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Innovative Practice and Application Research on Artificial Intelligence Empowering High School Chemistry Experiment Teaching

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Abstract: Against the backdrop of the global wave of Artificial Intelligence (AI) technology sweeping through the education sector, traditional high school chemistry experiment teaching faces numerous challenges such as safety concerns, cost, spatiotemporal limitations, and the difficulty in observing and understanding certain experimental phenomena. This study aims to systematically explore how artificial intelligence can empower high school chemistry experiment teaching to break through the bottlenecks of traditional teaching models and enhance teaching quality and learning experience. The research first reviews the core technologies of AI applications in education and relevant educational theoretical foundations, pointing out the deep alignment between AI technology and constructivist learning theory. On this basis, the paper systematically proposes four innovative practice pathways for AI-empowered high school chemistry experiment teaching: constructing intelligent virtual/augmented reality laboratories, achieving intelligent guidance and safety monitoring of experimental processes, enabling intelligent analysis of experimental data and report generation, and supporting personalized experiment design and inquiry-based learning. To integrate theory with practice, this study designs and proposes a P-I-A-E (Preparation & Prediction, Interaction & Inquiry, Analysis & Assessment, Evaluation & Extension) four-stage closed-loop teaching model, and builds a multi-dimensional evaluation index system covering knowledge acquisition, experimental skills, scientific inquiry, and data literacy around this model. Finally, the paper deeply analyzes the potential technical, teacher-related, cost, and ethical challenges in the promotion and application of this model, and provides an outlook on future development trends. The study believes that the deep integration of artificial intelligence will reshape the teaching form of high school chemistry experiments, propelling it towards a direction characterized by intelligence, personalization, precision, and safety.

Keywords: Artificial Intelligence, High School Chemistry, Experiment Teaching, Teaching Model, Innovative Practice, Virtual Reality.

1. Introduction

1.1. Research Background

Currently, AI in education is developing rapidly worldwide. Artificial intelligence technology, with its strong capabilities in data processing, simulation, and interaction, is bringing unprecedented changes to the field of education. However, in this context, high school chemistry experiment teaching faces several difficulties that need to be addressed.

Firstly, regarding safety, chemical experiments involve various hazardous chemicals and operations, like exposure to flammable, explosive, and toxic substances. Even with teachers constantly stressing safety rules, accidents can still happen during student operations, threatening personal safety.

Cost is also a big issue. Chemical experiments need numerous reagents and instruments, and frequent experimentation puts economic pressure on schools.

There are spatiotemporal limits too. School lab opening hours are restricted, making it hard for students to do experimental inquiries anytime. Also, some complex experiments can't be carried out due to venue constraints.

Another problem is unobservable microscopic phenomena. Students find it tough to directly see reaction processes at the molecular and atomic levels, making it harder to grasp the essence of chemistry. Experimental teaching is vital for students to master chemical knowledge, but current teaching has many issues[1].The environmental pollution problems stemming from chemical experiments also underscore the drawbacks of traditional experiments[2].

1.2. Research Purpose and Significance

This research aims to use AI to tackle challenges in traditional high school chemistry experiment teaching. Traditional methods are inadequate in resource development and fostering students' creative thinking[3]. AI can create intelligent virtual or augmented reality labs, resolving safety, cost, and spatiotemporal constraints. With intelligent guidance and safety monitoring, it ensures experiments follow standards. Intelligent data analysis eases teachers' workload. Personalized experiment design based on students' learning conditions can spark their creative thinking.These measures enhance teaching quality and students' learning experience, meeting the core competency requirements of new curriculum standards, cultivating students' chemical skills, and adapting to educational changes in the intelligent age[4]

2. Literature Review

2.1. Application of Artificial Intelligence in Education

The application of artificial intelligence in education is

increasing, particularly its core technologies like machine learning, natural language processing (NLP), and computer vision (CV), which have shown significant roles and effects in both higher education and K-12 education scenarios.

In higher education, for instance, in university English courses, AI can assist in teaching evaluation, analyzing student learning situations, and optimizing teaching methods, playing an important role. Cai Ming and Liu Yang (2024) stated that with the advancement of AI technology, its integration with the education field is becoming closer, offering significant advantages in areas like university English classroom teaching evaluation[5]. Machine learning can predict students' learning progress and potential problems based on their learning data, NLP can enable intelligent Q&A and text analysis, and CV can be used for exam proctoring.

In K-12 education scenarios, taking chemistry experiment teaching as an example, although current focus might be on junior high school chemistry experiment teaching resource development, AI's core technologies can provide assistance such as virtual experiment scenarios and intelligent guidance. Liu Jinying (2022) specifically studied the development and integration of junior high school chemistry experiment teaching resources[6], and these core AI technologies can offer help like virtual experiment scenes and intelligent guidance.

