques have not been completely solved yet. Various teaching methods, such as blended learning and flipped classrooms, have been suggested in both domestic and foreign researches. Some universities have also tried to enhance the teaching effect by using information-based teaching methods. But these explorations are mainly carried out in separate online or offline forms and lack enough interactivity and individualized assistance. For example, online learning platforms like MOOCs offer a lot of educational materials, but their main focus is on the transmission of contents instead of the real-time analysis of learning behaviors and adaptive feedback. Therefore, it is not easy to keep the students' interest and maintain their long-term learning motivation. Although the application of virtual experiments has somewhat reduced the restrictions caused by the laboratory equipment, its efficiency is still restricted by high technical difficulties and low interactivity, which makes it hard to provide an immersive learning experience.

In the field of AI applications, previous research has investigated the application of AI techniques in intelligent question answering and personalized learning suggestions. However, most investigations have concentrated on language and mathematical disciplines, whereas studies about natural sciences, such as Physical Chemistry, are still in an initial stage. Particularly, the construction of intelligent teaching assistants which utilize multimodal data, including text, images, videos and experimental datasets, has received relatively little attention. The existing AI-assisted instructional systems mainly focus on the transmission of knowledge and automatic evaluation, but lack the ability to analyze deeply the learning behaviors of students or to provide effective support for the improvement of experimental skills. At present, some universities have started to apply generative AI in education, which can provide personalized learning materials according to the characteristics and progress of the learners [4,5]. Nevertheless, these systems are primarily designed for basic courses and there is a lack of systematic research on the combination of multimodal generative AI in the education of Physical Chemistry, a subject which combines both the theoretical complexity and the experimental sophistication. Therefore, it is an important problem to be studied how to effectively combine generative AI with the theoretical framework and experimental parts of Physical Chemistry.

Considering the above situation, the study on multimodal intelligent teaching assistants based on generative AI has great academic and practical importance. As an important factor in the current technological progress and industrial change, generative AI shows strong potential in educational fields because of its excellent computational, analytical and information generating abilities. Its practical value is becoming evident in various aspects of education such as teaching processes, student learning and instructional evaluation. Compared with the traditional teaching methods, the multimodal teaching assistants driven by generative AI have special advantages in educational resource supply, learning assistance, teacher-student communication, experimental accessibility and instructional fairness [6]. In addition to its outstanding natural language processing function, generative AI can combine and produce different multimodal educational resources like textual materials, visual contents, animations and experimental simulations, thus giving students personalized and interactive learning support. For instance, by using virtual electrochemical experiment simulations, students can learn about the experimental steps and complex microscopic mechanisms without the need for actual laboratory equipment. These applications provide unique benefits in improving both the learning efficiency and practical skills.

Though the application of generative AI in Physical Chemistry teaching is at an early stage, several significant problems should be resolved. One major difficulty is the establishment of a comprehensive, accurate and frequently updated knowledge base to ensure the scientific validity and consistency of the generated information. Another problem lies in the development of efficient teaching strategies based on multi-modal data, which is anticipated to increase the students' interest in learning and their involvement in classes. Furthermore, it is challenging to provide individualized learning suggestions to help the students acquire knowledge according to their own progress and cognitive characteristics. However, the possible advantages and extensive applications of generative AI in education cannot be overlooked. Considering these problems and practical needs, our present research aims to integrate the multi-modal features of generative AI to create an intelligent teaching assistant with functions including knowledge base construction, personalized recommendations, virtual experiments and real-time communication in one system. This proposed system is intended to overcome certain teaching difficulties such as the shortage of instructional materials, lack of personalized assistance and constraints on the opportunities for experimental practice. By adopting this method, the study not only offers a feasible way to improve teaching efficiency, promote educational equality and enhance the students' practical skills, but also gives valuable theoretical and practical guidance for the future reform of science and engineering education and interdisciplinary teaching.

3. Necessity of Generative AI

Generative AI, a new technology which has progressed rapidly in recent years, shows great promise in many areas such as scientific research, industry, healthcare and education due to its abilities in natural language processing, image generation, speech synthesis and multi-modal integration [7,8]. Especially in the educational field, generative AI changes the teaching methods and learning ways by its ability to understand, reorganize and present complicated information in adjustable forms. In fields like material science, biotechnology and environmental engineering, AI technologies have been used to assist in the design of experiments and problem-solving, thus stimulating students' creativity and research consciousness. For Physical Chemistry, a subject with intensive theoretical knowledge, high conceptual abstraction and difficult experimental contents, the application of generative AI not only fits with the general trend of educational modernization, but also opens up new opportunities to solve the long-standing instructional problems.

One of the main advantages of generative AI is its ability to solve the problems in understanding abstract knowledge in Physical Chemistry. Important subjects like thermodynamics, electrochemistry and chemical kinetics contain many mathematical expressions and microscopic mechanisms which are usually hard for students to comprehend intuitively. By creating visual diagrams, animations and learning materials based on the teaching requirements, AI technology can show processes such as energy conversion, electron transfer and change of reaction rate in a clearer and easier way, thus helping students to understand the main concepts better. Moreover, generative AI can produce hierarchical explanations and different exercises, allowing teachers to adjust the teaching materials quickly and carry out more effective individualized instruction. Additionally, generative AI has great advantages in personalized learning. Traditional classroom teaching usually follows a fixed teaching speed, which makes it inconvenient to meet the differences among students' backgrounds and learning abilities. Through the real-time analysis of the learning data, the AI system can find out the weak points of each student and design appropriate learning routes according to their individual needs. For instance, if the students have difficulty in mastering the principle of Le Chatelier, the system can suggest relevant simulation experiments, explanatory videos and special exercises automatically to help them master the concept step by step. These adaptive supportive measures can improve the learning motivation and enhance the students' sense of achievement.

Moreover, the combination of generative AI greatly improves the interactivity and immersion in the learning process. With the help of natural language processing techniques, students can communicate with AI tutors at any moment and get immediate replies to their academic problems. At the same time, virtual experiment modules enable learners to perform experiments and watch the dynamic procedures, such as electrochemical reactions, in safe and inexpensive virtual settings. These features not only broaden the range of experimental teaching, but also facilitate the development of practical skills and inquisitive learning abilities. Besides, the use of generative AI helps to enhance educational equality. The AI-assisted instructional systems can offer ongoing learning assistance and various educational materials without being restricted by geographical locations and differences in teaching resources, thus providing more access to high-quality educational chances, especially in areas with scarce resources [9].

The application of generative AI in Physical Chemistry teaching has important theoretical and practical value. It helps to improve the understanding of concepts by means of visualization and production of multi-modal content, enhances the depth of learning and experimental ability through individualized teaching and virtual experiments, and also improves the instructional interaction and sharing of educational resources. Therefore, it is expected that the establishment of multimodal intelligent teaching assistants based on generative AI will become an important way to promote the reform and modernization of Physical Chemistry teaching.

4. Approaches for Integrating Generative AI into Physical Chemistry

4.1 Design and Application of a Multimodal AI Teaching Assistant

This research suggests a multimodal intelligent teaching assistant system using generative AI, which is designed according to four main aspects, such as intelligent resource combination, individualized learning suggestion, real-time communication and virtual experiment. The purpose is to overcome the shortcomings of the present teaching methods and make full use of the benefits of AI technology in educational activities.

The first step is to establish an intelligent knowledge base. By means of the specific training of GPT-based large language models, the system integrates the main parts of Physical Chemistry textbooks with the newest scientific research findings to construct a comprehensive knowledge framework which includes thermodynamics, chemical kinetics, electrochemistry and spectroscopy [10]. For example, when explaining the relationship between chemical equilibrium constants and Gibbs free energy, the intelligent assistant can not only acquire the related equations but also connect some practical cases, like the open-circuit voltage of fuel cells, to illustrate the connection between the thermodynamic laws and the actual energy conversion efficiency.