From a constructivist perspective, AI aligns well with constructivist learning theory. It can provide personalized learning support based on students' different characteristics, helping students actively acquire knowledge through interaction with the environment, which is consistent with constructivism's emphasis on active student participation and self-construction of knowledge.

2.2. International Research Status

In recent years, the application of AI in science education has gradually become a hot topic in international research. Lee et al. (2025) indicated that AI technology has garnered widespread attention in science education research. Its applications involve not only the reshaping of learning objectives and content but also extend to assessment methods, teacher professional development, and educational equity. However, related practices still face challenges such as ethics and explainability[7]. Meanwhile, Erümit and Sarıalioğlu (2025), through a systematic review, pointed out that the number of application studies of AI in science and chemistry education increased significantly between 2021 and 2024. Typical forms include conversational tools like ChatGPT and multimodal learning environments. These technologies perform prominently in promoting personalized learning, interdisciplinary integration, and the online transition of experiment courses, but also bring issues like gender and racial bias, academic integrity risks, and insufficient technical reliability[8]. Furthermore, Gaitantzi and Kazanidis (2025), in a systematic review of computer science education, found that AI tools like intelligent tutoring systems and code generators have effectively supported personalized teaching and instant feedback, but dilemmas remain, such as strong student dependency, algorithmic bias, and academic integrity risks, suggesting that future education needs to balance tool application and the importance of the teacher's role when promoting AI[9]. Overall, international research emphasizes both the potential and challenges of AI in science and related subject education, providing valuable theoretical references and practical insights for China's exploration of AI-empowered high school chemistry experiment teaching.

2.3. Domestic Research Status

Domestically, traditional high school chemistry experiment teaching has achieved some results in resource development, greening, and cultivating creative thinking, but there are also obvious shortcomings. In terms of resource development, Wang Hongbin (2021) pointed out that the development and application of high school chemistry experiment teaching resources under the new curriculum standards are not optimal, with low teacher enthusiasm for resource development, unsound operational mechanisms, and relatively low application effectiveness[10].

Regarding greening, due to increasing societal emphasis on environmental protection, Cheng Hongxia (2022) proposed incorporating green chemistry concepts into high school chemistry experiment teaching to effectively reduce environmental pollution[2].In cultivating creative thinking, Qin Liping (2021) emphasized that in high school chemistry teaching, teachers should follow creative thinking concepts to guide students in participating in experiments and improving chemical abilities[3].

These shortcomings indicate the limitations of traditional teaching, while the application of AI in education provides new methods to solve these problems, as demonstrated by Li Zhonghao et al. (2025) achieving good results using AI in molecular biology teaching, which offers insights for high school chemistry experiment teaching[11].

3. Innovative Practice Pathways for AI-Empowered High School Chemistry Experiment Teaching

3.1. Constructing Intelligent Virtual/Augmented Reality Laboratories

Building intelligent virtual or augmented reality laboratories is an important method for AI to assist high school chemistry experiment teaching. When constructing VR/AR experiment scenarios, advanced digital modeling technology is used to create highly realistic representations of various instruments, reagents, and reaction scenarios in chemical experiments. Students feel as if they are in a real laboratory, clearly experiencing every step of the experiment.

In terms of interaction design, through technologies like gesture recognition and voice interaction, students can freely operate virtual instruments and simulate experimental procedures. This highly interactive experience can significantly increase student engagement and learning interest.

From the perspectives of green chemistry and cost savings, virtual/augmented reality laboratories do not require real chemical reagents and instruments, thus consuming no reagents and causing no instrument damage, greatly reducing experiment costs. Simultaneously, chemical waste is reduced, aligning with the concept of green chemistry.

Regarding safety, virtual experiments differ from real ones; there are no risks of explosion, poisoning, or other dangerous situations, ensuring absolute safety in experimentation. Students can experiment freely without constant worry about accidents, thereby mastering experimental skills and related knowledge more effectively. Applying AI in education can bring new changes to teaching[12][13], and building intelligent virtual/augmented reality laboratories exemplifies

this.

3.2. Intelligent Guidance and Safety Monitoring of Experimental Processes

In high school chemistry lab class, AI technology is very important for smart guide and safe monitor. It can give real-time remind by speak or text, tell student about operation warning and main step follow the experiment process. Just like a smart teacher help student complete experiment smoothly.

Error warning is very important. AI watch student operation and give alert when student do something not correct. For example, if student add too much reagent or do step in wrong order, system will quickly remind them to fix it, so can reduce mistake in experiment.

The dangerous operation block system is the last way to keep experiment safe. If a student do something risky, AI will stop it at once, like shut down machine or cut off power, to avoid accident[14]. By this method, AI make sure experiment run in correct and safe way, give students a safer place to learn, and help improve experiment teaching quality[15].