The second part deals with the combination of multiple modes of instructional materials. The conventional teaching aids, such as textbooks and slide presentations, are developed into multimodal educational materials which include textual descriptions, pictures, animations and experimental videos. Especially, some visual examples and demonstrations are designed for the difficult concepts like electrochemistry and chemical kinetics in order to enhance the clarity and interest of the learning contents. For instance, in the molecular statistical thermodynamics, the students can directly see the particle distribution among various energy levels by using three-dimensional animations, thus obtaining a better understanding of the physical meaning of the Boltzmann distribution. In the electrochemistry module, the system can show the change of cyclic voltammetry curves dynamically, so that the students can establish the relationships between the electrode processes and the experimental results.

The third part deals with the recommendation of personalized learning routes. According to the students' learning behavior data, such as the accuracy of answers, study time and operation modes, the system constructs adaptive learning routes dynamically and recommends additional materials and special exercises based on their individual weaknesses. This method helps to provide more effective individualized teaching. For instance, when students have difficulty in grasping the transition state theory or the relationship between temperature and rate constants, the system can offer visual explanations of the Arrhenius equation along with reinforcement exercises and practical examples about reaction rate constants, thus aiding the students in gradually overcoming the conceptual difficulties.

The fourth part deals with the establishment of virtual experimental modules. The system provides virtual simulations for different Physical Chemistry experiments, which can overcome the difficulties of laboratory equipment, financial constraints and safety problems. It allows the students to repeat the practice of experimental procedures in an inexpensive and manageable environment, thus improving their practical skills and enhancing their ability of inquiry-based learning. For instance, the students can carry out galvanostatic charge-discharge experiments on the virtual platform and observe the variations of charge-discharge curves in real time under various current densities. In the spectroscopy modules, the system can simulate the acquisition of infrared and Raman spectra, so that the students can form clear relationships between the molecular vibration modes and the spectral peak characteristics. In the chemical kinetics experiments, the learners can change the parameters like temperature and concentration to study the variation of reaction rates, which helps them to gain a deeper knowledge of the kinetic equations and reaction mechanisms.

4.2 Integration of Physical Chemistry and Generative AI

In the teaching of Physical Chemistry, several aspects are highly abstract and conceptually complex, which is not easily solved by traditional teaching methods. Due to its strong ability in data processing and multi-modal assistance, generative AI can considerably overcome these difficulties by facilitating students' better understanding and mastery of difficult concepts, thus improving both the teaching quality and learning results [11,12]. Specifically, generative AI can be extensively applied in various fields of Physical Chemistry teaching to promote knowledge construction and enhance students' practical abilities.

(1) The combination of thermodynamics and generative AI. As an important part of Physical Chemistry, thermodynamics includes concepts like energy, work, heat and fundamental thermodynamic laws. The traditional teaching method in this field mainly depends on mathematical derivation and abstract theoretical models, which is usually hard for the students to understand intuitively. By means of automatically produced dynamic simulations, generative AI can show visually the processes of energy conversion and the connection between work and heat transfer. For example, when teaching the Carnot cycle, the AI system can generate animations to explain the temperature change and energy flow during the cycle at the same time, and also introduce the second law of thermodynamics in real time. Moreover, it can offer different exercises according to the students' abilities, such as Gibbs free energy calculations and thermodynamic function analysis, thus strengthening both the theoretical knowledge and practical application.

(2) Integrating chemical equilibrium with generative AI. The topics concerning chemical equilibrium include equilibrium constants, reaction rates and the impact of external factors on equilibrium states, which have a high degree of conceptual abstraction. By using virtual experimental systems, generative AI can simulate the changes of dynamic equilibrium under different temperatures, concentrations and pressures. For instance, AI can show the influence of temperature and pressure on equilibrium conversion in ammonia synthesis reactions and produce corresponding equilibrium diagrams at the same time. Moreover, by including actual industrial examples such as process optimization in ammonia synthesis, AI-assisted teaching can help to link theoretical knowledge with practical applications.

(3) The combination of electrochemistry and generative AI. Electrochemical processes include electrode reactions, ion migration and working principles of batteries, which are difficult to be investigated experimentally. Generative AI can build virtual electrochemical laboratories to simulate the charging and discharging processes of metal-ion batteries. Thus, students can observe the dynamic changes of electron transfer and ion diffusion and get the automatic analysis of experimental data and electrochemical curves. For instance, when studying cyclic voltammetry, AI systems can produce voltammetric curves at various scan rates and determine the corresponding kinetic properties of electrochemical reactions. These functions help students to establish a better connection between the observed phenomena and the reaction mechanisms, thus making up for the shortcomings in the practical laboratory experience.

(4) Chemical kinetics requires students to learn about rate equations, reaction orders and mechanistic derivations which often include much computation and logical problems. Generative AI can simulate reaction rates under different experimental conditions, allowing

students to change parameters such as temperature and concentration and see the corresponding variations in reaction rates in real time. For example, when teaching the Arrhenius equation, AI can draw the relationship curves between activation energy and reaction-rate constants and perform the linear fitting of experimental data, helping students to understand the exponential relationships in an intuitive way. Furthermore, AI-assisted systems can process the experimental data automatically and identify the possible rate-determining steps or reaction mechanisms, which is useful for enhancing students' logical reasoning and data-analytical abilities.

(5) Spectroscopy is important in Physical Chemistry, but novices often have trouble in interpreting spectra. Generative AI can produce animated visuals of molecular vibrations and rotations, which help the students to comprehend the causes of infrared and Raman spectral lines. For example, the AI can simulate the symmetric stretching and bending vibrations of carbon dioxide molecules and its related spectral patterns. By contrasting the simulated and actual spectra, the students can enhance their knowledge about spectral analysis. In ultraviolet visible spectroscopy, AI can also give dynamic displays of electronic energy level changes, so that the students can link the molecular orbital theory with the experimental results.

(6) Integrating virtual experiments with generative AI. Physical Chemistry experiments usually have limitations due to high cost of instruments, complicated operations and strict safety regulations. Virtual experimental modules based on generative AI offer a low-cost, reproducible and risk-free learning atmosphere for students. In these systems, students can carry out experiments such as acid-base titration and electrochemical measurements, and continuously improve their operating methods and check the experimental outcomes. For instance, when studying gas laws, students can modify the temperature and volume in the virtual system and see the pressure changes in real time, at the same time the AI generates the experimental curves to help them gain a better understanding of Boyle's law and Charles's law.

(7) Personalized learning together with generative AI. The combination of personalized learning and generative AI emphasizes the educational significance of intelligent teaching methods. Since the subject of Physical Chemistry is wide and students have different academic backgrounds and learning preferences, a one-size-fits-all teaching method usually cannot satisfy the individual learning requirements. By examining the learning behavior data, such as the accuracy of answers, performance in virtual experiments and studying time, generative AI can suggest appropriate learning routes in an intelligent way. For instance, when students find it hard to understand the concept of wave function in quantum chemistry, the AI system can offer relevant visual videos, exercises and experimental examples automatically, like the three-dimensional representations of hydrogen atomic orbitals. This kind of special assistance assists the students in gradually overcoming the conceptual obstacles and improves their learning confidence and enthusiasm.

5. Conclusion

This research comprehensively examines the use of generative AI in Physical Chemistry teaching and constructs a multimodal intelligent tutor aimed at overcoming some main shortcomings of the present instructional methods, such as the lack of sufficient educational materials, limited experimental facilities and insufficient individualized assistance. The results show that the combination of generative AI remarkably enhances both the teaching effectiveness and the instructional quality, and promotes the active learning and personal development of the students. Especially, significant improvements have been found in understanding of abstract ideas, improvement of experimental ability and optimization of adaptive learning procedures.