3.3. Intelligent Analysis of Experimental Data and Report Generation

In high school chemistry experiment, AI is very useful for data analysis and write report. It can collect data automatic, and record different information accurate when experiment doing. This can avoid mistake or miss that happen by hand write.

But the data collected usually have noise or miss some value. AI can pick out this bad quality data, make sure the other part is usable and good quality.

After clean the data, AI show it in charts or graphs so easy to understand. This help student and teacher to see the experiment result and data trend more clear. According to the analyzed data, AI also can make personal report for every student. The report content match each student’s experiment situation and data character, include experiment purpose, step, result analysis, and some advice.

This process very reduce teacher's work load, make them not need spend much time and energy on deal with data, analysis and write report. Use AI to handle high school chemistry experiment data can bring efficiency and convenient to teaching[16].

3.4. Supporting Personalized Experiment Design and Inquiry-Based Learning

AI help students make their own experiment and learn by asking questions. It look at how each student learning and give them special task. This can make student more creative and understand better.

AI collect data from student's chemistry experiment, homework and test score. It look at each student knowledge level, learning habit and thinking way, then make a special cognitive profile for them.

According to this profile, AI give experimental tasks that fit student's level and ability. For weaker students, it suggest basic experiments with step-by-step guide to help them understand knowledge better. For stronger students, it provide difficult extension experiments to let them explore deeper. This way can make every student improve in science learning.

This way is fit with Lu Tao (2025) say that use technology can improve student's practical skill [17], it can make student more creative and help them to learn more deep.

4. The "P-I-A-E" Four-Stage Closed-Loop Teaching Model

4.1. Model Design Philosophy and Structure

The P-I-A-E four-stage closed-loop teaching model aims to make chemistry experiment teaching more effective. It comprises four interconnected stages that form a teaching cycle to enhance student learning outcomes overall. The stages are Preparation & Prediction, Interaction & Inquiry, Analysis & Assessment, and Evaluation & Extension. In the Preparation & Prediction stage, teachers help students grasp the experiment's goals and principles, enabling them to predict results and set the stage for further learning. During the Interaction & Inquiry stage, students perform the experiment, discuss with peers, and thoroughly explore experimental phenomena and underlying patterns. In the Analysis & Assessment stage, students examine and summarize experimental data and results, reflecting on what they've learned. In the Evaluation & Extension stage, teachers assess students' overall performance and guide them in expanding their knowledge and skills. This closed-loop method aligns with constructivism and experiential learning theory. Constructivism emphasizes students' active acquisition of knowledge; the P-I-A-E model encourages students to engage actively in each stage and build chemical knowledge on their own. Experiential learning theory stresses learning through direct experience; the model's four stages enable students to continuously learn and progress through experimental experiences. Integrating AI into education can transform traditional teaching models; this model incorporates AI tools at every stage, offering fresh ideas and approaches for chemistry experiment teaching[18].

4.2. Specific Implementation of Each Model Stage

Preparation & Prediction Stage: Teachers employ AI tools to assess students' past learning data, like their skills in chemical experiment operations and knowledge mastery, to develop a cognitive profile for each student. Based on these profiles, students receive preview materials for high school chemistry experiments, including virtual experiment demo videos and knowledge explanation documents. Students review these for preview and predict experimental outcomes. The AI system tracks students' preview progress and questions, automatically generating a preview report for teachers. This helps teachers clearly understand students' preview status and prepare for class.

Interaction & Inquiry Stage: Students carry out chemical experiments in an intelligent virtual/augmented reality lab. AI serves as an intelligent guide, constantly reminding them of operational steps, issuing immediate warnings for incorrect actions, and blocking dangerous operations to ensure safe and standard experimentation. Students can ask AI questions anytime during the experiment, and AI provides detailed responses and guidance. Simultaneously, AI assigns different inquiry tasks based on students' cognitive profiles, fostering creative thinking and deep learning.

Analysis & Assessment Stage: AI automatically gathers various data during the experiment, such as timing of experimental phenomena and substance reaction data. It then cleans the data and presents it graphically. Using pre-set algorithms, it checks the correctness of student operations and the reasonableness of experimental results. AI writes

personalized experiment reports, detailing students' experimental performance and data analysis results, providing a basis for evaluation by both teachers and students.

Evaluation & Extension Stage: The teacher, combined with the AI-generated experiment report, provides a comprehensive evaluation of the student's experiment, highlighting strengths and areas for improvement. Simultaneously, AI technology is used to recommend extended learning content to students, such as related interdisciplinary knowledge and new achievements in chemical research, guiding students in extended learning to form an interdisciplinary, personalized lifelong learning state. New technologies can drive educational development; using AI enables effective evaluation and extension in high school chemistry experiment teaching[19].