Generative AI can overcome the shortcomings of the current one-way knowledge transmission method by integrating knowledge and generating information efficiently. It can produce different kinds of instructional materials such as visual information, animations and virtual experiments and give individualized help to the students according to their learning conditions and weak points. Thus, the AI-assisted systems can greatly enhance the students' interest in study and teaching effectiveness. These benefits are especially significant in the teaching of hard subjects like thermodynamics, electrochemistry and chemical kinetics. Moreover, the use of AI technology enlarges both the scope and content of teaching activities. Intelligent teaching assistants can offer virtual experiments, online academic aid and relevant resource suggestions in both classroom and after-class situations, so as to establish a complete learning framework which combines classroom teaching, virtual experiments and intelligent feedback. This arrangement can change the students' passive way of acquiring knowledge into an active and enquiry-based learning strategy. However, this study also reveals some issues in the AI-assisted instruction. It is necessary to develop and keep on improving the knowledge base to guarantee the scientific accuracy and credibility of the teaching materials. In addition, the relationship between the support given by AI and the teacher's guidance should be clarified to maintain an appropriate equilibrium between human teaching and intelligent methods. Furthermore, there are still considerable disparities in educational resources among different regions which influence the applicability and wider usage of the AI-based teaching systems.

Furthermore, with the continuous advancement of technologies like AI, virtual reality and augmented reality, generative AI is leading the education of Physical Chemistry towards a new era which combines intelligence and individualization. The establishment of realistic and interactive teaching systems is anticipated to improve the learning processes and experimental abilities, as well as to facilitate the exchange of educational resources and educational fairness. Additionally, the teaching method proposed in this paper may offer useful guidance for the curriculum reform in other sciences, engineering and interdisciplinary areas, and is probably to play an important role in future educational innovations.

Acknowledgments

This work was supported by the 2024 Guangdong Provincial Higher Education Teaching Reform Project (No. 82625410).

References

[1] J. T. DuBose, S. B. Scott, B. Moss. Physical Chemistry Education and Research in an Open-Sourced Future. ACS Physical Chemistry Au, 2024, 4(4): 292-301.

[2] L. Yu, Z. Xiuping, C. Jin. Optimisation of Teaching Methods and Practical Exploration of Teachers' Teaching Methods in Vocational Education Based on AI Assistance. Applied Mathematics & Nonlinear Sciences, 2025, 10(1).

[3] S. V. Singh, K. K. Hiran. The Impact of AI on Teaching and Learning in Higher Education Technology. Journal of Higher Education Theory and Practice, 2022, 22(13): 135-148.

[4] Z. Epstein, A. Hertzmann, Investigators of Human Creativity, et al. Art and the Science of Generative AI. Science, 2023, 380(6650): 1110-1111.

[5] Y. Dong. Generative AI Technologies and Educational Outcomes: A Comprehensive Meta-Analysis Comparing Traditional and AI-Driven Approaches. Humanities and Social Sciences Communications, 2026.

[6] M. Giannakos, R. Azevedo, P. Brusilovsky, et al. The Promise and Challenges of Generative AI in Education. Behaviour & Information Technology, 2025, 44(11): 2518-2544.

[7] D. Baidoo-Anu, L. O. Ansah. Education in the Era of Generative Artificial Intelligence (AI): Understanding the Potential Benefits of ChatGPT in Promoting Teaching and Learning. Journal of AI, 2023, 7(1): 52-62.

[8] U. Mittal, S. Sai, V. Chamola, et al. A Comprehensive Review on Generative AI for Education. Ieee Access, 2024, 12: 142733-142759.

[9] S. Gabriel. Generative AI and Educational (in) Equity. International Conference on AI Research, 2024, 4(1): 133-142.

[10] F. Fui-Hoon Nah, R. Zheng, J. Cai, et al. Generative AI and ChatGPT: Applications, Challenges, and AI-Human Collaboration. Journal of Information Technology Case and Application Research, 2023, 25(3): 277-304.

[11] E. A. Alasadi, C. R. Baiz. Multimodal Generative Artificial Intelligence Tackles Visual Problems in Chemistry. Journal of Chemical Education, 2024, 101(7): 2716-2729.

[12] A. S. George. The Potential of Generative AI to Reform Graduate Education. Partners Universal International Research Journal, 2023, 2(4): 36-50.