5. Multi-Dimensional Evaluation Index System

5.1. Principles for Constructing Evaluation Indicators

When designing evaluation indicators, four principles should be observed: Scientificity, Comprehensiveness, Operability, and Developmental nature, while also aligning with the core literacy requirements of the new curriculum standards. The Scientificity principle means that indicator design should be based on scientific theory and educational laws, ensuring accurate reflection of teaching effectiveness. The Comprehensiveness principle requires the evaluation content to cover multiple aspects such as knowledge, skills, and emotional attitudes, judging student development from different angles. Operability means indicators should be clear, specific, easy to understand, and the collection and analysis of data should be practically feasible. The Developmental principle focuses on student growth and progress, so indicator design should be dynamic, encouraging continuous student improvement. An evaluation system established according to these four principles can provide a scientific and effective quality assessment method for high school chemistry experiment teaching, thereby meeting the core literacy requirements of the new curriculum standards.

5.2. Specific Evaluation Indicator Content

After collecting data for the evaluation elements in the above four dimensions, using the corresponding AI analysis algorithms can provide deep insights into students' performance in high school chemistry experiment learning, enabling accurate diagnosis and feedback, and providing useful references for improving teaching and student development.

6. Application Challenges and Countermeasures

6.1. Technical Challenges and Response Strategies

Regarding device compatibility, the specifications of existing hardware equipment vary between schools, and the devices required by AI technology may not work well with older equipment, affecting the normal use of the teaching system. In terms of algorithm explainability, AI algorithms often resemble a "black box," making their decision-making process difficult to understand, leading to distrust from teachers and students regarding the results. Data privacy issues are also significant; students' experimental data contain much personal information, and leaks could have serious consequences.

For solutions: Address device compatibility by developing software interfaces adaptable to various hardware types for greater universality. For algorithm explainability, conduct research to make algorithms more transparent and provide clear explanations. Protecting data privacy requires establishing strict data security management systems. For upgrades and maintenance, formulate regular update plans to promptly patch vulnerabilities and improve performance.

6.2. Teacher-Related Challenges and Training Measures

Problems faced by the teaching faculty include: insufficient AI knowledge and skills, and a lack of teaching application ability. Layered training involves dividing teachers into beginner, intermediate, and advanced classes based on their foundation and needs. Beginner classes teach basic knowledge, intermediate classes improve application ability, and advanced classes focus on innovation. School-enterprise cooperation can involve enterprises providing technology and cases, while schools provide practical application scenarios. The AI mentor accompanying training mechanism uses AI mentors to answer teacher questions anytime, provide personalized guidance, and help teachers comprehensively improve their AI teaching capabilities.

6.3. Cost Challenges and Resource Optimization

In high school chemistry experiment teaching, cost is a major difficulty. The government can play a guiding role by providing financial subsidies, special funds, etc., to offer financial assistance for schools purchasing AI experiment equipment and software. Schools need to arrange funds reasonably, improve fund utilization efficiency, and avoid redundant construction and resource waste. Enterprises can also participate through equipment donations and technical cooperation. Furthermore, establishing an open and shared resource pool allows for the shared use of experimental equipment, teaching materials, etc. Implementing green experiment schemes, using low-cost, environmentally friendly experimental materials and methods, reduces experimental consumption, thereby effectively lowering teaching costs.

6.4. Ethical Challenges and Normative Guidance

The integration of artificial intelligence into high school chemistry experiment teaching brings forth notable ethical concerns, necessitating clear guidelines to prevent technology misuse.

Data Ethics: Establish regulations for data collection, storage, use, and sharing to safeguard student data security and privacy.

Algorithm Transparency: Ensure algorithmic decision-making is explainable and monitorable to prevent bias and unfairness.

Digital Literacy: Educate students on technology awareness and discernment to foster rational and safe technology use.

7. Conclusion

7.1. Technological Development Trends

Generative AI will give new life to experiment teaching. It can make personal experiment plan and guide information depend on student need. It also can simulate many kind complex experiment phenomenon, and make student's experiment horizon more wide. Edge computing let data from experiment equipment be processed and analyzed in real time, so it can reduce delay, and improve experiment response speed and accuracy. Digital twin technology can build virtual experiment model match with real experiment, let student practice again and again in virtual environment. This can reduce cost and risk of experiment, and change experiment teaching situation very deep.

7.2. Teaching Model Innovation Trends

Future high school chemistry experiment teaching will have many new change. Interdisciplinary integration will more and more obvious, like combine chemistry experiment with other subject. Cooperation between different social sector in do experiment will be very common, because can use many resource. Also, virtual experiment and real experiment can connect each other smooth, this can help build a personal lifelong learning environment. Student can choose virtual or real experiment depend on need, and do lifelong learning base on own situation, so can meet different stage of learning need.

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